International R&D Conclave

Emerging Opportunities & Challenges of R&D in Indian Power Sector

Date: 20TH -21ST FEBRUARY, 2018,

Venue: HALL NO.5, VIGYAN BHAWAN, NEW DELHI

Organized By:

CENTRAL ELECTRICITY AUTHORITY

LIST OF SELECTED PAPERS PRESENTED IN THE CONCLAVE

DAY 1: 20TH FEB 2018, SESSION 1 : THERMAL GENERATION

S.No.	ORGANIZATION	PAPER NAME	CATEGORY	AUTHORS
1	BHEL	Experimental Study On The De-NOx Efficiency Of Various Vanadium Based (V_2O_5)Catalysts For Selective Catalytic Reduction(SCR)In Coal Fired Power Plants	**THERMAL**	N.SIVA RAMA KRISHNA,I. NAGA MOHAN, DSM RAO,CM MADHUSOODANA,G. THIRUPATHI,PRABHUDEVA
2	NTPC	Biomass Co-Firing In Indian Power Plants	**THERMAL**	AMIT KULSHRESHATHA, ASHWINI KUMAR VERMA
3	GE	Coal Plants Flexibility In India : Impact Of Efficiency, Reliability And Life Time	**THERMAL**	CHINMOY MOHANTY, PRABHU, MAHESH KENDHE, HENRIK NIELSEN, MICHAEL HAUX, XIAO-YI ZHANG, NITIN AGARWAL
4	CSIR-CIMFR	High Ash Coal Gasification In Fluidized Bed Gasifier Challenges And Opportunities	**THERMAL**	P.D. CHAVAN, ARGHYA BANERJEE, VISHAL CHAUHAN, NAVNEET K GUPTA, G. SAHU, SUJAN SAHA, P. DUTTA, P.K. SINGH
5	TATA POWER	Design & Operational Challenges In Flexibilization Of Thermal Powers Plants	**THERMAL**	N GOPALAKRISHNAN UNNI, CP TIWARI
6	JCOAL JAPAN	Updates on R&D of IGCC in Japan	**THERMAL**	TETSUO SHIKATA
7	SIEMENS	Flexible Operation Of Thermal Power Plants In India	**THERMAL**	SANDEEP CHITTORA

DAY 1: 20TH FEB 2018, SESSION 2 : HYDRO GENERATION

S.No.	ORGANIZATION	PAPER NAME	CATEGORY	AUTHORS
1	SJVN LIMITED	First Filling Of Water Conductor Systems- Challenges And Mitigations With Specific Reference To Rampur Hep-412 Mw	**HYDRO**	L.M.VERMA,RAKESH SEHGAL, JASWANT KAPOOR
2	THDCIL	Alternative Methods For Design Of Support System For Underground Power House Caverns Of JTHEP(108MW): DPR Stage	**HYDRO**	R.K. VISHONI, T.S. RAUTELA, A.K. BADONI, Sr. MRG.
3	MANGDECHHU HYDROELECTRIC PROJECT AUTHORITY,BHUTAN	Innovations Implemented in 720MW Mangdechhu Hydro-Electric Project, Bhutan	**HYDRO**	A.K. MISHRA, R.K. CHAUDHARY, I. AHMED
4	NHPC LIMITED	Targeted Solution Through Emerging Geophysical Technology In Resistivity Imaging, Seismic Tomography & Ground Penetration Radar (GPR) For Optimization Of Geological Uncertainties In Hydropower Project	**HYDRO**	S.L. KAPIL, JYOTIRMOY, MOHINDER PAL SINGH, S.S.BARIHA
5	TATA POWER	Geological Surprises In Hydro Power Plants/ Projects	**HYDRO**	ANJALI KULKARNI, SURENDRA CHANDOLKAR
6	HPA DIVISION CEA	Challenges In Hydro Sector In India	**HYDRO**	ARPITA UPADHYAY, SHARVAN KUMAR, P C JILOHA
7	IIT ROORKEE/THDC	Design Challenges on Redundancy in Power and Control Circuit of Large Variable Speed Hydro Generating Unit	**HYDRO**	RAGHU SELVARAJ, KARTHIK DESINGU, ANTO JOSEPH, THANGA RAJ CHELLIAH

DAY 1: 20TH FEB 2018, SESSION 3 : RENEWABLE ENERGY

S.No.	ORGANIZATION	PAPER NAME	CATEGORY	AUTHORS
1	CPRI	A Snapshot Of Research And Development Projects Undertaken By CPRI during The 12th Five Year Plan	**RENEWABLE**	A. CHAKRABORTY, R.A. DESHPANDEY
2	YELLOW TROPUS	Energy Generation And Water Savings From Floating Solar PV (FSPV)Power Plants	**RENEWABLE**	VIVEK JHA
3	I.I.T. BOMBAY	Emerging Issues In Large-Scale Wind Intergrated Power Systems And Their Potential Solutions	**RENEWABLE**	ZAKIR H. RATHER, HAZEM KARBOUJ
4	B.B.M.B.	Perovskite-Based Low-Cost And High-Efficiency Solar Cells	**RENEWABLE**	TAJINDER KAUR
5	MSPGCL	Municipal Solid Waste To Energy Power Plant By Feasibility Study Of Waste To Energy Possibility In India	**RENEWABLE**	RAVINDRA DESHPANDE,AJAY BAMNE,
6	VISION MECHATRONICS PVT. LTD.	Economic Energy Storage Solution In Renewable Energy Specifically For India	**RENEWABLE**	RASHI GUPTA
7	NTPC	Battery Energy Storage System For Optimum Solar Energy Integration And Enhancement Of Grid Security At Andaman Island.	**RENEWABLE**	S.S. MISHRA,SUBIR KARMAKAR

DAY 2: 21ST FEB 2018, SESSION 1 : TRANSMISSION

S.No.	ORGANIZATION	PAPER NAME	CATEGORY	AUTHORS
1	KLOVER TEL,PFIFFNER TEC. LTD.	Power Quality Measurement; Importance, Gaps and Technologies	**TRANSMISSION**	ERIK SPERLING, MR. ROMAN RÖTHLISBERGER,KUMAR MUKUND
2	STERLITE POWER TRANSMISSION LTD	Challenges & Achievements Of Indian Transmission Line Industry And Emerging New Global Technologies	**TRANSMISSION**	Dr. DEEPAK LAKHAPATI
3	STERLITE POWER TRANSMISSION LTD	Power Voltage Transformers An Innovative Solution For Directly Tapping Power From EHV Lines To Reduce Diesel Consumption For Telecom Towers	**TRANSMISSION**	SANIL C NAMBOODIRIPAD, NK. PANDA, SACHIN DESHPANDE, VISHAL GOKHALE, VIVEK KARTHIKEYAN
4	CPRI	An Innovative Solution For Online Testing Of Power Transformers	**TRANSMISSION**	MANOHAR SINGH, VISHNUVARDHAN.T, K.S. MEERA
5	ARCTURUS BUSINESS SOLUTIONS	Unmanned Aerial Vehicle (UAV) Enabled Stringing	**TRANSMISSION**	SANDESH MISHRA
6	APPLIED MATERIALS INDIA PVT.LTD.	Fault Current Limiter Selection Considerations For Utility Engineers	**TRANSMISSION**	K.TEKLETADIK, P. LUBICKI, S.NICKERSON, J.LUDLUM,P.MURPHY, V.DABEER
7	POWERGRID	Smart Grid Towards Energy Transition	**TRANSMISSION**	I.S. JHA, SUBIR SEN, S. VICTOR P. SELVAKUMAR , HENANDRA AGARWAL, BHARAT HOTWANI, MANISH KUMAR TIWARI, ANKUR CHAKRABORTY, VINEETA AGARWAL, AWANISH KUMAR

DAY 2: 21ST FEB 2018, SESSION 2 : GRID OPERATION

S.No.	ORGANIZATION	PAPER NAME	CATEGORY	AUTHORS
1	COIMBATURE INSTITUTE OF TECHNOLOGY	Optimization Of Energy Harvesting From Solar Micro Grids Through Distributed Storage & Vehicle Grid Integration Strategy With Demand Response/Predictive Scheduling Framework	**GRID OPERATION**	Dr. MANIKANDAN, Dr. ELANGO, Dr. G. MANAVAALAN, A.D. THIRUMOORTHY, D. VIJESWARAN, S. RAVICHANDRAN,Dr. RAJIT
2	G.E. POWER	Reliability Assessment Of Indian Power System For Renewable Integration In 2022	**GRID OPERATION**	Dr. ANKITA SAMUI, RUSHIKESH DESHPANDE, ARUN UNNI, Dr. RAVI SEGAL, DEEPAK GUPTA, DISHA AGARWAL
3	ERDA-SUZLON	Power Quality Monitoring And Assessment As Per CEA Guidelines	**GRID OPERATION**	VIKR AM K. NAWADKAR, NIKHIL S. GUJAR, SHEFALI TALATI, NARESH PANCHAL, PULIN SHAH, V NANDAKISHORE REDDY
4	STERLITE POWER TRANSMISSION LTD	Enhancing Flexibility Of Transmission System Using Power Flow Controller & Dynamic Line Rating	**GRID OPERATION**	MOHAN BABU PALADUGU, ANANTHA KUMAR R
5	ODISHA POWER TRANSMISSION CORPORATION LTD.	Load Accessed Directional Relay (LADR) An Innovative Approach To Power System Stability.	**GRID OPERATION**	P.K. PATTANAIK, MRITYUNJAYA BISWAL, GURU PRASAD MISHRA, SIBAN BALA
6	SIEMENS	Synchronous Rotating Equipment As Backbone For Renewables	**GRID OPERATION**	MATTHIAS BACA
7	CEA IRP	Optimal Generation Mix To Meet The INDC Targets	**GRID OPERATION**	HIMANSHU UPADHYAY, P.E. KAMALA, AMMI R TOPPO, PRAVEEN GUPTA

DAY 2: 21ST FEB 2018, SESSION 3 : DISTRIBUTION

S.No.	ORGANIZATION	PAPER NAME	CATEGORY	AUTHORS
1	SAVITA POLYMERS LIMITED	New Natural Ester-based Transformer Fluid Development - Evaluation of Technical Benefits in the present Indian context	**DISTRIBUTION**	Dr C.S.NARASIMHAN
2	CARGILL INDIA	Evaluation Of Natural Ester Filled Distribution Transformer- Am Emerging Trend	**DISTRIBUTION**	RAJARAM SHINDE, NAVEEN JAIN, RAJIB CHAUDHARY
3	CESC CALCUTTA	PQ Issues In CESC's Distribution System	**DISTRIBUTION**	RAJIB KUMAR DAS
4	I.I.T.BOMBAY	How Supply Side Constraints Affect The Rural Residential Feeder Parameters	**DISTRIBUTION**	SNEHA SWAMI, GANESH HEGDE, ANAND B. RAO, SATISH B. AGNIHOTRI
5	ARUNAI ENGINEERING COLLEGE, TGDC, BDU	Prospects Of DC Microgrid In Triuvannamalai District, Tamil Nadu	**DISTRIBUTION**	V. SARAVANAN, M. ARAVINDAN, V. BALAJI, M. ARUNUGAM
6	KNIT,MMMTU	A Novel Approach For Improvement Of The System Power Factor By Optimally Placed DG And STATCOM In Distribution Systems	**DISTRIBUTION**	BINDESHWAR SINGH, PRABHAKAR TIWARI, S.N.SINGH

DAY 2: 21ST FEB 2018, SESSION 4 : TRADING/MARKETING & TARIFF

S.No.	ORGANIZATION	PAPER NAME	CATEGORY	AUTHORS
1	NREL	India And Cross- Border Energy Trading	**TRADING**	JAQUELIN COCHRAN, DAVID PALCHAK, AMY ROSE, BRENDAN MCBENNETT
2	STERLITE POWER TRANSMISSION LTD	Brazil Transmission Market – Experience of concession model	**TRADING**	AMITANSHU SRIVASTAVA, NAMRATA MUKHERJEE
3	IDAM	Addressing Challenges For Grid Integration Of Renewable Energy In Indian Power System And Framework For Hybrid Renewable Energy Development	**TRADING**	AJIT PANDIT
4	IIT DELHI	Flexibility In Transmission Switching For Congestion Management	**TRADING**	AKHIL KUMAR GUPTA, DEEP KIRAN, A.R. ABHYANKAR
5	CEA IRP	Long Term Power Purchase Agreements (PPA's) And Its Impact On Coal Based Thermal Power Plants	**TRADING**	PRAVEEN GUPTA, AMMI TOPPO, RAHUL RAJ,
6	LJUNGSTROM	Thermal Power Plant Environmental Compliance At A Much Reduced Cost	**TRADING**	PRADIP DHIR, Dr. JONAS S. KLINGSPOR
7	CERC	General Network Access- The Concept	**TRADING**	SHILPA AGARWAL, AGAM KUMAR

DAY 1: 20TH FEB 2018

SESSION 1:

THERMAL GENERATION

Experimental study on the De-NOx efficiency of various Vanadium based (V_2O_5) catalysts for Selective Catalytic Reduction (SCR) in coal fired Power plants

N Siva Rama Krishna*, I. Naga Mohan*, DSM Rao*, CD Madhusoodana*, G. Thirupathi*, Prabhudeva

*IGCC Dept., BHEL Corporate R&D Division, Vikasnagar, Hyderabad-500093, India

E-mail id: sivaram@bhel.in. Phone: +040-23882380, Fax: +040-23773363

ABSTRACT

The influence of vanadium pentoxide composition in Selective Catalytic Reduction (SCR) catalyst for De-NOx system was studied experimentally. The Vanadium Pentoxide (V_2O_5) content was varied from 0.85 to 2.2% on weight basis and tested under flue gas conditions in coal fired power plants. The flue gas was generated from an existing 200mm diameter Advanced Pressurized Fluidized Bed Gasification (APFBG) pilot plant by operating in a combustion mode. There are four modules of 8mm pitch plate type catalyst, which are tested by varying the vanadium pentoxide composition from 0.85 to 2.2% on weight basis for De-NOx efficiency. By increasing the vanadium content, the effect of space velocity and SCR operating temperature on the De-NOx efficiency have been evaluated. The space velocity was varied in the range of 1500 to 2500 per hr and flue gas temperatures were varied in the range of 300 to 350 deg. C. Anhydrous ammonia was used as reducing agent and the ratio of ammonia (NH_3) to Oxides of Nitrogen (NOx) was maintained as 1.0 for all the experiments. Based on the experimentation, it was found that when vanadium content increases in SCR catalyst the De-NOx efficiency also increases.

Key words: Selective Catalytic Reduction (SCR), Vanadium Pentoxide (V_2O_5), De-NOx Efficiency, Space Velocity, ammonia (NH_3) and Oxides of Nitrogen (NOx).

1. INTRODUCTION

Selective Catalytic Reduction (SCR) is an advanced active emissions control technologies that offers an economic and effective means of reducing Oxides of Nitrogen (NOx) emissions from flue gas by injecting a reducing agent through a special catalyst into the exhaust stream of flue gas. The SCR process is based on the reaction between NOx and NH_3, which is injected into the flue gas stream, to produce water and nitrogen. The selective catalytic reduction (SCR) of NO with ammonia has been extensively studied as a catalytic technology for NOx elimination from stationary sources [1], and a great deal of efforts have been made for the development of new catalysts for SCR reaction.

Catalytic tests performed with various oxide catalysts for the selective reduction of NO with ammonia indicated that Vanadium based catalysts are the most active in giving excellent results [2].

SCR technology is one of the most cost-effective technologies available to reduce NOx emissions from power plants. All power plants installed after 1st January, 2017 must meet the latest Environmental Protection Agency (EPA) emission standards. Out of all emissions, the oxides of nitrogen (NOx) has to be reduced to less than 100 mg/Nm^3 levels from the present level of 300 mg/ Nm^3. In order to achieve these emission norms, set by Ministry of Environment and Forest (MOEF), Government of India for NOx level for the newer power plants, BHEL has decided to establish a SCR based in-house test facility, which can handle higher ash content of Indian coals.

In view of the above, for optimizing the De-NOx efficiency, BHEL has manufactured the various SCR Plate type catalysts by varying the vanadium pentoxide (V_2O_5) composition and tested under different flue gas conditions in coal fired power plants.

2. EXPERIMENTAL

2.1. Pilot scale SCR Plant

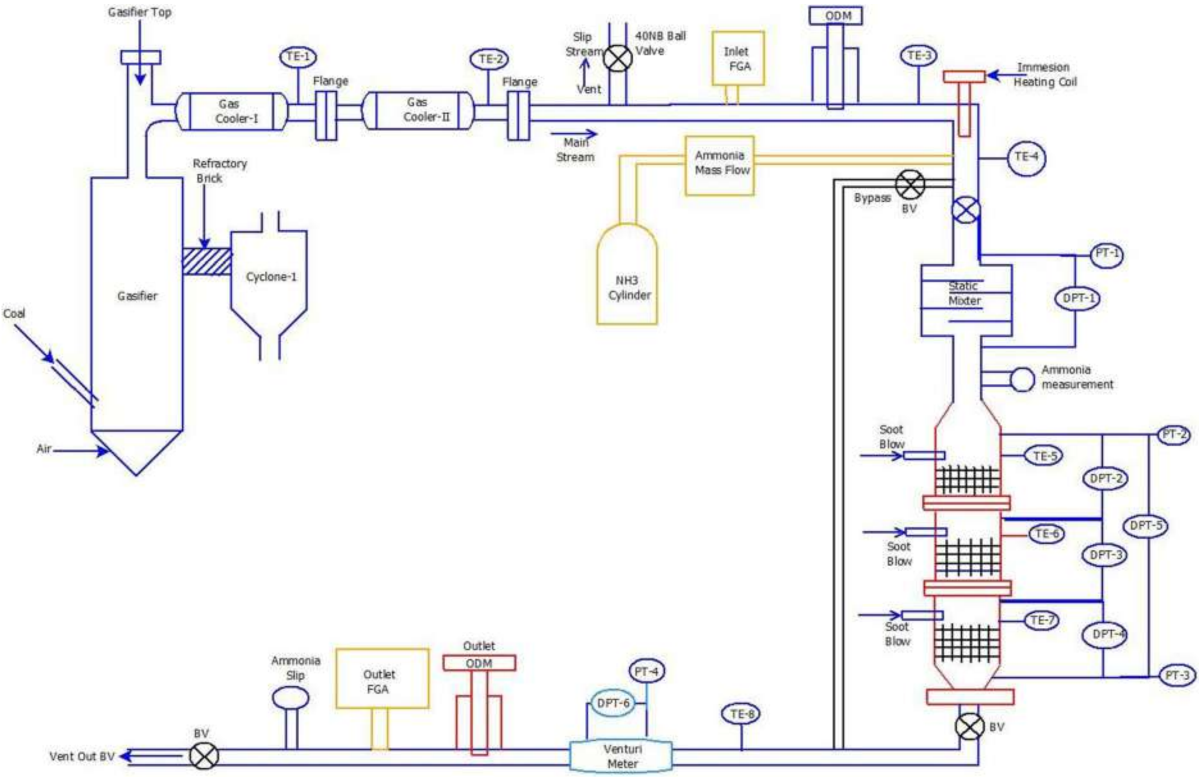


Fig. 1. Process & Instrumentation Diagram (P&ID) of 20 Liters SCR test Facility.

The existing 200mm APFBG pilot plant was operated in a combustion mode by maintaining the oxygen level by 4-6 Vol % and generated flue gas for testing of 8mm pitch plate type SCR catalyst for De-NOx efficiency. The Process and Instrumentation Diagram (P&ID) of 20 litres SCR test Facility for De-NOx process is shown in Fig.1. The performance of Plate type catalyst was tested by varying the vanadium composition in the catalyst under flue gas conditions with 30-45 grams/Nm^3 of dust.

2.2 SCR Catalyst:

Catalyst is the heart of De-NOx process. A plate type catalyst has been used for reduction of oxides of nitrogen (NOx) from flue gas. Anhydrous gaseous ammonia reacts with NOx in flue gas to form nitrogen (N_2) and water vapour (H_2O) in presence of plate type catalyst. The primary base material of catalyst is titanium dioxide (TiO_2), with smaller amounts of other metal oxides including tungsten dioxide (WO_2) for thermal support and vanadium pentoxide (V_2O_5), which is the primary active material.

Four types of Plate catalysts named as G1, G2, G3 and G4 with Vanadium Pentoxide composition of 0.85, 1.05, 2.0 and 2.20 percentage on weight basis respectively. The total volume of each catalyst is 0.016197 m3.

2.3. Experimental procedure

For testing of plate type SCR catalyst, the flue gas generated from an existing 200mm Advance Pressurized Fluidized Bed Gasification (APFBG) pilot plant by operating in combustion mode. Subsequently Anhydrous Ammonia was admitted tangentially in to flue gas pipe line and the same was passed through static mixture system for better mixing of ammonia and NOx in the flue gas. The quantity of anhydrous ammonia is calculated based on the flue gas flow rate and NOx concentration in the flue gas. When the ammonia is admitted more than the required amount, it is not reacting with NOx in the flue gas and left out in the SCR reactor. The unreacted ammonia is called "Ammonia slip". Then the mixture was passed through SCR reactor to remove the oxides of nitrogen (NOx) in presence of catalyst and converted in to nitrogen and water vapour. After SCR, the flue gas was passed through Venturi meter for measurement of flue gas flow rate.

The NOx concentration at inlet and outlet of the SCR reactor was measured using flue gas Analyzer. The NOx conversion efficiency was calculated based on the inlet and outlet NOx concentration of the SCR reactor. The efficiency of the catalyst is also depending on ammonia slip, when the ammonia slip is greater than 5% it indicates of an unhealthy SCR system, this phenomenon caused due to flow distributions, fouling (or) catalyst deactivation. Due to more ammonia slip (>5%), the flue gas has the tendency to form the ammonium bisulphate (NH_4HSO_4). Normal allowable ammonia slip is around 2 to 3%.

3. RESULTS AND DISCUSSION

The experiments were conducted with Plate type catalyst by varying the Vanadium Pentoxide (V_2O_5) content to evaluate the De-NOx efficiency in 20 litres SCR Test Facility. The Flue gas is generated through APFBG by operating in combustion mode at IGCC Test Facility, Moula Ali site, Hyderabad. Raw sub bituminous coal of grade E and of –10 mm size from Singareni collieries was obtained for this experimentation. The various analysis of coal has been pursued using in-house available techniques and shown in table 1.

2.1.1 Physical properties of Sub-bituminous coal:

S.N o	**Physical properties**	
01	The mean diameter of the particle (mm)	1.75
02	Bulk Density of coal (kg/m^3)	810.04
03	Particle Density of coal (kg/m^3)	1665.1
S.No	**Proximate analysis**	
01	Moisture (%)	2.55
02	Ash (%)	29.25
03	Volatile Matter (%)	28.93
04	Fixed Carbon (%)	39.27
S.No	**Ultimate analysis**	
01	Carbon (%)	49.82
02	Hydrogen (%)	3.64
03	Nitrogen (%)	1.02
04	Sulphur (%)	0.58
05	Oxygen (%)	13.14

Table 1. Sub-bituminous coal properties

The flue gas composition consists of carbon di-oxide (CO_2), water (H_2O), oxygen (O_2), nitrogen (N_2), nitrous oxide (NO), nitrogen di-oxide (NO_2), sulphur di-oxide (SO_2), and Argon (Ar). The generated flue gas composition in volume percentage wise is shown in Table 2.

Flue Gas Composition (Vol %)	
Carbon di-oxide (CO_2)	12.00
Water (H_2O)	8.50
Oxygen (O_2)	6.23
Nitrogen (N_2)	72.00
Oxides of Nitrogen (NOx)	0.04
Sulphur Oxides (SOx)	0.03
Argon (Ar)	1.20
Avg. Mol. Wt.	29.46952

Table 2. Flue gas composition

The generated flue gas was sent to plate type catalysts to evaluate the De-NOx efficiency. There are four modules named as G1, G2, G3 and G4 of 8mm pitch plate type catalysts were tested by varying the vanadium pentoxide composition in plate catalyst for De-NOx efficiency. By increasing the vanadium content, the effect of space velocity and SCR operating temperature on the De-NOx efficiency have been evaluated. The space velocity was varied in the range of 1500 to 2500 per hr and flue gas temperatures were varied in the range of 300 to 350 deg. C. Anhydrous ammonia was used as reducing agent and the ratio of ammonia (NH_3) to Oxides of Nitrogen (NOx) was maintained as 1.0 for all the experiments.

3.1. De-NOx Efficiency Vs space velocity at 300 ^{0}C at various Vanadium(V_2O_5) Compositions

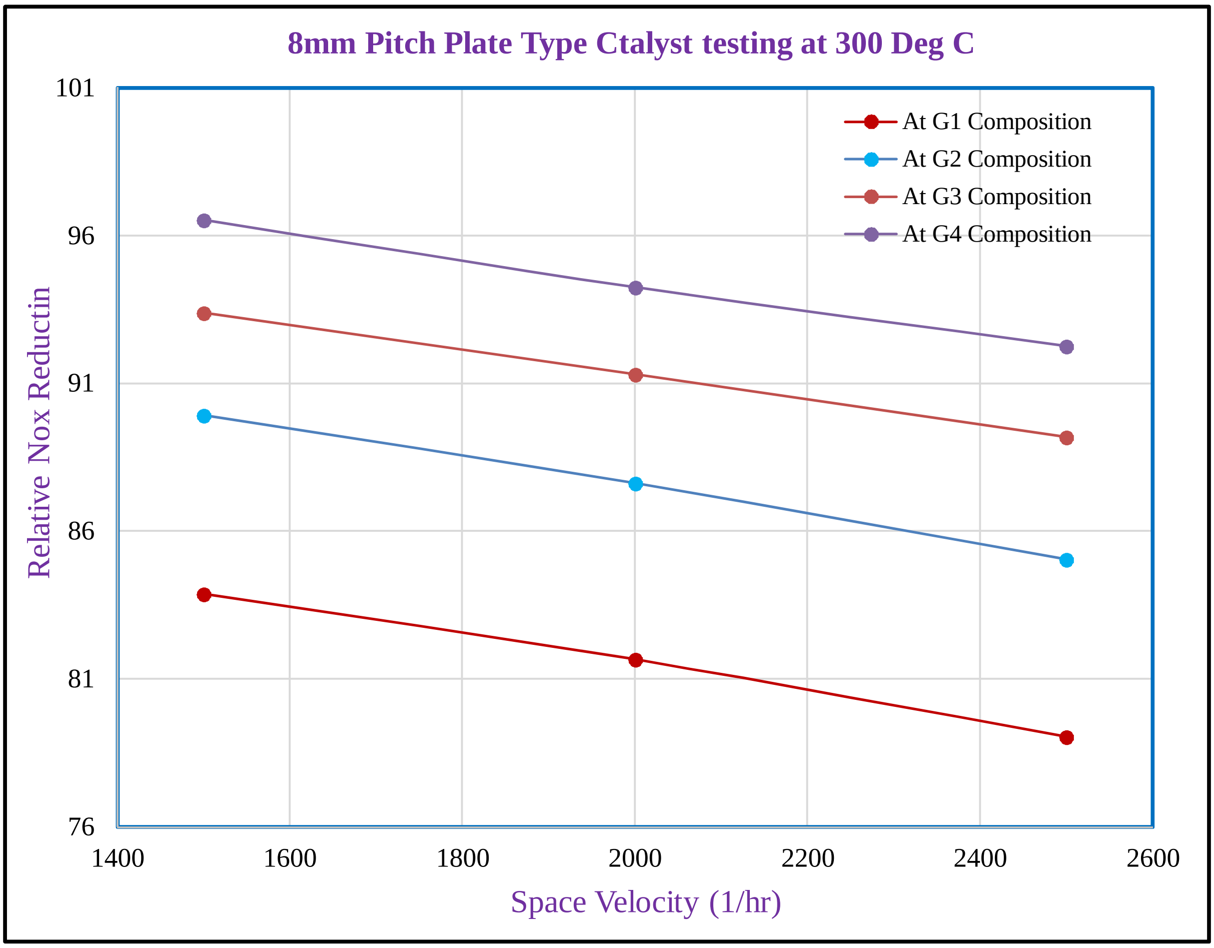


Figure 2. De-NOx Efficiency Vs Space Velocity (1/hr) at 300 Deg. C

Figure 2. Shows the De-NOx efficiency as a function of space velocity at an average temperature of 300 Deg. C. at SCR. This experiment was conducted with G1, G2, G3 & G4 plate type catalysts by changing the dust concentration is in the range of 30 to 45 grams/Nm^3 at different space velocities of 1500, 2000 & 2500 /hr and the corresponding flue gas flow rates are of 24.30, 32.40 and 40.50 Nm^3/hr respectively. Anhydrous ammonia has been used as a reducing agent and admitted in to SCR reactor is equivalent to NOx. The molar ratio of ammonia (NH_3) to oxides of nitrogen (NOx) has been maintained as 1.0 for all experiments.

It has been observed that the De-NOx efficiency decreases by increasing space velocity. Efficiency reduced from 96.53 to 79.06% by increasing space velocity from 1500 to 2500/hr.

3.2. De-NOx Efficiency on space velocity at 325 ^{0}C at various Vanadium(V_2O_5) Compositions

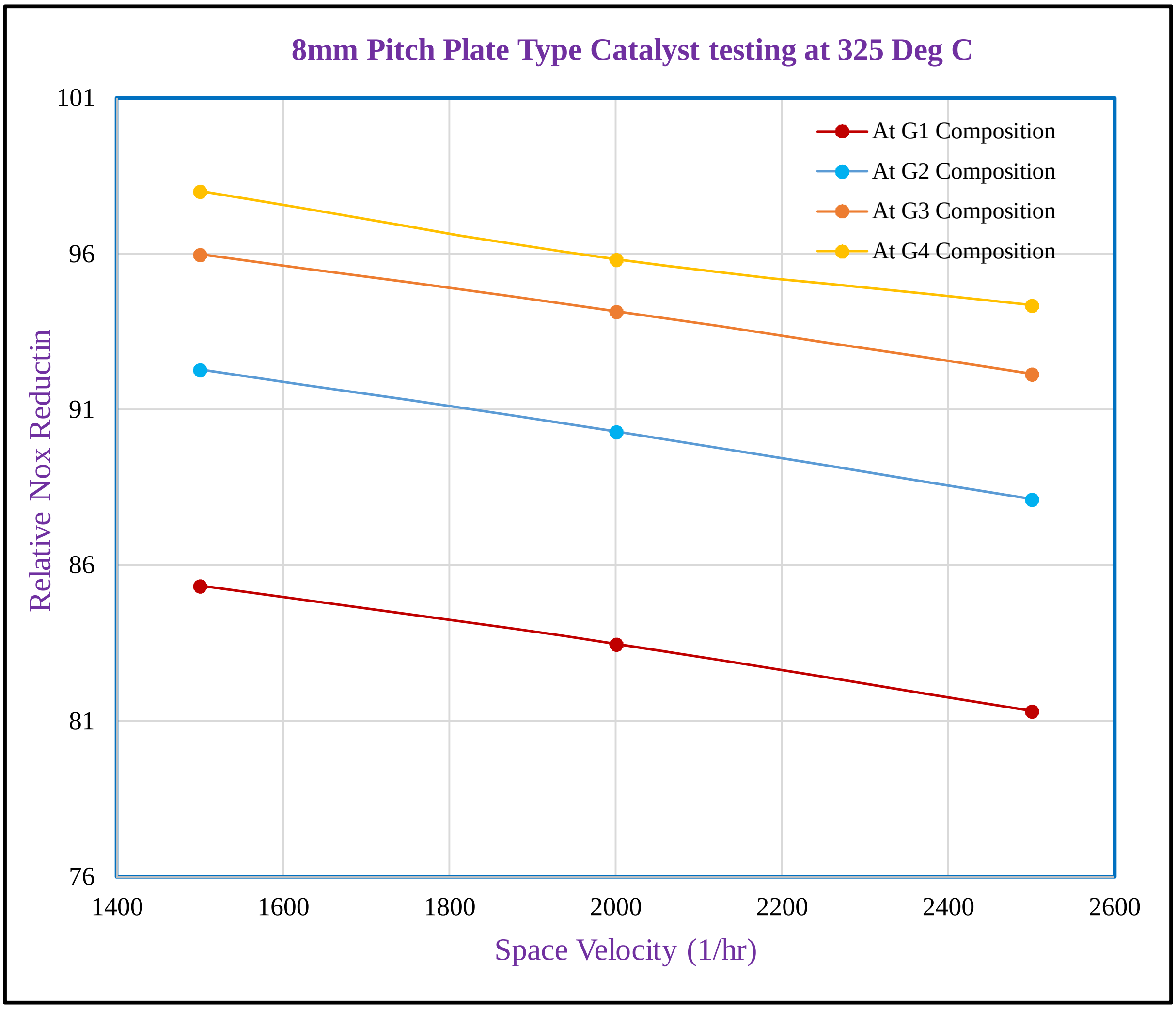


Figure 3. De-NOx Efficiency Vs Space Velocity (1/hr) at 325 Deg. C

Figure 3. Shows the De-NOx efficiency as a function of Space velocity at an average temperature of 325 Deg. C. at SCR. This experiment was conducted with G1, G2, G3 & G4 plate type catalysts by changing the dust concentration is in the range of 30 to 45 grams/Nm^3 at different space velocities of 1500, 2000 & 2500 /hr and the corresponding flue gas flow rates of 24.30, 32.40 and 40.50 Nm^3/hr respectively. Anhydrous ammonia has been used as a reducing agent and admitted in to SCR reactor is equivalent to NOx. The molar ratio of ammonia (NH_3) to oxides of nitrogen (NOx) has been maintained as 1.0 for all experiments.

It has been observed that the De-NOx efficiency decreases by increasing space velocity. Efficiency reduced from 98.03 to 81.33% by increasing space velocity from 1500 to 2500/hr.

3.3. De-NOx Efficiency Vs space velocity at 350 ^{0}C at various Vanadium(V_2O_5) Composition:

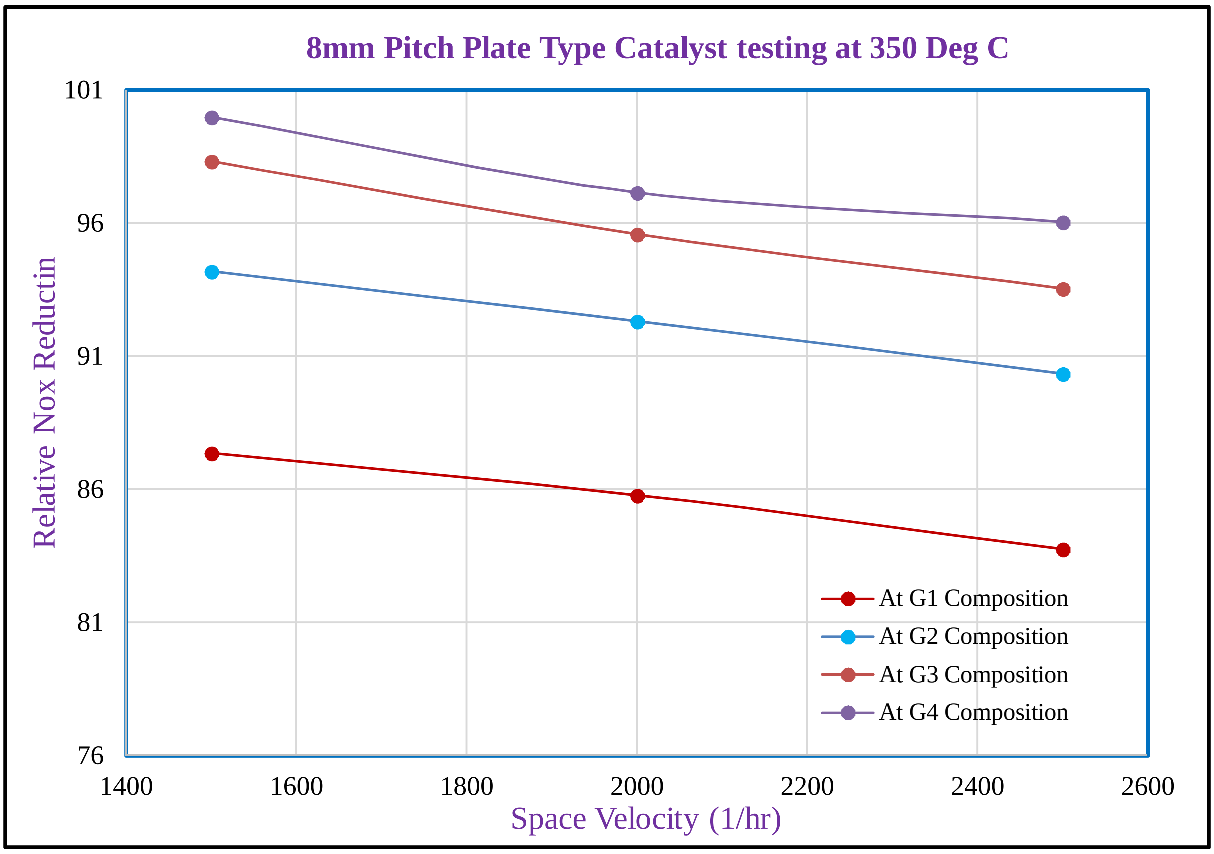


Figure 4. De-NOx Efficiency Vs Space Velocity (1/hr) at 350 Deg. C

Figure 4. Shows the De-NOx efficiency as a function of space velocity at an average temperature of 350 ^{0}C. at SCR. This experiment was conducted with plate type catalyst by changing the dust concentration is in the range of 30 to 52 grams/Nm^3 at different space velocities of 1500, 2000 & 2500 /hr and the corresponding flue gas flow rates of 24.30, 32.40 and 40.50 Nm^3/hr respectively. Anhydrous ammonia has been used as a reducing agent and admitted in to SCR reactor is equivalent to NOx. The molar ratio of ammonia (NH_3) to oxides of nitrogen (NOx) has been maintained as 1.0 for all experiments.

It has been observed that the De-NOx efficiency decreases by increasing space velocity. Efficiency reduced from 100 to 83.75% by increasing space velocity from 1500 to 2500 /hr.

4. CONCLUSION:

Experiments were conducted to study the performance of various plate type catalyst (G1, G2, G3 & G4) by varying the vanadium Pentoxide (V_2O_5) composition by weight basis in 20 Litre Capacity SCR pilot plant. The De NOx efficiency and ammonia slip was investigated with dust concentration of 30-45 grams/Nm^3 in flue gas by varying the space velocities (2500-1500 per hr.) and flue gas temperatures (300–350 ^{0}C) using anhydrous ammonia as reducing agent.

- It has been observed that increase in vanadiumcontent in SCR catalyst leads to increase in De-NOx efficiency. The percentage of increase in De-NOx efficiency for G2, G3 & G4 compared to G1 ($\eta_{NOx} \approx 83.89$) at 300 Deg C & 1500 per hr was 7.21%, 11.3% and 15.0%.
- It has been observed that increase in vanadium continent in SCR catalyst leads to increase in De-NOx efficiency. The percentage of increase in De-NOx efficiency for G2, G3 & G4 compared to G1 ($\eta_{NOx} \approx 85.36$ at 325 Deg C & 1500 per hr was 8.13%, 12.4% and 14.8%.
- It has been observed that increase in vanadium continent in SCR catalyst leads to increase in De-NOx efficiency. The percentage of increase in De-NOx efficiency for G2, G3 & G4 compared to G1 ($\eta_{NOx} \approx 87.36$) at 350 Deg C & 1500 per hr was 7.8%, 12.55% and 14.46%.
- It is also observed that increase in SCR temperature leads to increase in De-NOx efficiency.
- It is also observed that decrease in space velocity leads to increase in De-NOx efficiency.
- The maximum De-NOx efficiency observed at 350^{0}C & 1500 /hr with G4 Composition.
- Ammonia slip was measured in the range of 3-5 ppm and the ratio of ammonia (NH_3) to oxides of nitrogen (NO_x) was maintained as 1.0 for all experiments.
- The total differential pressure (DP) across SCR catalyst is 10-17 mmWc over a 3mlength at a flue gas flow rate of 24.3 to 40.5 Nm^3/hr.
- No plugging of fly ash particle in catalyst cells was found, during testing.

Acknowledgements

Authors would like to thank Ceramic Technology Institute (CTI) group of BHEL Corporate R&D, for providing various plate type catalysts along with vanadium composition.

References:

1. B.M. Weckhuysen, D.E. Keller: Catal. Today, 78 (2003)
2. R.M. Heck, R.J. Farrauto **Catalytic Air Pollution Control: Commercial Technology;** Van Nostrand Reinhold, New York (1995).

Biomass co-firing in Indian Power Plants

Amit Kulshreshtha (AGM) and Ashwini Kumar Verma (Manager)

NTPC Limited.

Introduction

Because of the short window available between Kharif and Rabi crop, the farmers have been burning crop residues left after harvesting right in the field for last several years, especially in the Northern part of India, for getting the field ready for the next crop as they consider burning is the easiest, quickest and the most economical way for disposal of these residues. As per estimates, in the case of Punjab and Haryana, every year around 30 million tons of paddy straw is burnt in the field after paddy harvesting at the end of October which causes the serious harm to the environment and public health with heavy smog in Delhi/NCR and nearby regions every year at the end of October and also to some extent in the month of April after crop harvesting. Creating economic value for the crop residue can go a long way in controlling this menace and can also increase the income of the farmers.

As a solution to this problem, we have explored the potential of utilizing crop residue for power generation in conventional pulverized coal-fired power plants and has attained a considerable knowledge about biomass co-firing. A renewable resource, biomass reduces carbon dioxide emissions when fired in a coal-based power plant by replacing coal. The carbon-dioxide emitted by burning biomass, as against burning coal, is absorbed in the next crop cycle, therefore, the environmental concentration of carbon dioxide remains unchanged.

Having several advantages over other renewables such as solar and wind, biomass power can be generated as and when required by the consumer, thus reducing the requirement of storage or compensatory cycling of conventional plants. Further, co-firing of biomass not only reduces carbon footprint of power generation, but also helps in improving air quality by averting farm burning of agro residue. Furthermore, the ecosystem that is established to process biomass fuel creates additional jobs for biomass processing, and additional incomes for the farmer by selling farm residue, which was earlier burnt into the field.

Biomass Co-firing, however, is a challenging task due to very high volatile content, low ignition temperature, higher alkali and chlorine content. These properties of biomass create several problems regarding storage, handling, safe milling and issues regarding performance and corrosion of the steam generator. We have gained sufficient know-how to address these issues.

We have recently successfully demonstrated up to 10% biomass co-firing along with coal at NTPC Dadri. This has established that biomass can be blended with coal at controllable biomass ratios and can be fired in the boiler without negatively impacting the safety concerns and mechanical performance of the existing milling and firing system if due care is taken.

NTPC is soon to commence commercial scale biomass firing at NTPC Dadri from the next paddy harvesting season in Punjab and Haryana.

Methodology

As the biomass is of fibrous nature, it cannot be pulverized to fine particles in conventional coal mills. Additionally, it has higher volatile content (in range of 60-70%) and lower ignition temperature (230-250 C), it presents high fire risk if it accumulates in the milling and firing system. A cautious approach is therefore, necessary while firing biomass in conventional plant without any modification in milling and firing system.

To address the non-grindability issue, it was decided not to use raw biomass directly, but use the biomass pellets having pre-pulverized constituent particles which can pass through the classifier of the conventional coal mill.

To address the issue of fire hazard, mill inlet temperature was reduced to safe limits. This however, deteriorated the boiler efficiency due to non-utilization of heat to be picked up from air heater and consequent increase in flue gas temperature. The presentation will discuss about the fine tunings of operational parameters for safe co-firing and resultant performance parameter deterioration.

Challenges

Agro residue ins abundantly available in the fields, however, it is not processed in the form of pellets which can be conveniently be used in power plants. Total pelletization capability in the country is very limited and needs to be developed in order to encourage its use in power sector.

Lower pelletizing capacity also results in higher cost of pellets which may increase the cost of electricity from present levels. Creating large scale pelletizing capacity can potentially bring down the cost as a result of economy of scales, exploration of better technology and creation of related infrastructure such as collection, storage and transport. Enabling polices are needed to impart a thrust to this sector.

Environmental issues

As agro residue is a carbon neutral fuel, 10% incorporation along with coal will bring the net carbon emission by 10%. Bringing the sub critical plants at par with super critical plants in terms of carbon emissions.

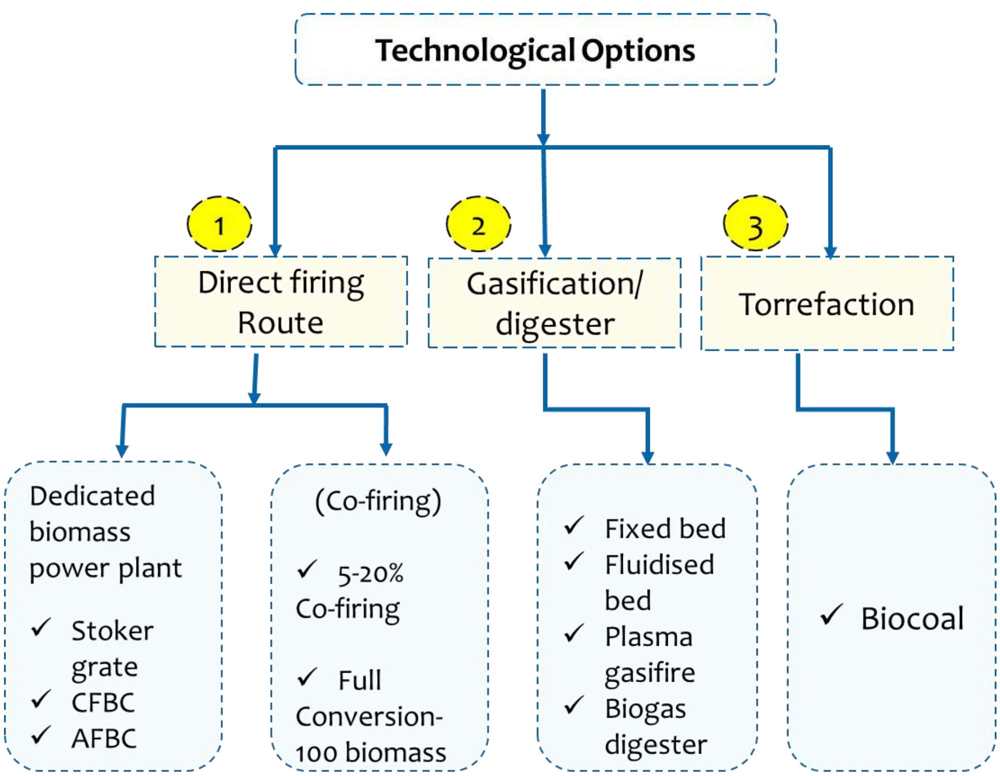
Further, the sulphur in the agro residue is far less than that of coal improving the Sox emission, furthermore, alkali present in the biomass also absorbs Sox generated due to sulphur in the coal which reduces overall Sox emission. Moreover, the fireball temperature is reduced due to biomass co-firing because of high volatile content of biomass which also helps in reducing Nox emission to some extent.

Indian coal as used for power generation has high ash content of the order of 30-50%, however, the biomass has content has the ash content of the order of 2-15%. Mixing of 10% of biomass in coal will bring down the total ash generated as discussed in the presentation.

However, biomass co-firing presents some challenges while using pollution reduction devices such as FGD/SCR, which shall be discussed in the presentation.

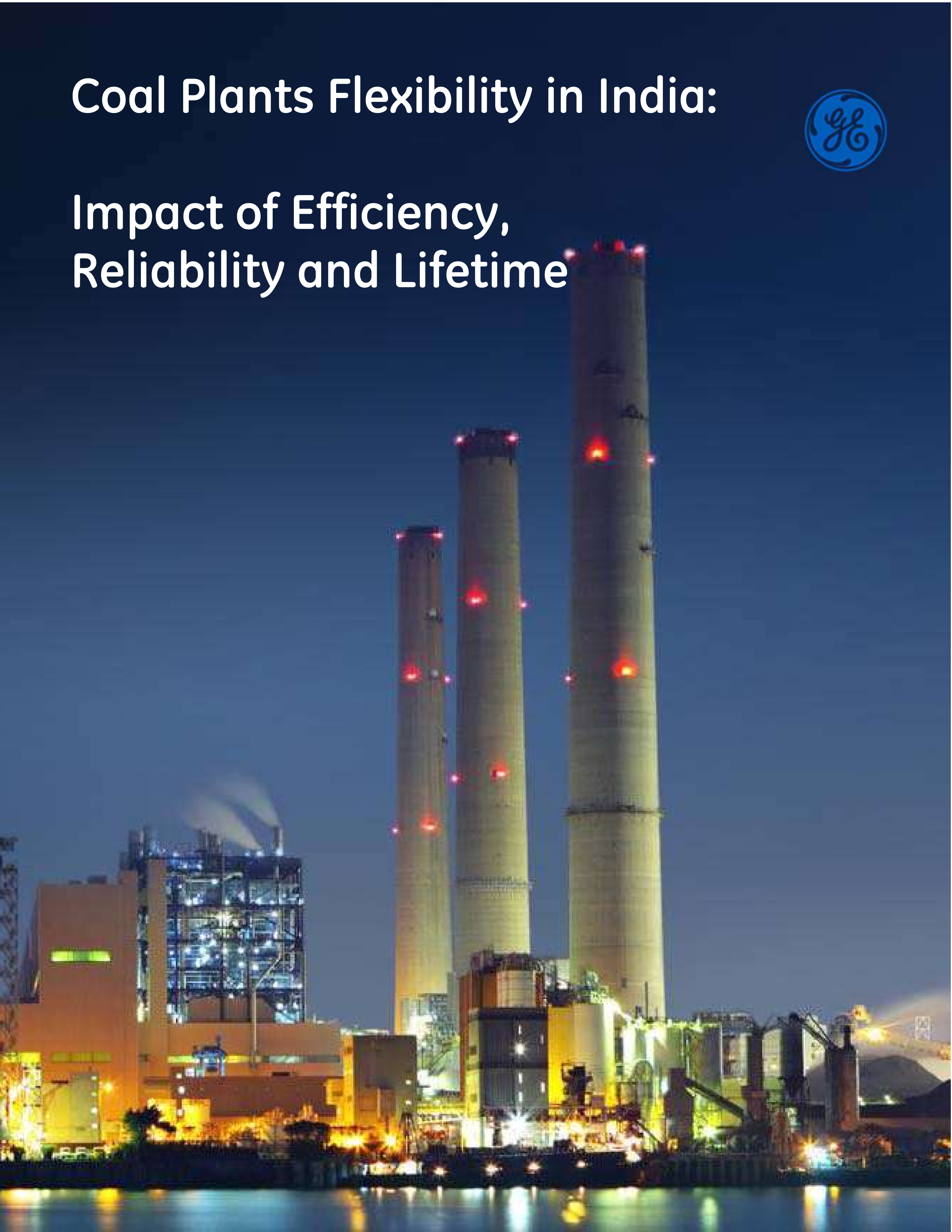
While biomass co-firing reduces air pollution by discouraging open burring of farm residue, however, the nutrients from the fields are carried away along with biomass to the power plants, and subsequently to the ash. To address the issue, another technology called torrefaction can be of greater help to return the soil nutrients back to the soil while producing quality fuel for power plants. Furthermore, ash from the 100% biomass fired power plants can also be used as farm fertilizer.

Technology Options



Coal Plants Flexibility in India:

Impact of Efficiency, Reliability and Lifetime



Coal Plants Flexibility in India: Impact of Efficiency, Reliability and Lifetime

----

Preface:

The key challenges plaguing the coal plants presently in India is to remain competitive with the modern machines at this pivotal time in the Indian Power Sector, where the average Plant Load Factor (PLF) is in the tune of 55 to 60% which is expected to settle at this level going forward. Coupled with increasing demand, the influx of the Renewables will also be one of the key reasons for lower PLFs staring at Coal plants.

Efficient, Reliable and Cost Effective Cycling, Low Load Operation (LLO), load ramp and start/shut capabilities with compliance to emissions would be imperative. The track elaborates on the challenges and solutions to enable Utilities in India meet these challenges in order to maintain a stable grid.

Rev - A	Prepared	Checked	Approved
27 Jan 2017	Chinmoy Mohanty I Prabhu Mahesh Kendhe Henrik Nielsen Michael Haux Xiao-Yi Zhang Nitin Agrawal	Sanjeev Duggal Klaus Zinser Rajeev Sharma Rolf Hestermann William Miller	

Coal Plants Flexibility in India: Impact of Efficiency, Reliability and Lifetime

Table of Contents:

1 EXECUTIVE SUMMARY

With solar/ renewables gaining scale and backed by preferential dispatch, these sources bring in an element of variability into the grid due to their nature of generation. This puts additional requirement on coal plants to remain as standby capacity to pitch in as soon as the Renewable generation drops. This would mean faster ramp up needs and higher turndown.

Flexibility is used for different context of power plants, such as operational flexibility (capability of running unit at various loads, lower loads, faster ramping and start-up/shut-down), maintenance flexibility (optimizing short and thus cost effective outages), or fuel flexibility (example co-fired biomass in case of conventional plants or syngas and oil in case of combined cycle plants). This track focusses on aspects of Operational flexibility.

Flexible operation calls for fast and reduced start-ups and will be a key feature in the future market mechanism. Both, fast start-ups and LLO could have an impact on the lifetime consumption. Flexible operation will also result in reduced efficiency at lower loads, increased emissions, increased operational costs, lifetime consumption and potential component failures (ex boiler tubes, critical piping, last stage blades, turbine rotor, valve components etc). Therefore improved performance, improved control and advanced monitoring & diagnostics will be the differentiating way to operate in the future power market to improve efficiency, reliability and availability.

On one hand India is building up new supercritical and advanced supercritical capacity, but these units become inefficient at lower/ part loads (a large sized/ supercritical unit will lose more efficiency at part loads compared to a smaller sized subcritical unit) and have significant initial investment now coupled with emission control measures and they start suffering under merit order with other sources of dispatch, even more at lower loads. On the other hand most of the 200 MW and 500 MW class units are matured installed base with many units having only limited residual lifetime for critical components. Efficiency enhancing retrofits and plant system modernizations with features that enhance flexible operation are required to ensure safe and economic operation of the plants and to dispatch power under merit order regime.

Due to the complexity, technology mix and inter-dependency of the various plant systems, there is no "one size fits all solution" so engineering expertise with technology solutions for the different plant systems has to go hand in hand for coal plants to provide cleaner, more reliable, flexible and efficient power to India.

2 COAL PLANTS OVERVIEW

2.1 Coal Fired Power Plants in India

India has the fourth largest installed capacity of power generation in the world clocking currently 307 GWs. Coal being the major source of power generation with 60.7% of the total installed capacity followed by hydro 14%, renewable energy sources (RES - solar, wind, small hydro plants, and biomass) 14.9%, and the rest by Gas, Nuclear and diesel. The installed coal fired base of 186 GW is distributed among Central, State, and Private sector entities with a share of 25%, 33% & 42% respectively. Out of the current coal plant base, almost ~10% is based on Supercritical technology and with current discussions/ initiatives underway to graduate to the next level Ultra supercritical (USC) and Advanced Ultra supercritical technology (A-USC).

The actual production of electricity from the coal base contributes 77.1% of the total generation. The Central sector contributes 37%, private sector 32% and state sector 31% respectively.

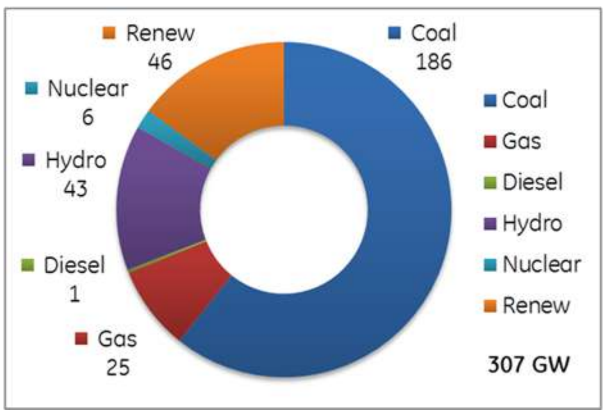


Figure-1: Installed Capacity (India – Oct 2016)

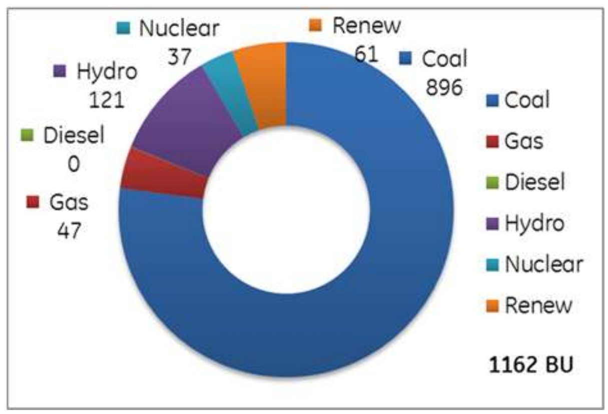


Figure-2: Electricity Generation (India- FY-2015-16)

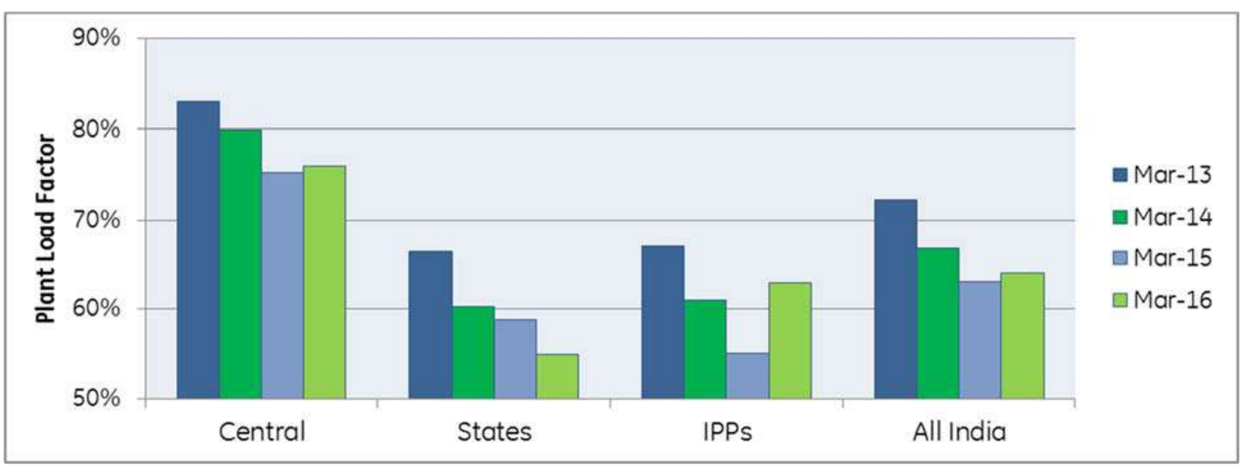


Figure-3: All India PLFs evolution in last 4 years

The trend of Plant Load Factor of coal fired power plants in India has been on a slightly declining mode as evident in figure 3. The economic impact on conventional generation source is significant due to expected influx of variable generation sources resulting in further falling PLFs as units need to be run at lower loads and be able to ramp up/ down faster to compensate the fluctuation introduced by Renewables.

As coal power will continue to be a key pillar of electricity generation in India, it is essential that existing assets are optimized for maximum efficiency and flexibility. Coal generating assets face competition from other sources of energy, increasingly renewable energies which are benefiting from rising policy support, advancing technologies and even falling prices. Investment in the installed base is needed to meet emission and environmental regulations, enhance the performance and operational flexibility as well the plant availability.

Plant improvements translate to lower operating costs and higher income for power plant operators. Increasing the relative merit order and competitiveness of a specific generation unit is needed to ensure the successful operation in an ever-changing environment and provides answers to challenging market factors for coal power generation in India.

2.2 Merit Order Dispatch mechanism in India

In earlier times, the utilities were incentivised based on production rather than availability, which led to constraints on managing grid stability. With the inception and implementation of Availability Based Tariff (ABT) there has been significant streamlining in the grid stability with improved frequency and voltage variations. This was achieved by reducing overdrawals during peak loads and providing incentives. Similarly, high frequency situation was controlled by encouraging reduction in generation during off peak hours. One of the key factors is Merit Order Dispatch mechanism, under which the fixed and variable charges were separated and generation as per merit order, i.e. the least variable cost of generation is encouraged. With flexible and low load operation, the efficiency or gross heat rate of the units start deteriorating significantly. The challenge will be faced with renewable generation achieving scale. Renewable generation with very low/ almost nil variable costs and grid priority is typically first in the merit order, followed by nuclear and then Coal. While the SC, USC plants are very efficient as base load, when operated at part loads/ low load the efficiencies drop significantly.

2.3 Key Challenges for Coal Plants

An overview of some key challenges that coal power generators are facing currently and expected to face going forward is presented below:

- Merit order dispatch - When the electricity price falls below the production cost, it becomes essential to minimize loss of operation leading to a trade-off between maintaining operation at minimum load and shutting down the plant. This in turn, reduces the capacity factor leading to higher variable costs, i.e., the plant is slipping up the merit order.

- Challenges on coal quality consistency and need for constant optimization of equipment to have best performance.

- Utilities are under constant pressure to increase lifetime, minimize downtime of operating assets and reduce spend on maintenance and spare parts/ repairs. This calls for a move from failure and time based maintenance to a regime of Predictable maintenance is the next norm for O&M for optimizing OPEX and enhancing availability of the unit.

- Operational flexibility – with solar/ renewables gaining scale and backed by preferential dispatch, these sources bring in an element of dynamism into the grid due to their variable nature of generation. This puts additional requirement on coal plants to remain as standby capacity to pitch in as soon as the Renewable generation varies. This would mean faster ramp rates and better turndown.

- Utilities having diverse Generation mix need proper forecasting methodology/ programs for predicting optimized dispatch mix while maintaining overall efficiency and having lowest cost of generation.

2.4 New Emission & Water Regulations

Emission Regulations

India is world's third largest carbon emitter, behind the U.S. and China. Coal plants are one of the top sources of carbon dioxide (CO2) emissions, the primary cause of global warming. In India coal-fired plants contribute approximately 60% of particulate emissions; 45-50% of SO2 emissions; 30% of NOx emissions; and more than 80% of mercury emissions. Burning coal is also a leading cause of smog, acid rain, and toxic air pollution. Emissions can be significantly reduced with readily available pollution control systems and modernizations, but many, especially older coal plants have either not yet installed these technologies or systems and equipment for emission control. A study carried out by Centre of Science and Environment (CSE) revealed that CO2 emission of coal-fired plants in India was 1.08 kg per kWh, which is 14% higher than China and 7% higher than the global average.

In the recently ratified Paris Convention, India has committed to a National Determined Contribution (NDC) of 25% reduction on Green House Gases (GHGs) on 2005 levels by 2020 and to achieve 40% of total installed base in form of Non Conventional Energy Sources

(NCES) or Renewables by 2030. For coal plants, complying to emissions, improving efficiency and flexibility will play a significant role in achieving these targets.

The new emission norms introduced by Ministry of Environment & Forests (MoEF) in Dec 2015, necessitates monitoring of NOx, SO2 and mercury in addition to PM, the only pollutant that was regulated prior to Dec 2015.

Emissions mg/Nm3	Frame size specific	Before 31st Dec'03 (Old sets)	1st Jan'04 upto 31st Dec'16 (Recent sets)	From 1st Jan'17 (Future Sets)	Previous Standard
SPM		100	50	30	150
SO2	< 500 MW	600	600	100	na
	> 500 MW	200	200	100	na
NOx		600	300	100	na
Hg		0.03	0.03	0.03	na

Table 1: New Emission Norms specified in Dec 2015

Cleaner air means a higher acceptance of coal-fired plants in local communities, and equally important, by lenders and financial institutions–leading to better financing terms for our customers. From flexibility point of view one challenge will be to maintain emissions during flexible operation.

Water Regulations

The MoEF has also come out with Water utilisation regulations for Thermal Power Plants as per table 2 below. One of the key challenges in some sites will be space constraints to incorporate closed cycle cooling system (Cooling Tower based).

	Before 31st Dec'03 (Old sets)*	1st Jan'04 upto 31st Dec'16 (Recent sets)*	From 1st Jan'17 (Future Sets)	Previous Standard
Water Consumption	All plants with Once Through Cooling (OTC) to install Cooling Tower (CT) and have max specific water consumption of 3.5m3/MWh	All existing CT based plants to reduce specific water consumption to below 3.5m3/MWh	New plants after 1st Jan. 2017 to have max specific water consumption of 2.5m3/MWh and achieve "zero waste water discharged"	Cooling tower installation was mandated in 1999

Table 2: New Water Consumption Norms specified in Dec 2015

Efficiency becomes more important not to exceed specific water consumption per MW and also on water side management to comply with regulation. With flexible operation the challenge utilities can face is to ensure being within the specific water consumption levels at part loads. This would require to review the plant part load efficiencies and any need to upgrade/ improve.

3 EFFECT OF FLEXIBILITY ON INSTALLED COAL PLANTS

3.1 Operational Flexibility

From the era of conventional operation, coal plants nowadays require to be quicker to respond to grid requirements in terms of faster ramps, able to operate on a sustainable basis at a lower technical load at times of lower demand/ higher renewable feed in, All these are to be looked in conjunction with life consumption, maintenance cost and risk mitigation strategies to meet these challenges. In countries like Germany, US, coal plants need to start/ stop twice a day during peak load thereby needing to start up and shut down at faster rate to minimise variable costs. Such capabilities need a holistic approach to existing critical equipment/ system to undertake modifications for enabling flexible operation.

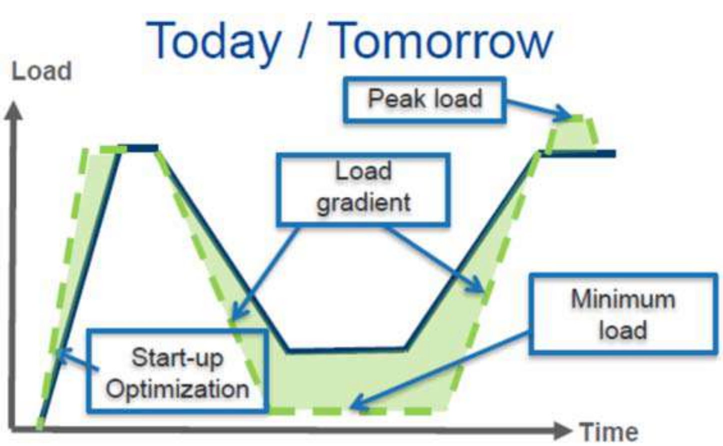


Figure-4: Evolution of operation requirements from Coal plants

A study carried out by Eurelectric compares the flexibility parameters for various sources of generation below in table 3.

Flexible Parameter	Nuclear Power Unit	Coal Fired Unit	Lignite Fired Unit	Combined Cycle Gas Unit	Pumped Storage Unit
Start up time - Cold	~ 40 hrs	~ 6 hrs	~ 10 hrs	~ 2 hrs	6 mins
Start up time - Hot	~ 40 hrs	~ 3 hrs	~ 6 hrs	~ 1.5 hrs	6 mins
Ramp Rate	5%/ min	3%/ min	2%/ min	4%/ min	40%/ min
Technical Minimum Load	50% MCR	40% MCR	40% MCR	50%	15% MCR

Table 3: Start up and Ramp rates of various sources of generation (Eurelectric Report)

In current context, with feed in laws to promote renewables and supply side constraints of gas for power generation, more flexible response is needed from coal plants which form the base of electricity generation in the country. From the perspective of flexibility of a Coal-fired Power Plant, ramp rates (ramp ups/ ramp downs), number of starts/ stops and the Technical Minimum are of key consideration.

With respect to Indian perspective, the installed base (IB) of Pumped Storage hydro, and Nuclear plants is very less as a share of total IB from a flexibility/ grid support perspective. With current fuel supply situation the Gas Plants with average ~ 25% PLF are also not in a position to cater to grid variation support. Hence it is Imperative for coal plants to take up this role in India.

Looking at the installed base of coal fired units in India, if we broadly segregate the installed base to three pillars, the 200 MW class fleet, the 500MW class fleet and the 660/ 800 MW class supercritical fleet, the flexibility parameters compare as below in table 4:

Flexible Parameter	200 MW class fleet	500MW class fleet	660/ 800 MW class supercritical fleet
Unit start up time - Cold	10-12 hrs	10-12 hrs	8-10 hrs
Unit start up time - Hot	4 hrs	3 to 4 hrs	2 to 3 hrs
Ramp Rate	0.4 to 1%/ min	0.6 to 3%/ min	3 -5%/ min
Technical Minimum Load	70% MCR	55% MCR	40% MCR
Control Range	60% to 100%	60% to 100%	50% to 100%

Flexible Parameter	200 MW class fleet	500MW class fleet	660/ 800 MW class supercritical fleet
Design Net Efficiency @ 100%	~ 34%	~ 36%	~ 37.5%
Design Net Efficiency @ 50%	~ 31.5%	~ 32.5%	~ 34%

Table 4: Start up and Ramp rates of various fleet of Coal Fired Power Plants

Operational flexibility is required to reduce operating costs on a sustained basis in a during situations where coal plants are backing up renewables by operating at lower/ standby loads. Start-up costs are reduced by faster start-up procedures (firing system, the steam generator, and the steam turbine).

3.2 Lifetime of Critical Components

In a fluctuating demand situation for coal plants and regulatory context, utilities, independent power producers and merchant power generators are all looking to maximise their return on investment by optimizing plant lifecycle costs. GE's technology leadership is key to enhance performance and ensure safe operation and a balanced investment using the available funds for maintenance as well as upgrade related investment.

Lifetime mechanisms

Regular cycling of power plant also puts the firing system and furnace through many more transients of air –fuel ratio and starts and stops of fuel preparation equipment. A careful review of the plant safety and integrity systems is required to ensure the long term integrity of the plant.

Figure-5: Overview of equipment/ system side challenges

The loading, the temperature and the material properties determine the strength and lifetime of components. There are two basic lifetime mechanisms that influence the life of a specific component in rotating equipment, e.g. steam turbines. Both depend to a great extent on the operating mode of the power plant. Base load units with few thermal cycles will be more affected by creep, which will result in material elongation. On the other hand components and systems in a power plant with frequent start stop cycles are significantly subjected to cycle fatigue and, as a consequence for example the development of cracks. In addition, thermal and mechanical stress and corrosion may have an impact on the material behaviour of other systems and impact plant parameters (example: the electrical insulation of rotor or transformer windings and its impact on the plant reliability in case of failure).

Planned maintenance is performed on all power plant systems and equipment at fixed times and intervals with different levels of work scope with the overall objective to establish and maintain optimal equipment and process conditions and allow safe operation. While the scope of planned maintenance, whether performed time- or condition based, does include repair and replacement of components subject to wear and tear, replacement of major structural components of a power plant such as rotors, casings, steel structures and the like are not foreseen under design conditions throughout the useful life of a plant.

Continuous monitoring of operational parameters and structural components as well asset specific planning together with the plant operator is the GE recommended approach to schedule optimized repair and replace intervals of installed base assets. When economic repair or maintenance is not anymore possible, a complete replacement of certain structural components or retrofit of core systems may be the preferred solution.

The GE digital suite of products combined with GE expert assessment will be able to deliver additional value and deliver maximum lifetime potential and therefore contributing greatly towards higher availability, higher productivity and overall better return on investment.

3.3 Concerns of Utilities

With flexible operation involving lower loads, faster ramp ups and ramp downs, the lifetime of critical components are impacted and residual life starts decreasing.

The key challenge at lower loads and even close to technical minimum level of operation is increasing heat rate, increase in % auxiliary power and specific oil consumption to maintain stable combustion which all together increases the energy charges/ variable cost of operation thereby impacting position in merit order. Utilities opting for providing flexible capacity need to be compensated for such impact in energy costs or be able to invest to reduce such effects.

4 SOLUTIONS FOR ENABLING FLEXIBILITY

4.1 Lifetime Assessment & Advance Monitoring

Through close collaboration with our customers GE is in a unique position to match distinctive needs and goals of our partners. The GE team has already commenced to customize individual solutions that unleash the full performance and long-term value for specific installed base assets. As the world's premier digital industrial company we deliver these solutions by connecting the physical and digital world. Sensing, predicting and responding to make our customers generating assets work better. Lifetime assessment, digital offerings and advanced monitoring solutions are able to drive real results. Deliver power quickly in response to changing grid demands, elimination of slow, inefficient start-ups and reduction of start-up costs, management of variable fuel sources and coal qualities and reduction of emissions to meet compliance standards.

The GE digital suite of products, for example Digital Twin Analytic Models which comprise physics models that analyze flow, thermal, combustion and mechanical aspects of equipment to provide unprecedented insights into equipment operation combined with GE expert assessment will be able to deliver additional value and deliver maximum lifetime potential. GE's digital solutions will contribute greatly towards higher availability, higher productivity and overall better return on investment.

Lifetime assessment

Lifetime assessment and studies are performed to assess the present state of aged equipment. Monitoring and study results can be used as a basis for decisions on the future operation of a unit and required investments. Main drivers for repair/modification or replacement are:

- Ensure safe operation
- Higher availability
- Higher efficiency
- Less maintenance or extended lifetime
- Increased flexibility of operation

As life of any component is limited and mechanical or electrical integrity may decrease with time below acceptable limits, safety and availability aspects suggest to perform thorough monitoring and evaluation of the status of critical components.

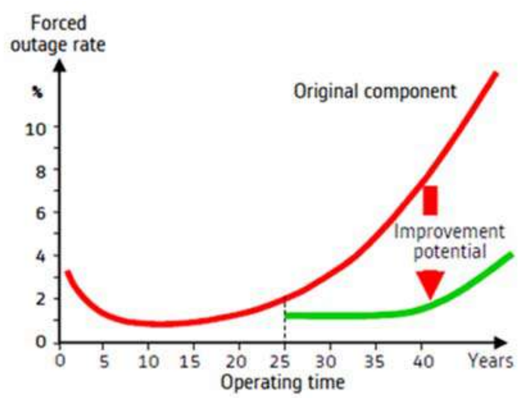


Figure 6: Generic failure rates ("bathtub curve") and reliability enhancement from system modernization

GE's expertise is based on significant experience on installed base as well as other OEM turbines, boilers, environmental control systems and components. The assessment typically includes, depending on the respective system or component, the current condition evaluation, remaining lifetime calculation or assessment, provision of short term measures for improvement or proposal for investment needs for retrofit measures or system replacements/modernizations in alignment with the needs and goals of the customer.

Advanced Monitoring

GE provides power plant operators with best in class advanced monitoring and communication infrastructure which is needed to optimize operational efficiency, reliability and safety. By expanding data collection to balance of plant systems and grow the data using GE's Predix platform, our customers can even start the digital transformation by attaching and monitoring of plant assets to the industrial internet.

The Advanced Plant Control System is the natural evolution of GE's established Mark VIe distributed control system into GE new Industrial Internet Control System platform (IICS). It allows connecting the plant to a new ecosystem relying on a solid foundation of Cyber Security and cloud based business applications and analytics.

It features a reliable high-speed network input / output (I/O), supports redundant systems for availability and is distributed plant wide across all applications. Additionally, the Mark VIeS is a stand -alone safety control system for safety-critical applications (conforms to IEC®-61508 standards). This must be combined with boiler safety equipment validated and enhanced to meet NFPA 85 and other local standards.

Field Agents provide a mechanism to transfer data from the plant or any asset to the Predix cloud over secure, encrypted channels and an IICS Control Server allows hosting on premise complex Predix Apps, non-critical supervisory control capabilities and functional consolidation.

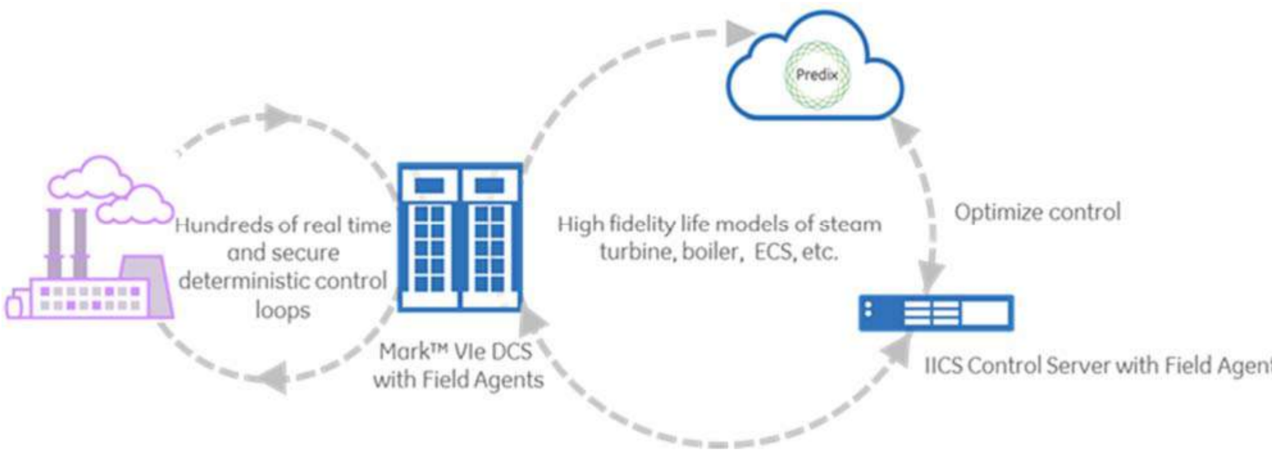


Figure 7: Advanced Mark VIeS based Plant Control System

GE's digital capabilities enable advanced predictive analysis using the existing station instrumentation data. These are explained in the GE digital section.

Boiler monitoring and optimization

Another key offering from GE's advanced monitoring and online real time tuning solutions for power plant systems is the BoilerOpt® boiler optimization solution which optimizes power plant boiler performance to achieve unit emissions, efficiency, reagent reduction and availability goals - thus reducing the risk of forced outages, reducing emissions and improving net heat rate.

BoilerOpt® is GE's total boiler optimization software solution that optimizes power plant boiler performance to achieve overall unit availability, efficiency and emissions goals. BoilerOpt uses its CombustionOpt® and SootOpt® modules to manage tradeoffs between the combustion and heat transfer processes. Combustion quality, fuel and air mixing, gas and steam temperatures, fouling and slagging, tube erosion and emissions control are examples of the interrelated variables that the combustion and soot optimization modules, working together, manage in order to achieve optimal boiler operations. Over forty (40) boilers have already implemented BoilerOpt® boiler optimization system, the industry-leading integrated boiler optimization package.

The boiler optimization package uses multiple optimization methodologies in hybrid ways and coordinates them through BoilerOpt® optimization platform. Model Predictive Control (MPC) technology supports the rapid response times often required for steam temperature and CO control in fast ramping situations and other dynamic processes; adaptive neural networks (NN) address the constantly-changing relationships between air biases, fuel biases, and NOx; and unit-specific expert rules are combined with adaptive neural models to consistently execute appropriate soot cleaning procedures while optimizing unit objectives.

BoilerOpt® provides a complete service package to optimize boiler efficiency and reduce fuel costs. This solution includes support throughout the process from commissioning the system to diagnosing boiler problems once the system is in operation. The package integrates industry-leading software, which continuously adjusts boiler parameters to achieve optimal performance, through GE's fleet knowledge obtained through the design and supply of thousands of fossil-fired boilers, the execution of hundreds of low NOx firing system conversions and over 100 years of field service experience in optimizing equipment.

4.2 Improvements for Flexibility

GE has developed the Flex Suite offering for Coal power plants. This solution is a comprehensive basket of solutions and products for faster & cost effective start up, performance and response to peaking loads, frequency response, improved part load efficiencies and reserve & sustained lower load operation.

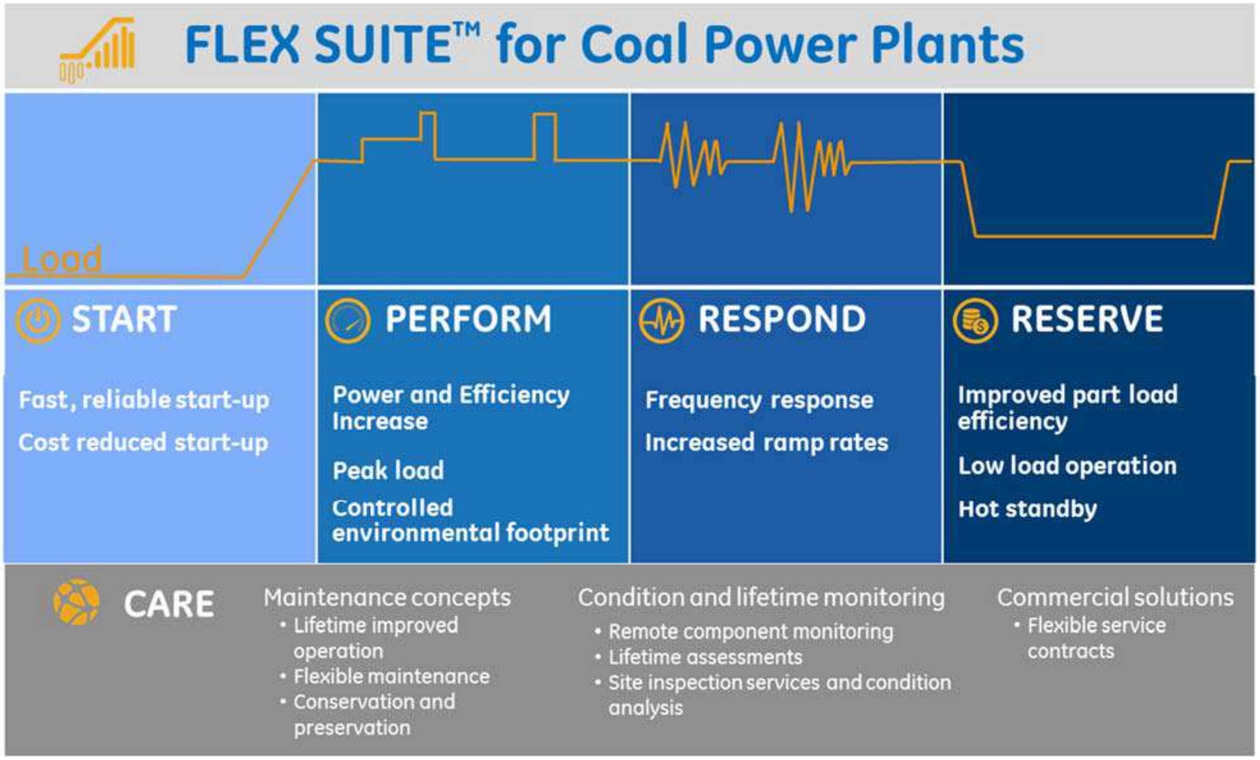


Figure 8: GE's FLEX SUITE offering

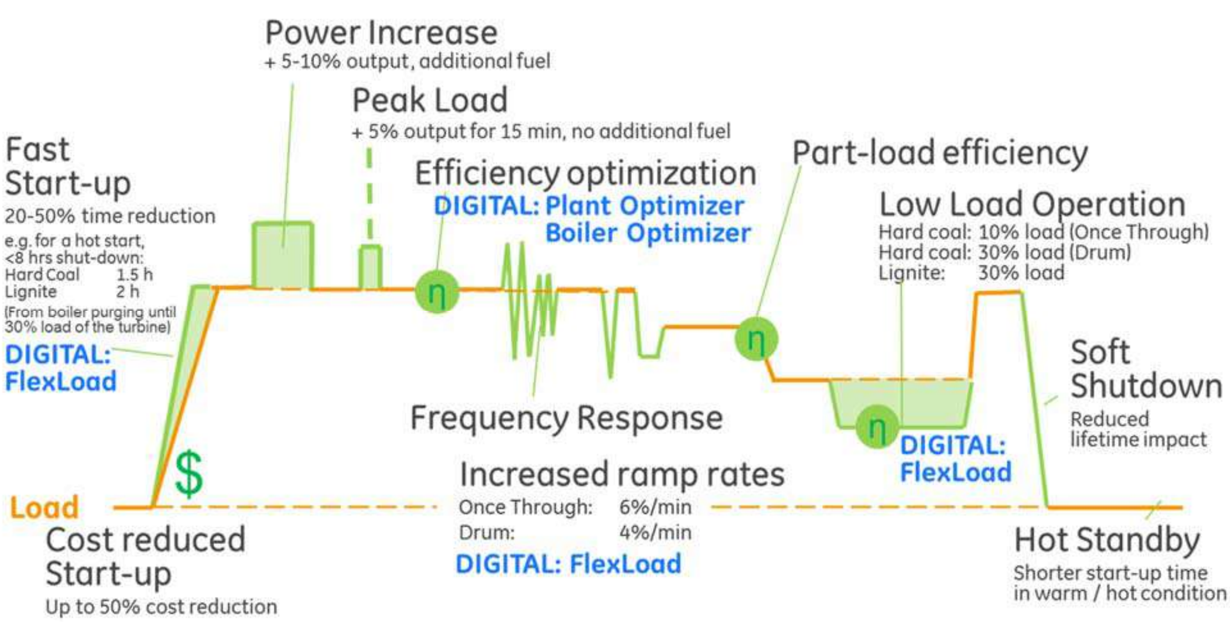


Figure 9: Indicative benefits of Flex Suite offerings

GE Offering:

For a plant, following a detailed assessment, first step recommendations are made to operational adjustments to help improve flexibility using existing elements and controls. As a second step GE works along with its customers to prioritize and carefully choose among the various options available w.r.t its benefit vs cost for modification. Various suits and individual product offerings are depicted in Figure 10.

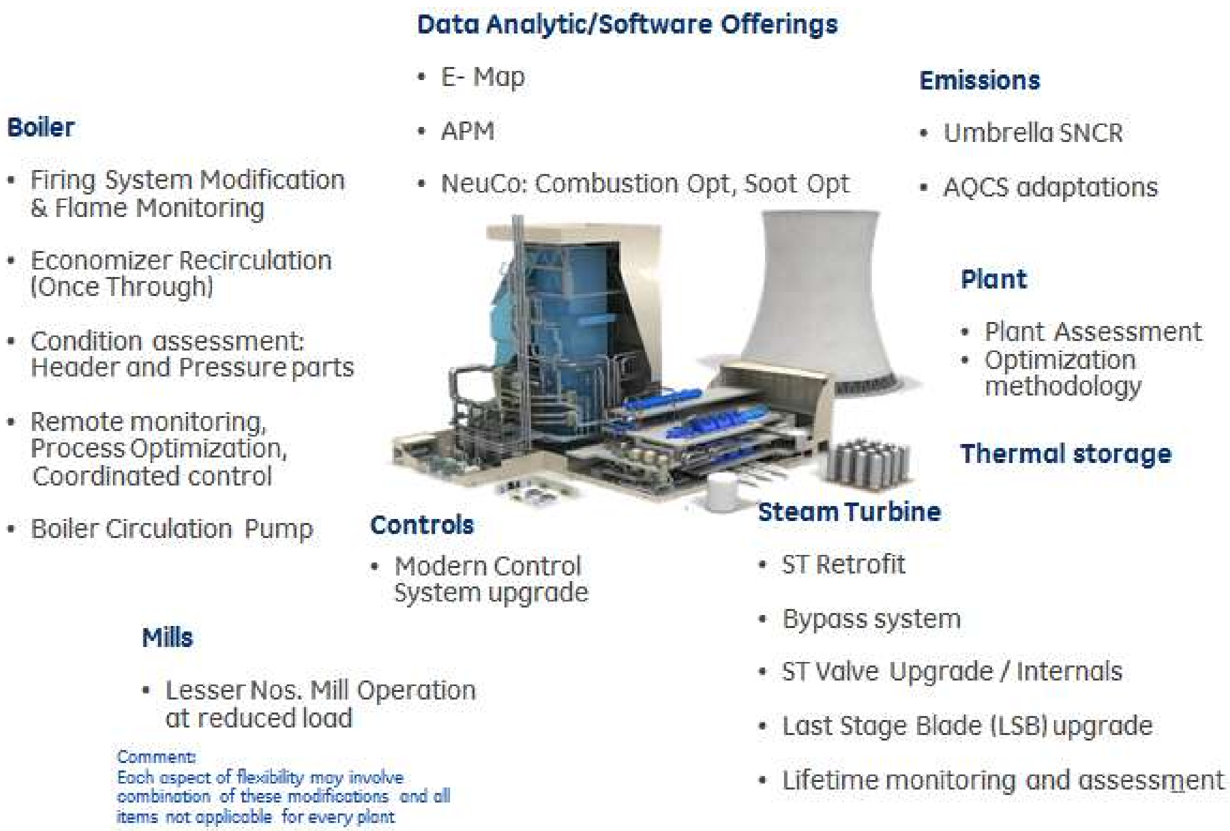


Figure 10: Product Wise Offerings to improve plant level flexibility

Boiler and Emission Control equipment related considerations or modifications:

- **Flame Stability**: Flame stability and effectiveness of flame scanners is one of the prime concern at low loads. Upgrade/ replace faulty Flame Scanners and Flame Stability Monitors to ensure reliable and safe operations for low load and ramping. For fuels with lower reactivity, improved burners with flame attachment features to allow lower load and lower unburned carbon loss.

- **Metal Temperature Concerns**; In the superheater, damage to tubes is usually caused by overheating that results from low or no flow of steam during startup and/or poor flue gas temperature management. Damage to superheater is usually evident by bowing/ bent panels and thermal distortion due to overheating of tubes fully exposed in the gas path. Also, superheater tube damage can result from condensate formation, and stagnation flows during startup. Similar damages often can be experienced in reheater. Although temperature levels are much lower in the economizer, thermal damage can still occur there. Economizer tube failures are usually caused by thermal shocking of the inlet header and tubing with relatively cold water, often during startup.

- **Saturation/ Steaming**: Flexible operation challenges the ability of a plant to maintain water chemistry, can lead to increased corrosion and accelerated component failure. Increased levels of dissolved oxygen in feedwater and also steam temparatures closer to saturation at lower loads can result to accelerate damage to superheater, reheater tubes and waterwalls

- **Pulveriser safety**; Coal pulverizers are prone to fireside explosions and require careful fuel purging and the addition of an inert gas blanket (inerting) when they are cycled off-line. Also, pulverizers are prone to much increased mechanical wear when they are cycled or operated at the low end of their design minimum flow rates. Upgrade Mills to enhance low load and unburned carbon efficiency, improve mill turndown to reduce the number of firing system starts and stops.

- **Thermal Expansions/ Cracked Headers**: Thermal loading and deflections during start up and load gradients result in

- **Emission Control Equipment**: Load following and other modes of flexible operation can affect the performance and reliability of flue gas desulfurization (FGD) equipment and selective catalytic reduction (SCR) systems. The chemical processes involved in these systems require precise control of the reaction conditions, which are influenced by reagent flow, water flow, and flue gas temperature.

Steam Turbine & Generator related considerations or modifications:

- **Extension of Stress Limits**: To limit thermal stresses during transient operation, steam turbines are equipped with online stress control. When the thermal stresses approach the threshold limit, the stress controller takes corrective measures, wherein exceeding beyond this limit results in a turbine trip. In order to improve turbine availability and to avoid unnecessary trips, the stress limits can be recalculated and increased. This is a change in the control software and does not necessarily require the implementation of additional hardware. However, this will definitely affect the lifetime consumption, and thus extension of stress limits requires a closer supervision of the remaining lifetime. Thus, the installation of an Operating Data Counter (ODC) is mandatory, if the stress limits are extended. The ODC counts up events for which the stress exceeded a certain limit and is therefore a (weak) indicator for the progress in lifetime consumption.

- **Enhanced Stress Control**: Turbine protection simply meant to protect the turbine during start-up from overly high stresses. As a result, the turbine protection followed the same simple mechanisms as in case of boilers, where the stress is limited by limiting the temperature difference across the components (example casing and rotor temperature difference). Install thermocouples and monitor temperature gradients and ramp rates. GE can assess the design by finite element analysis and operational procedures to optimize stresses. A modern approach in control theory is to replace old fashioned controls by advanced concepts, like a predictive control. It is not useful to simply compare the performance of a turbine model once controlled with standard PI controls against the same model, where a predictive control corrects the set points. In such a case, the performance of a predictive control will always be improved, especially if the PI controls are badly set up.

- **Rework/ Refurbish Rotors**: Machine out shallow cracks and re-profile to reduce stress concentrations; monitor crack growth. There are two major reasons to rework a rotor, the repair of already initiated cracks, and/or the removal of material with high low cycle fatigue (LCF) lifetime consumption, or the reshape of the critical zones with state of the art groove geometries, resulting in significantly lower stress amplification factors.

- **Valve Internals and LSB health monitoring**: During cyclic and flexible operation the control valves are subjected to frequent throttling/ cycles and experience higher wear in valve stems/ seats/ internals. At lower loads/ backpressure effects during coasting down, the Last Stage Blades (LSBs) could be subject to churning and windage. These phenomenon need careful monitoring to ensure that reliability of the steam turbine is not compromised.

- **Pre Warming**: The thermal inertia of thick walled or large diameter components is limiting the start-up time, whenever the component is in thermal contact with the life steam or hot reheat. As mentioned, this may be mitigated using pre-warming or warm-keeping of these components. The warming reduces the temperature difference between the steel and the steam and with it the stress within the component. GE's modern stress control will allow a seamless integration of the pre-warming and warm keeping to the start-up process. This reduces the start-up times to very short times, especially, if high temperature heating is envisioned. After a preheating installation, many start-up parameters, which are usually set during the commissioning phase of the plant, are out of date. Reconfiguring and validation of such parameters are an important part of a warming concept. Else, poorly implemented integration will either extend the period of investment return or even have some negative effects on the maintenance cost.

- **Generator Rotor**: Due to the movement between the rotor and casing during "barring" (the use of slow turns to keep rotors from being left in one position too long during turning gear operation); the rubbing creates copper dusting, which can also cause ground faults in the rotor. It is recommended to monitor condition of generator by installing Generator Health Monitoring packages.

- **Generator Rewinds**: Consideration to be given for replacement of end rings with better alloys. For older/ deteriorated stator/ rotors, suitable rewinding and life extension to be considered for gearing up for flexible operation.

- **Steam Turbine Retrofit**: With energy efficient Steam Turbine Retrofit with GE technology, there is a potential to regain 5 to 15% from current levels of gross plant efficiency in addition to implementing flexible features. These features are further elaborated in Section 4.4.

4.3 Digital

The concept of efficient coal plant with added feature of GE's digital platform Predix™ will enable utilities to generate competitively and sustain with other competing sources of power generation.

As the competitive landscape for power generators is constantly changing GE Digital helps to provide an operational advantage. The path towards digital transformation can be described with the following steps for which GE provides new solutions:

Connection — provides the foundation to leverage analytics by enabling the collection of machine sensor data from assets and processes data, as well as management of that data to derive value.

Monitoring — focuses on understanding the performance and health of your assets and processes, and visualization of events.

Analyzing — determines the root cause of issues based on historical and real-time data to understand relationships, correlations, and trends, and facilitates effective problem resolution.

Predicting — Provides foresight into impending problems to avoid issues before they occur and drives greater process consistency and asset uptime.

Optimization — maximizes the performance and profitability potential of assets, plants and fleets to achieve the best possible outcomes. Allows simulation modelling to test "what if" scenarios.

GE's software suite of applications will help Utilities reduce production costs and plant downtime through physics-based and predictive analytics. Focussing on key power plant outcomes that influence Utilities KPIs, GE has developed the Digital Power Plant based on GE's digital platform Predix™. The Digital Coal Fired Plant has three application suites namely:

- **Asset Performance Management (APM)** - APM is a software application designed to increase asset reliability and availability while reducing maintenance cost.

- **Operation Optimization (OO)** - Operations Optimization (OO) is a suit that provides Key Performance Indicator (KPI) focused analytics. It provides analytics on both the stable and transitional activities that occur in a power plant, enabling operators to detect and address non-optimal processes.

- **Business Optimization (BO)** - Business Optimization is a cloud-based suite designed to help coal power producers to take full advantage of predictive analytics to make improved decisions around power trading, fuel purchases and portfolio management.

Figure 11: Predix™ Platform and GE Digital offerings to deliver outcome to our customers

GE Power Digital Offerings Drive Real Results

Offering	Real Customer Results	Customer Benefits
Asset Performance Management	**$10 MM/year from early detection failures and reduced insurance costs**	• Improve reliability with advanced proprietary analytics that predict potential equipment failure to effectively plan maintenance • Improve availability — accurate diagnosis of equipment issues toward no unplanned downtime • Reduce maintenance costs — customize maintenance strategy to reduce maintenance activity
Operations Optimization	**Enabled load ramping up to ±50 MW/min, 2.5 times the normal rate, allowing quick response to market demands in ancillary markets**	• Additional economic insight into maintenance decisions based on plant operations • Higher accuracy in communicating commitment to trader and dispatcher • A component-level view of the impacts to fuel efficiency
Business Optimization	**Predicted availability 2-3% more accurately — offers trading team the option to bid additional capacity into the market**	• Real-time transparency to power production grants additional MW to sell • Avoiding penalties by making offers with confidence to meet delivery commitments • Accurate and profitable fuel purchasing decisions based on data-driven analytics • Real-time insights into financial KPIs for executives, traders and plant managers
Advanced Controls / Edge Computing	**10% increase in output capacity** **2% increase in fuel efficiency** **Achieved both through AGP flange to flange replacement and GE Advanced Controls / Edge Computing software solution**	• Deliver power quickly in response to changing grid demands • Eliminate slow, inefficient start-ups and reduce start-up costs • Meet more demand within existing markets to increase revenues • Manage variable fuel sources with smoother power output • Reduce emissions to meet compliance standards

4.4 Lifetime extension and retrofits

Boiler Retrofit:

GE offers low load retrofits targeting reduction in the average minimum load of 30-40% to 10% for hard coal and from 50-60% to <30% for lignite fired plants, both for tangentially fired boilers. Wall fired boilers will due to the limitations of the firing system and mill configuration typically is limited to 20%.

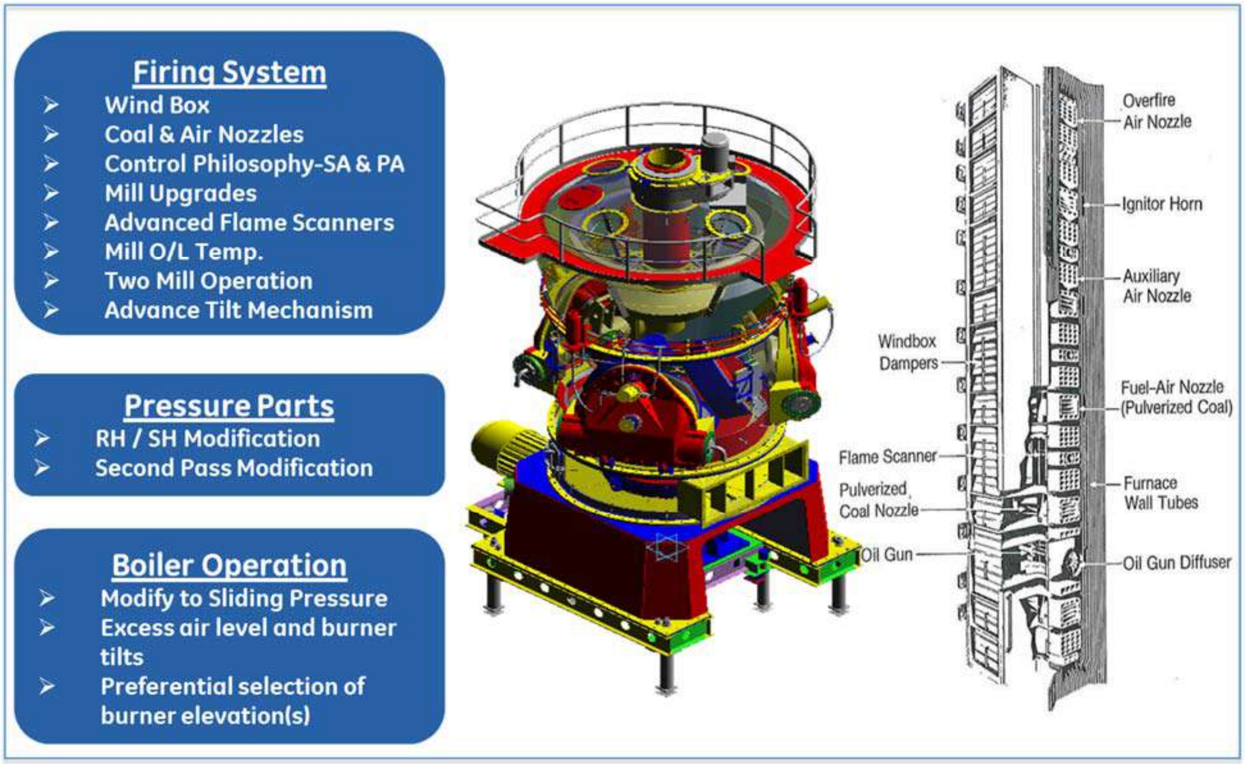


Figure 12: Various Boiler component modifications and evaluations for enabling higher flexibility

Such retrofits include optimized configuration/operation of mills and burners in combination with flame scanners and digital solutions to ensure safe and proper combustion, emission compliant operation and heat distribution to maintain steam temperatures within allowable limits.

Steam Turbine Retrofit:

With energy efficient Steam Turbine Retrofit there is a potential to regain 5 to 15% from current levels of gross unit heat rates. In addition to any performance improvement, retrofitting with the latest technology also provides:

- Improve efficiency to reduce fuel consumption, resulting lower emissions
- Conversion of steam entry to better suit part operation by introduction of the control stage and changing steam admission from full to partial arc, hence higher part load efficiency can be achieved
- Increased operational flexibility
- Shorter start-up & shut-down times compared to existing unit
- Reset the residual life clock
- Improved reliability and extend the period between overhauls

As a result of efficiency improvement, the sizing needs of emission controlling equipment (DeSOx and DeNOx) get optimized. Furthermore due to application of DeSOx equipment (FGDs, Scrubbers etc) additional parasitic loads are introduced which can be recovered by uprating while implementing the Steam Turbine Retrofit.

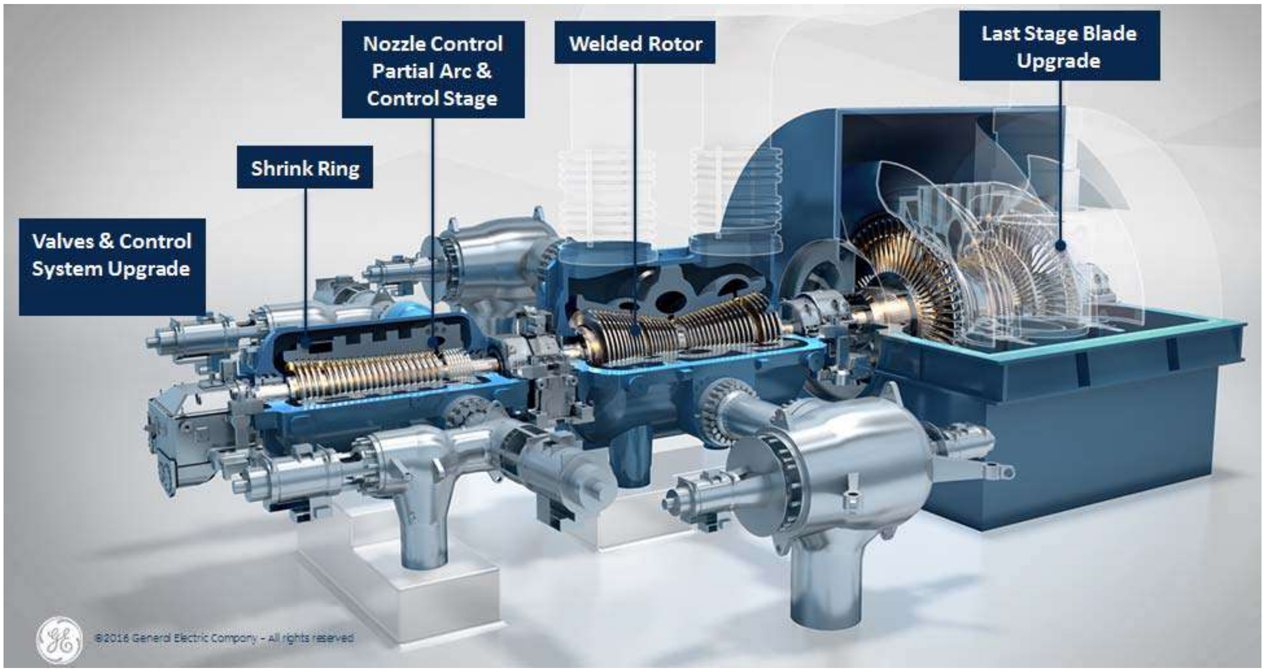


Figure 13: GE Steam Turbine Retrofits' Flexible Features

4.5 Plant & Integrated Solutions

Optimised Plant Retrofit (OPR):

Optimised Plant Retrofits (OPRs) are integrated plant solution approach which look into the thermal model, water steam cycle, boiler performance model in a holistic manner to achieve full optimisation and integration of new components into the plant.

Bypass Operation (Start Up Boost):

In India many older units still have Pressure Regulating and Desuperheating Stations (PRDS) which are about 10 to 20% of the steaming capacity of boiler. Replacement with a Turbine Bypass System to such existing fossil fired steam power plant, consisting of a high pressure bypass valve and a low pressure bypass valve with steam dump device (see Figure 1). With this arrangement, the boiler can, to a certain degree, be operated independently from the turbine. A turbine bypass system provides the opportunity to improve startup flexibility and ensure cooling steam flow through the superheater and reheater during starts and load rejections.

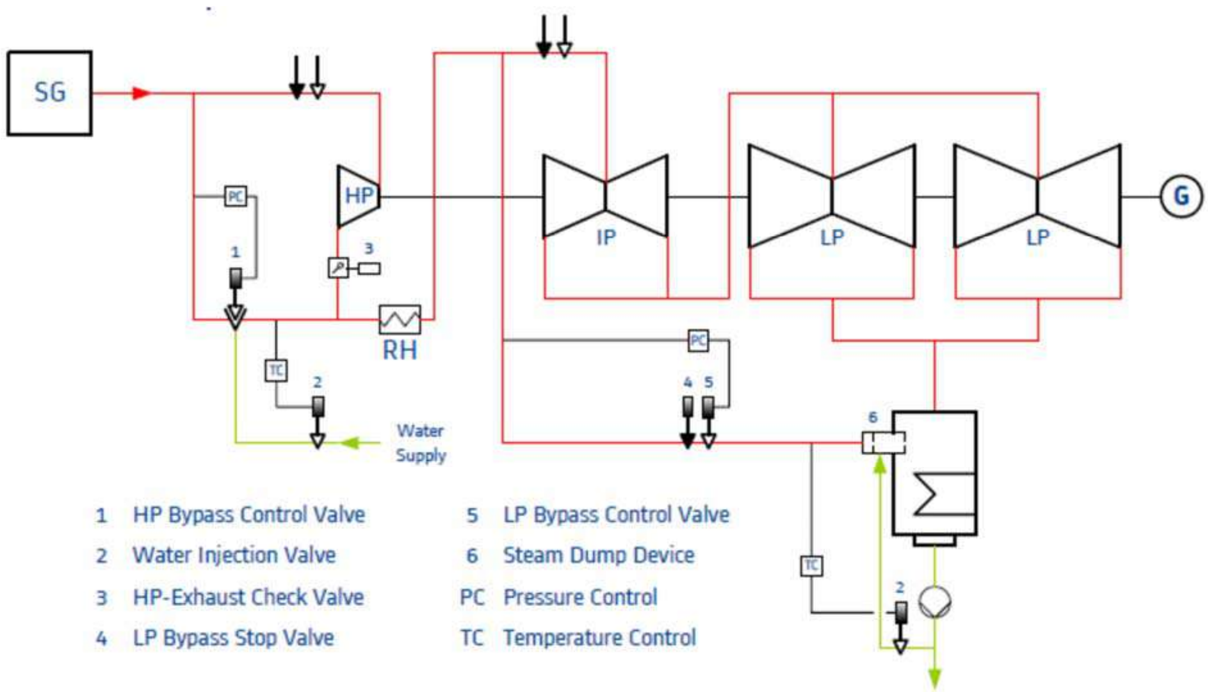


Figure 14: HP & LP Bypass Control

With a 100 % HP bypass, the blowing of main steam safety valves can be avoided and the reheater can be optimally cooled during load rejection. With 60 % LP bypass capacity, the maximum design steam capacity of the condenser will not be exceeded at turbine trip. Reheater safety valves or boiler vent valves will release the excess steam. This configuration will ensure that the capacity of the installed components is adequate for warm and hot starts. Furthermore, the boiler can remain in operation at reduced load (after load rejection) and be ready for further grid demand.

Cold End Optimisation:

Most older thermal units suffer from poor performing Cold End cycle, which comprises of Condenser, Cooling Tower and the CW pumps. Some thin condenser tubes are susceptible to tube failures during cyclic operations. Available solutions could be partial upgrade, condenser retubing or modular retrofit. The Cooling Range (CR) in the condenser is given by the current water massflow through the condenser. A reduction of the CR could be realised by increasing the water flow with an upgrade of the CW-pump.

5 CASE STUDIES

5.1 Flexibility Asks Globally

The needs for generators are varied globally because of different market dynamics varying from region to region. Generators in mature markets experience high levels of competitiveness not only to achieve greater cost competitiveness but also to comply with environmental norms. In developing markets, the aspect of cost competitiveness and compliance to stringent emission norms are fast catching up. The US and EU countries are at the forefront of experiencing and tackling the flexibility aspect due to their strong focus to enhance capacity addition of renewables and demand/supply situation. Interestingly, from 1990 to 2012, the emissions increased 52% globally and the corresponding increase in power sector was 91%. Thus, the aspects of efficiency and emission compliance are now at the forefront irrespective of a matured or developing economy. The table below shows a snapshot of typical flexible operation asks of Utilities in few select Countries:

Flexibility Asks	Denmark	Germany	UK	US
Fast Starts				
Fuel Costs during start up	Yes	Yes		
Minimum Stable Load requirement	Yes	Yes	Yes	Yes
Fast Ramping	Yes	Yes	Yes	Yes
Part Load Efficiency	Yes	Yes	Yes	
Fuel Flexibility	Yes	Yes	Yes	
Peak Load		Yes		
Reliability			Yes	Yes

Table 6: Typical Flexibility asks from Customers globally

In following sections case studies of the US and German power sector scenario are discussed.

5.2 The Scenario in US

In the US, 29 states, the District of Columbia, and three territories have committed to Renewable Portfolio Standards (RPS). Furthermore, environmental rules like the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, and the Endangered Species Act drive the need of enhanced flexibility of power generation sources.

Large sized fossil units in US have operated on baseload historically. However with increase in Renewables and daily/ seasonal peak load variations, fossil units have entered cyclic duty mode. NREL carried out a study on impact of cycling wind and solar on the western grid. As part of the findings of Phase I of Western Wind & Solar Integration Study (WWSIS – I) the system dispatch plot was generated to study the impact of variability of wind and solar for the most challenging weeks in a three year period

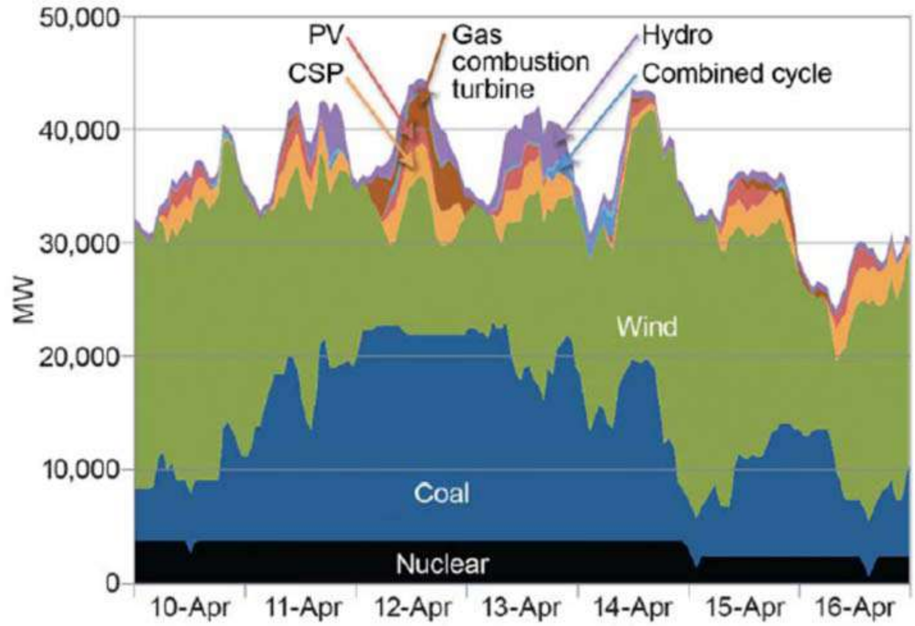


Figure 15: WWSIS I System Dispatch for most challenging week

In US, the combination of low natural gas prices and must-run renewables capacity results in high capacity factors for gas units which offer the flexibility advantage of multiple trains that can be started and stopped. However, in isolation a single train does not provide the high turndown ratio of a coal-fired generator and equipment life gets consumed faster. They fluctuating fuel prices in US also drive the need for flexibility.

5.3 The Scenario in Germany

The principal objectives of the Energiewende (Germany's energy policy) are:

- o Transitioning power supply to one mainly based on renewable energy;
- o Keeping power prices on a competitive level for industry and an affordable level for private households;
- o Ensuring continuous, secure electricity supply.

The Renewable Energy Sources Act provides feed-in tariffs for renewable energy for 20 years after plant is commissioned. Grid operators are obliged to purchase the entire quantity of renewable electricity with priority. The trade companies pass on the deficit (i.e., feed-in tariff minus market price) to customers by imposing a reallocation charge.

With the increase in renewable energy, power producers also face a new challenge. In the past a main focus was offsetting fluctuations in consumption between day and night, workdays and weekends, and seasonal variations. Today, feed-in intermittency has added a new source of fluctuations that are at least the same magnitude as those from changes in consumption.

The need for load adjustments by flexible power plants is particularly critical when an increase in electricity demand occurs at the same time as the feed-in from wind power plants dramatically decreases. There has been a need for load adjustments of >50 GW (i.e., >60% of the peak load) within an eight- to 10-hour period. This sort of demand fluctuation is generally random, but can be forecast up to two days in advance (e.g., via a wind forecast). Thus, conventional power generation plants are faced with massive technical and economic challenges. The below example aptly represents the situation:

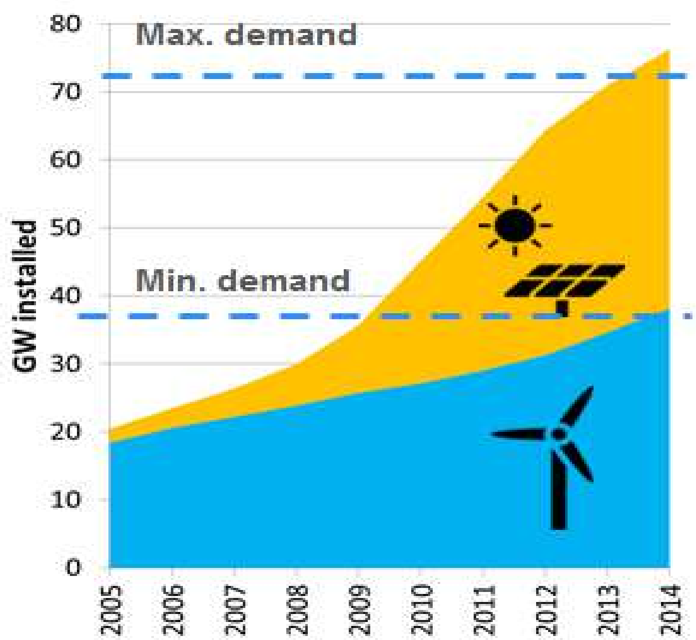


Figure 16: Demand Profile in Germany - Ref 2014

A brief overview of two typical days of the German electricity demand are very good examples to demonstrate the changing and variable nature of duty of conventional coal fired power plants. Due to the high demand and low feed-in of electricity from renewable energies, on 24 January 2013 up to ~74GW which is 92% of the peak demand of ~80GW in Germany, had to be covered by conventional power plants. On contrary, on 24 March 2013, a Sunday with low electricity demand coupled with high feed-in from wind and solar, a minimum of ~14GW had to be covered by conventional power stations. This represents a tremendous shift in the role of conventional power plants.

Many of the conventional power plants operating in Germany today were built in the 1980s and 1990s, before expansion targets for wind and photovoltaic plants had been adopted. In many plants, measures to allow greater flexibility have been implemented subsequently, so that power plants can meet increased requirements for market load adjustments. German power plant operators have also made it possible to reduce the minimum load of operation at existing power plants by optimizing the boiler-turbine system using modern control systems. Today's optimized coal-fired power plants are able to operate at a partial-load level of less than 20% of full-load capacity.

5.4 Case Study of 800MW Heilbronn 7

GE had modernised EnBW Energies' Heilbronn unit # 7, a hard coal fired 800MW unit with tower type GE boiler and GE steam turbine-generator. The unit, originally built in 1985, caters to district heating and power generation with an original design low load capacity of 30% MCR. The project was taken up with target low load capacity of 15% MCR. The scope included start up optimisation, optimisation of bypass operation and recalculation of boiler-turbine sequencing controls.

Figure 17: EnBW Energie Heilbronn PP

Upon completion of the project, the unit is capable to operate at a technical minimum level of 14% load with one mill operation.

Parameter	Full Load	Minimum Load
Heat Input	100%	14%
Net Efficiency	41%	26%
Live Steam Temperature	540 deg C	505 deg C
Reheat Steam Temperature	540 deg C	467 deg C
Unit Load	812 MW	105 MW

Table 6: Achieved parameters in Heilbronn 7 Low Load project

5.5 Cost of Cycling

A report released by NREL on a study of cost of cycling provides a detailed overview on cycling costs of power generation sources with an intent to provide awareness to utilities on cost of cyclic operations and for policymakers to consider while planning renewables integration. A brief snapshot of the summary is presented in table below:

Sl. No.	Parameters	Coal - Small Sub Critical	Coal - Large Sub Critical	Coal -Large Super Critical
1	O&M Costs ($/MW capacity)			
	Hot Start up	High	Medium	Low
	Warm start	High	Low	Medium
	Cold start	High	Medium	Low
2	EFOR Impact (% Add in 1yr EOFR)			
	Hot Start up	High	Medium	Low
	Warm start	High	Low	Medium
	Cold start	High	Medium	Low
3	Non cycling related cost -Baseload variable cost ($/MWh)	Medium	Low	High
4	Load following cost ($/MW)	High	Medium	Low
5	Range of load follow (% of Gross Dependable capacity)	Medium	High	Low
6	Multipying factor (Faster ramp rate-1.1-2x) Range	Low	Medium	Medium
7	Startup fuel cost (MMBTU/MW)			
	Hot Start up	Low	Medium	High
	Warm start	Low	Medium	High
	Cold start	Low	Medium	High
8	Other startup cost (Aux power & Chemicals etc.) ($/MW)			
	Hot Start up	Low	Medium	High
	Warm start	Low	Medium	High
	Cold start	Low	Medium	High
9	Heat rate Impacts (% Increase per start up/ SD cycle)	High	Medium	Medium

Table 7: Comparative Cost of Cycling (Source NREL Report)

The takeaways from above table is the start ups for larger sized units are higher compared to smaller frames.

6 CONCLUSIONS

6.1 Advocacy & Regulatory Landscape

There is a notion that due to large amount of Renewables coming in thus resulting in overcapacity, the prices of electricity will go down. However, this notion neglects the additional cost of operational flexibility. Operation flexibility increases the variable (marginal) costs of a plant by start-up costs and part load efficiencies. Hence there needs to be mechanism in place to suitably compensate the Generator who is investing to make the unit/s flexible to support and protect the Grid due to the large influx of Renewables coming in.

A snapshot of standard frames on varying part load design Net Unit efficiency is shown in graph:

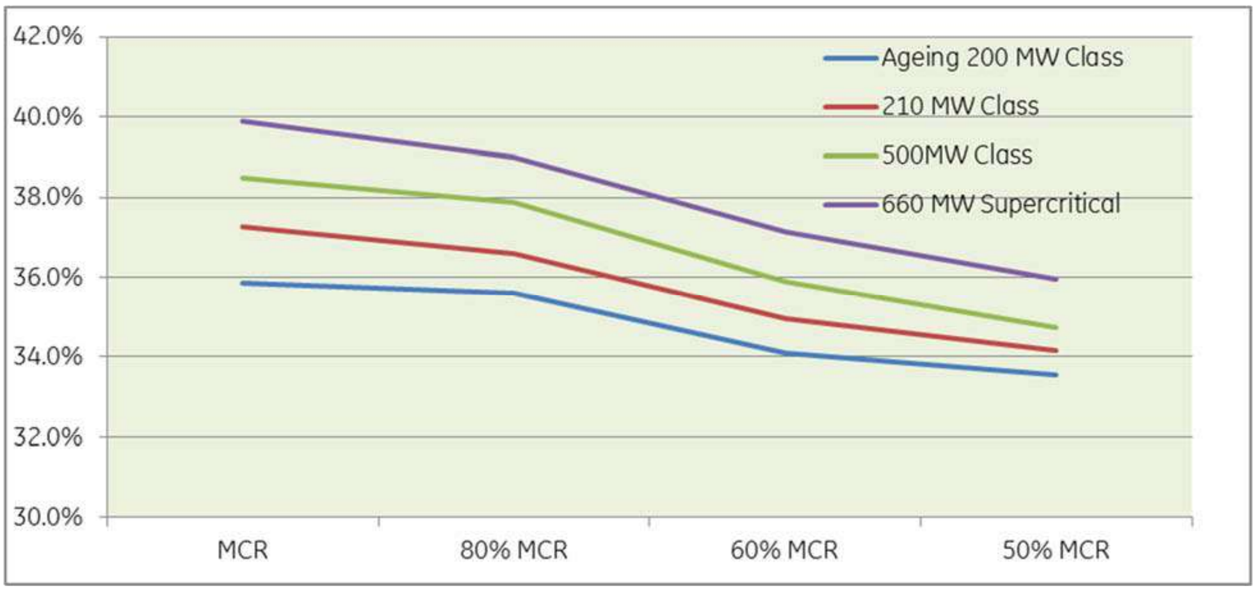


Figure 18: Typical Part load efficiency degradation curve

In order to understand how to compensate Flexibility; we must first define an Index to measure the Flexibility or the **Flexibility Index (FI)**. The Flexibility Index can be defined as the capability/ degree to which a coal fired unit can be flexible, i.e. a combination of part load efficiencies, ramping rates to/ from the lowest possible technical minimum unit can achieve.

The Central Regulator (Central Electricity Regulatory Commission – CERC) has recently brought out aspects of Flexibility in the Indian Electricity Grid Code wherein CERC has defined the technical minimum at 55% MCR and with compensation in Station Heat Rate (SHR) for part load operation arising due to grid requirements. The actual operational constraints/ capabilities of existing base load units must be taken into consideration to suitably workout the compensation and necessity of modification to meet the specified flexibility index.

Above takes care of operational cost of flexibility. The aspect of compensation for the life consumption or the capital cost of flexibility is still not in place and needs to be deliberated and proposed. There are two aspects for flexibility capex compensation:

- The upfront Capex for implementing the flexibility operation enabling features in critical equipment/ systems being allowed in the fixed cost of tariff discussed in the next section

- The aspect of relatively earlier life consumption due to flexible operation. While these is not straightforward to estimate, but international agencies like EPRI and NREL have come out with detailed analysis for recommended cost of flexibility/ cycling

6.2 Investment for Flexibility

Cyclic operation results in faster lifetime consumption, potential failures of critical components, and other issues not limited to below:

- Turbine stop and control valve internals
- Turbine rotors operating in high temperatures
- Turbine last stage blades facing windage
- Turbine drain system valves
- HP and LP bypass valve internals
- Boiler superheater and reheater tube failures due to peak temperatures
- Critical piping/ header joints
- Pulveriser components
- Higher auxiliary energy consumption
- Ensuring continued safety and integrity

Existing base load 200MW class and 500MW class can be upgraded/ retrofit units with state of art technology to also make them flexible and efficient and competitive in the market while complying to emission requirements. Upgrading existing plant has a very strong potential to reuse bulk of existing infrastructure, Balance of Plant and quick gestation period of 18 to 24 months compared to 36 to 45 months for a new build unit thereby realising early returns for the Utilities and keeping them within the merit order.

The enhancements in existing base load units to implement flexibility enabling capability would result in implementation of following upgrades/ retrofits/ add on which will be the Capex cost (fixed cost) of flexibility:

- Boiler firing system upgrade
- Air/ gas flow system revision

- o Steam turbine upgrade
- o Generator rewinds
- o Digital and advanced controls
- o Replacements/ maintenance for wear/ failures

The Opex cost (variable cost) of flexibility will comprise of following aspects

- o Increased heat rate due to part/ low load operation
- o Higher auxiliary energy consumption
- o Modern O&M practice

6.3 Recommendations for Installed Base

To maintain a competitive business with sustainable power generation, utilities must defend their position in the merit order with active improvements of the operational flexibility of their plants. Otherwise, the increasing hours, when the electricity price falls below their production cost, will lead to a constant turn down. It begins with frequent de-loading of the plant to reduce the variable costs during times of negative income. This in turn, reduces the capacity factor leading to higher variable costs, i.e., the plant is slipping up the merit order.

The higher efficiency of large sized units gives them a competitive advantage because of the lower specific electricity production cost. However with very frequent start-stop cycles and lower loads, this advantage melts away.

Flexible Parameter	200 MW class fleet	500MW class fleet	660/ 800 MW class supercritical fleet
Ramp Rate	2 to 3%/ min	2 to 3%/ min	3 to 5%/ min
Technical Minimum Load	70% MCR	55% MCR	40% MCR
Recommended Priority in Flexing & Rationale	1 Implement flex enabling modifications, comparatively lower cost of flexing	3 flex few units implementing modifications and rest fleet run base load due to higher cost of part loading	2 flex few units because of inherent capabilities and rest fleet run base load, large units have higher cost in part loading

Table 8: Start up and Ramp rates of various fleet of Coal Fired Power Plants

While above table demonstrates the ramp rates as designed, in practicality Utilities are unable to declare in such range and typically the ramp rate declared to Load Dispatch Centres (LDCs) and possibility to achieve flexible parameters with current available technology is as follows:

Flexible Parameter	200 MW class fleet	500MW class fleet	660/ 800 MW class supercritical fleet
Typical design Ramp Rate	2 to 3%/ min	3 to 5%/ min	3 to 5%/ min
Typical operating Ramp Rate	0.4 to 0.6%/ min	0.6 to 1%/ min	1 to 3%/ min
Technical Minimum Load	70 to 75% MCR	65% MCR	~ 55% MCR
Possible Ramp Rates with Modifications	3 to 5%/ min	3 to 5%/ min	5 to 6%/ min
Possible Technical Minimum with Modifications	~ 30% MCR	~ 30%	~ 30%

Table 9: Ramp rates of various fleet in India as declared to LDCs

Due to the higher flexibility capability of the 660/ 800 MW class supercritical units, these units can be flexed to support Grid at times of variability. A snapshot of upcoming renewable share is presented in table below:

India - Regional Renewable targets in 2022 (GWs)	Solar	Wind	Small Hydro	Biomass
Northern Region	31.1	8.6	2.5	4.1
Western Region	28.4	22.6	0.1	2.9
Southern Region	26.5	28.2	1.7	2.6
Eastern Region	12.2		0.1	0.2
North Eastern Region	1.2		0.6	

Table 10: Share of Renewable Capacity planned by 2022 in Indian regions in GWs

The aspect for need for flexible coal plants will vary from state to state due to the proposed renewable capacity addition and accordingly there could be potential in some states upto 30% of coal plants need to be flexible.

It is recommended to modernise and upgrade the 200MW class and few 500MW class with state of art technology to also make them flexible and efficient and competitive in the market. At GE we acknowledge the need making the conventional fleets more flexible and as the world's premiere digital industrial company, we believe, the solution can be found connecting the physical and digital world.

7 ACKNOWLEDGEMENT

The authors would like to thank all the writers/ contributors/ reviewers of the GE team for their critical contributions towards building the content of this white paper.

8 REFERENCES

[1] Powering India: Benefits of Digitization of Coal-fired Power Plants, GE Power Position Paper 2016.

[2] Flexibility Requirements in Indian Power System, POSOCO, January 2016

[3] Flexible Generation: Backing up Renewables, Eurelectric Renewables Action Plan, October 2011

[4] Central Electricity Regulatory Commission, Indian Electricity Grid Code, IEGC Fourth Amendment Apr 2016, www.cercind.gov.in

[5] Central Electricity Authority, www.cea.nic.in

[6] E&Y – The Paris Agreement, What it means for India, www.ey.com

[7] Flexible Improvement of Steam Turbines of Conventional or CCPP presented in Powergen Europe 2013, J Vogt, T Schaaf, W Mohr & K Helbig, GE Power

High Ash Coal Gasification in Fluidized Bed Gasifier: Challenges and Opportunities

P.D. Chavan*, A. Banerjee, V. Chauhan, N. K. Gupta, G. Sahu, S. Saha,

S. Datta, P. Dutta and P.K. Singh

Gasification and Liquefaction Research Group
CSIR-Central Institute of Mining and Fuel Research Institute
Digwadih Campus, PO-FRI,
Dhanbad 828108 Jharkhand, India

Corresponding Author: Dr. Prakash D. Chavan; email- chavanpd@gmail.com,
Mob.- 9931313637; Ph.- 03262388315

Abstract

In the country like India, coal is the prime energy source and it will continue to play its role for the coming several decades. 70% of electricity generation in India is inferior grade high ash coal based. These coal-based conventional power generation technologies have several drawbacks and coal technologies are of utmost importance. In this regard, Coal gasification is one of the important clean coal technologies, because it is a mean to utilize the coal more efficiently meeting stringent environmental regulations. Thus, efficient use of coal meeting environmentally acceptable parameters as well as lowering the dependency on petroleum source has been the driving force in developing gasification technologies. Among all the available technologies worldwide, Fluidized Bed Gasification (FBG) is the most suitable option to handle high ash coal. Presently, FBG Technology is under developing stage. In India, numbers of stake holders are involved in the development of fluidized bed gasifier. However, some gaps need to be addressed for its commercial exploitation like, development of proper feeding and ash withdrawal systems for handling wide variety of feed stock, establishing proper hydrodynamics in side gasifier bed to minimize operational issues like agglomeration and clinker formation as well as to enhance the gasification performance. Further, establishing the suitable operational philosophy for gasification of different feed stock and their blends in FBG is necessary. Also, understanding the physico-chemical properties of feed stock and establishing its relevance with gasification performance parameters like carbon conversion, gas yield and heat value, etc. is necessary. In this direction, CSIR-CIMFR has developed FBG facility for high ash coals with feed rate 20 kg/h. During experimentation in FBG, it was observed that high ash Indian coals can be successfully gasified without any operational problems like agglomeration and clinker formation with proper synchronization of different operating parameters. Further, it is also observed that blending of small quantity of biomass with coal improves its overall performance parameters. Considering the importance of co-gasification, three types of biomass such as rice husk, sawdust and press mud were taken with one high ash Indian coal in different proportions. The main objectives of this study are assessing the performance of a fluidized bed gasifier (FBG) pilot plant based gasification process using blends of high ash Indian coal and various biomasses as fuels.

Key Words: *High ash coal; gasification; biomass; fluidized bed gasifier*.

1. Introduction

Coal is one of the most important energy sources in the world not only for power generation but also for the production of various chemicals such as methanol, substitute natural gas (SNG), ammonia as well as for fertilizers. 30% of the global primary energy needs and around 42% of the global electricity generation are met by coal (Aranda et al., 2016). Coal becomes more valuable energy source due to the gradual diminution of oil and natural gas reserves throughout the world. In the country like India, coal is the prime energy source and it will continue to play its role for the coming several decades. However, only 13% of the Indian coal is of good quality coking coal and the remainder is mostly of high ash non-coking coals with typically more than 40% ash. 70% of electricity generation in India is inferior grade high ash coal based. These coal-based conventional power generation technologies have several drawbacks, such as lower efficiency, environmental loading and damages thereof. 38% of the total greenhouse gas emissions caused by these low-efficient-coal-based power plants and it has been reported that the CO_2 emissions may be expected to increase in India at an annual growth rate of 3% up to 2025 (Saha, et.al., 2018).

Therefore, clean coal technologies are of utmost importance including new coal combustion and conversion technologies for improving efficiency of coal utilization and reduction of CO_2 and other pollutant emissions in the environment. This may require the capture of the CO_2 waste stream, and its subsequent sequestration or utilization. In addition, there may be options where coal may be converted into other fuels or energy carriers, such as liquid fuels, hydrogen or other industrial chemical feed stocks. In this regard, Coal gasification is one of the important clean coal technologies, because it is a mean to utilize the coal more efficiently meeting stringent environmental regulations. Thus, efficient use of coal meeting environmentally acceptable parameters as well as lowering the dependency on petroleum source has been the driving force in developing gasification technologies. These have been developed to provide electricity, synthesis gas, hydrogen with zero emission of green house gases as well as various chemicals such as, methanol, substitute natural gas (SNG), ammonia, fertilizers etc. from the same platform. This cogeneration option of gasification technologies improves its overall efficiency as well as reduces environmental damages.

Among the three types of gasifiers (Entrained Flow, Fixed Bed and Fluidized Bed), entrained flow gasifier is not suitable to handle high ash coals. For entrained flow gasifier, an increase in coal ash content will lead to an increase in slag production and disposal as well as decrease in cold gas efficiency. Further, coals selected for entrained flow gasifiers should thus have an ash fusion temperature below the operating temperature of the gasifier (1400–1600 ^{0}C). Ash fusion temperature is also high (>1400 ^{0}C) for Indian coals. As the ash is removed in the form of slag in case of entrained flow gasifier, huge heat loss occurs during handling high ash coals having high ash fusion temperature and efficiency of the plant decreases severely. Therefore, entrained flow gasifier is not at all suitable for handling the high ash Indian coals.

On the other hand, Moving bed (Fixed Bed) gasifier has limitations to handle high ash coals. From the JSPL's experience (JSPL, Angul), it can be stated that fixed bed dry bottom (FBDB) Lurgi gasifier can handle Indian coals with ash content up to 30%. Coals with higher ash content need to be washed or blended with lower ash containing coals to bring down the ash level up to 30% for utilization through fixed bed technology. Another major drawback of this technology is the generation of huge tar in the process and difficulties in handling the fines as feed. The raw gas needs to be free from tar and suspended particles for most of the applications considering the technological and environmental issues. Therefore, installation of coal washing plant as well as enormous downstream processing increases the CAPEX and OPEX at the cost of efficiency.

On the contrary, Fluidized Bed Gasifier (FBG) is the most suitable to handle high ash coals. It can handle high ash coals without need of washing, removal of fines and also does not generate tar and associated byproducts improving syngas quality and minimizing overall CAPEX and OPEX resulting in higher syngas yield per kg of coal and lower syngas production cost. Advantages and disadvantages of FBG have been described in the next section. FBG is also suitable to handle different types of biomass or co-gasification with coals. Usage of high-ash coal and biomass as individual feedstocks in the fluidized bed gasifier (FBG) have following advantages (Basu, 2006; Patil-Shinde et al., 2014): (i) high feedstock tolerance, that is flexibility to handle wide range of materials including low-rank coals and agricultural/industrial/forest waste biomasses, (ii) provides better mixing between the fuel and the air/steam (gasifying agent) resulting in good heat and mass transfer effects in the reactor, (iii) negligible formation of tar and phenol, and (iv) high solid residence time. Thus, co-gasification is also an emerging and promising technique that thermo-chemically converts—at escalated temperatures, and under oxygen-deficient conditions—carbon-containing feedstock into a product gas mixture comprising hydrogen, methane, carbon monoxide, carbon dioxide, nitrogen, and smaller quantities of hydrocarbons (Stevens, 2011). Co-gasification adds flexibility to the energy systems by enabling the use of high-ash coal, solid biomass, and industrial/municipal/agricultural waste for several applications like power generation, transportation fuels and chemical production (Fermoso et al., 2010). This technique acts as an important "green" medium for the production of energy by co-employing the conventional and non-conventional fuels. It not only alleviates air pollution and release of volatile organic compounds but also diminishes soil and water pollutants that are emitted due to chemical constituents of coal (Emami-Taba et al., 2013). (Higman and Van Der Burgt, 2008; Watanabe and Otaka, 2006). For more than two decades, an increasing number of studies have been performed involving co-gasification in fluidized bed gasifiers (Aigner et al., 2011; Andre et al., 2005; Aznar et al., 2006; De Jong et al., 1999; Fermoso et al., 2009; Li et al., 2010; Mastellone et al., 2010; McLendon et al., 2004; Pan et al., 2000; Pinto et al., 2003; Sjostrom et al., 1999; Velez et al., 2009). The scale of these studies clearly indicate the importance of co-gasification in FBG emerging as a prominent alternative technology for new generation of power plants, proving to be economical in terms of controlling the pollutant emissions, better efficiencies, and a promising substitute to fast depleting fossil fuels. But very little knowledge about co-gasification studies is available with high ash Indian coals and different biomass. Therefore, present paper proposes to study the co-gasification of high ash Indian coal with three biomasses such as rice husk (RH), saw dust (SD) and press mud (PM) in different proportions in FBG gasifiers.The main objectives of this study are assessing the performance of a fluidized bed gasifier (FBG) pilot plant based gasification process using blends of high ash Indian coal and various biomasses as fuels.

2. Advantages and Disadvantages of Fluidized Bed Gasifier

Fluidized bed gasification has a number of advantages over the other gasification technologies. These are:

i) The rapid and thorough mixing of solids with the gas which leads to almost uniform isothermal conditions inside the gasifier. It also prevents the rapid temperature changes inside the bed and avoids formation of cold or hot spot. ii) The heat and mass transfer between gas and solids are higher in case of fluidized bed gasifiers compared to other gas-solid reactors. iii) Fluidized bed gasifiers have higher degree of contact between gas and solid reactants. It increases fractional conversions of solids and provides a uniform product pattern. iv) Tar formation is almost negligible in the fluidized bed gasifiers. It makes gas cleaning system easier. Moreover, in situ sulphur capture is possible in fluidized bed gasifiers by adding sorbent in the bed. v) The liquid like behaviour of the bed is most ideal for setting up an easy and reliable process control, which also helps the removal of ash and addition of fresh feed in the gasifier. vi) The absence of moving parts in the hot region lowers the operating and maintenance cost. vii) The fluidized bed gasifiers have wide turndown ratio and additionally, viii) the great operating flexibility makes it possible to utilize different fluidizing agents.

The fluidized bed gasifier offers a simpler and more robust method for generating power from coal. It is unique among coal gasification technologies in the sense that it is cost-effective when handling low rank coals with high moisture or high ash contents. Moreover, the fluidized bed gasifier is capable in both air- and oxygen-blown operations and this inherent flexibility allows it for other applications beyond power generation, such as the production of chemicals.

Based on above supposition, fluidized bed gasifiers will be more suitable for high ash Indian coals, biomass and their blends. In comparison to entrained flow and fixed bed gasifiers, fluidized bed gasifiers have advantages in terms of auxiliary power consumption both for air separation and feed coal preparation. It is also advantageous with respect to lower sensible heat losses and longer refractory life. When high-ash coal is used in FBG, the drainage rate of bed ash is higher which reduces accumulation of coarse particles on the distributor, thereby preventing hotspot formation and clinkering of the bed. Fluidized bed gasifiers generally have advantages in load flexibility over entrained flow gasifiers.

Contrary to fixed bed reactors, different reaction zones cannot be distinguished in fluidized bed reactors. This is due to the intense mixing between feedstock and gasifying agent which facilitates simultaneous reactions within the reactor. The turbulence in the reactor promotes uniform bed temperature and enhances the heat and mass transfer which lead to increases of reaction rates and carbon conversion efficiency (up to 97%). Typically, fluidized beds are designed for large-scale and high capacity gasification (greater than 10 MWth) applications. Two primary fluidized bed designs are bubbling fluidized bed and circulating fluidized bed (Biomass Technology Group, 2005). To achieve high carbon conversion, feedstock is usually fed near the bottom of the hot bed in order to lengthen the residence time. The major advantage of this system is that the hot fluidized media breaks up the feedstock fed into the bed thus enabling homogeneous mixing, good heat and mass transfer between solid and gas, and better temperature control. Moreover, the bubbling fluidized bed permits addition of catalysts such as nickel, alkali metals, dolomite, olivine or alumina to reduce contaminants and improve quality of syngas for suitable end applications (Pinto et al., 2009).

The disadvantage of fluidized-bed gasification compared with fixed-bed and entrained-flow gasifiers is that the carbon conversion is lower. The lower carbon conversion is due to lower temperature, attrition and bypassing of char in the reactor and low char reactivity. (Engelbrecht et al., 2011) Therefore, from above discussion, it is clear that fluidized bed gasifier is most suitable in Indian context for gasification of high ash coals, biomass and their blends.

3. Fluidized Bed Gasifier Development Programs in India and Challenges

In India, numbers of stake holders are involved in the development of fluidized bed gasifier. BHEL has developed PEDU (18 TPD) and demo scale(168 TPD) fluidized bed gasifier. Thermax and EIL have also installed Oxy-blown Pressurised Fluidized Bed Gasifier having capacity ~150 kg/h. Earlier CSIR-IICT had experience of operating ~4 TPD FBG. Still some gaps need to be addressed for its commercial exploitation like, development of proper feeding and ash withdrawal systems for handling wide variety of feed stock, establishing proper hydrodynamics in side gasifier bed to minimize operational issues like agglomeration and clinker formation as well as to enhance the gasification performance. Further, establishing the suitable operational philosophy for gasification of different feed stock and their blends in FBG is necessary. Also, understanding the physico-chemical properties of feed stock and establishing its relevance with gasification performance parameters like carbon conversion, gas yield and heat value, etc. is necessary.

CSIR-CIMFR has developed FBG facility for high ash coals with feed rate 20 kg/h in 2009. Using this facility, gasification performance of high ash coals (up to 49%) from different coal fields of India and different biomass feeds in the form of blends with coal have been studied successfully. Now, CSIR-CIMFR has initiated up scaling of the FBG facility to 1.5 TPD Oxy-blown PFBG having 10 kg/cm^2 pressure. Details of various FBG systems in India are shown below:

Table 1: Various FBG systems in India:

Pilot / Demo Scale Gasification Facilities in India					
Sl. No.	**Organization**	**Facility**	**Specifications**	**Operational study**	**Present status**
1	CSIR-CIMFR	Bubbling Fluidized bed gasifier(target Multiple applications)	100 mm ID Capacity: 0.5 TPD Air blown Oxy blown PFBG ID 200mm	Up to 3 bar pressure 10 bar 1.5TPD	In operation Installed in 2009 Tested 4 high ash (27-49%) coals, coal-biomass (4 Nos.) blends successfully. Established smooth feeding, ash withdrawal and fluidization without operational problems Being setup
2	BHEL	Fluidized Bed Gasifier- Trichy (*Target- IGCC*) Plant at Corp R&D	*refractory lined with 3 stage cyclone* Capacity: 168 TPD Air blown Air blown	Designed for 10 bar, operated 8 bar Results available 1.2ata approx. 12tpd plant	Trichy Plant needs major revamping to make it operational. Under operating condition. Additionally Oxy blown gasification study planned at Corp R&D test facility. Planned to be completed in another 2-3 months.
3	EIL	Fluidized Bed Gasifier (*Target- CTL*)	200 mm ID (*refractory lined with 2 stage cyclone) and gas cleaning system and ground flare system Capacity: 3.6 TPD* O2 & Steam blown	Designed for 30 bar Runs carried out with air blown upto 6 bar (coal with ash ~ 42%)	Being modified to remove operational bottlenecks
4	Thermax	Circulating Fluidized Bed Gasifier Bubbling Fluidized Bed Gasification Facility.	1 MW capacity 200 KW capacity	Fast fluidization Operated in air blown mode. Operated for 2000 hrs	To be integrated with Methanol facility. Under working condition.

4. Experimental Setup

Co-gasification experiments were performed using the fluidized bed gasifier (FBG) pilot plant (shown in **Fig. 1**), located at the *Central Institute of Mining and Fuel Research* (CSIR-CIMFR), Dhanbad, India. This plant, with a capacity to operate 10-20 kg fuel/h, consists of following systems: (i) fuel feeding system, (ii) gasifying agent (air and steam) feeding system, (iii) fluidized bed gasifier, (iv) cyclone separator, and (v) product gas cooling and cleaning system.

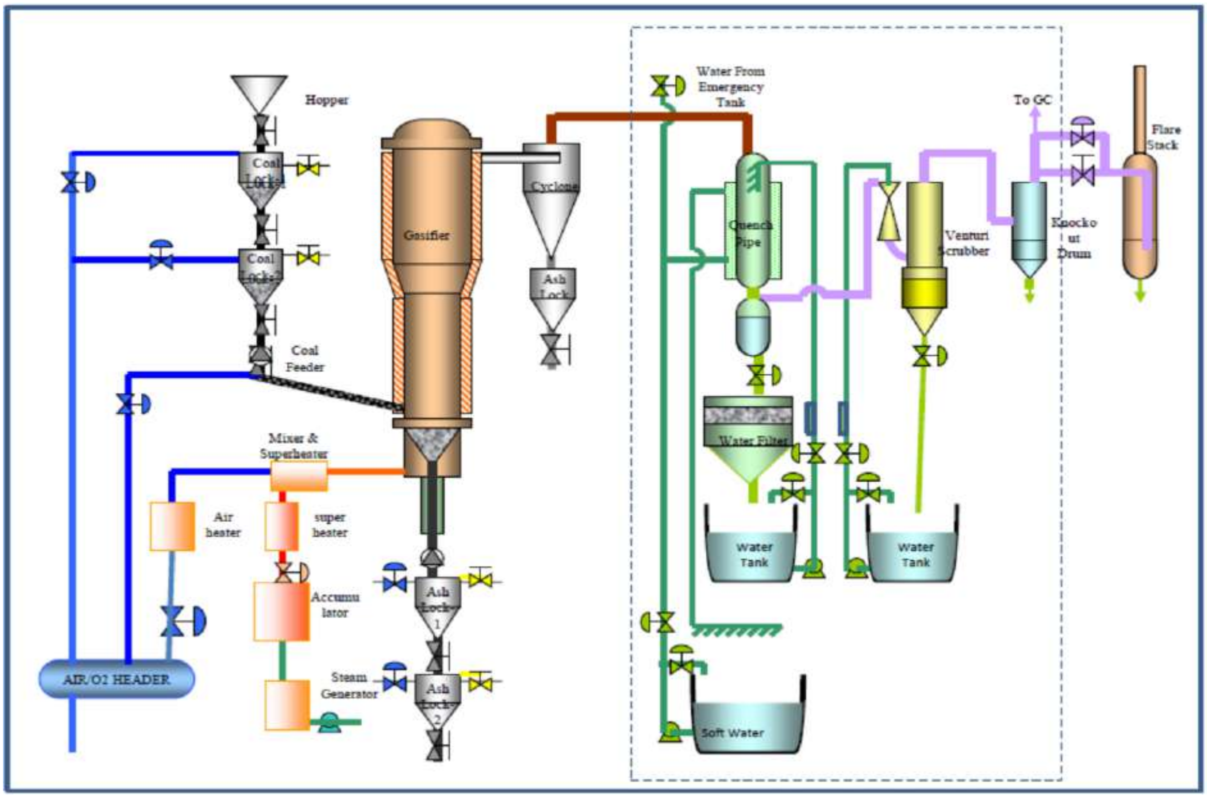


Figure 1: Schematic of Fluidized Bed Gasifier

High ash (40.8%) coal of Talcher coalfield situated in Angul district, Odisha, India and three different biomasses, namely, rice husk, sawdust and pressmud, were used as a feedstock in individual co-gasification experiments. The feed materials were individually crushed and sieved to obtain a particle size of ~1mm for coal, sawdust and pressmud, and ~3mm for the rice husk. Co-gasification experiments were conducted for different coal-biomass feeds by varying the blending ratio of coal-biomass in various proportions of biomass weight percentages (10, 20 and 35 (rice husk) and/or 40 (sawdust and pressmud) %). Proximate analysis, ultimate analysis and heat values of the feed materials are depicted in Table 2.

Table 2: Proximate & Ultimate Analyses and Heat values of coal and different biomass samples

Sample	Proximate Analysis				Ultimate Analysis					Higher Heating Value (Kcal/Kg)
	Fixed Carbon (%)	Volatile Matter (%)	Ash (%)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)	
Coal	27.8	26.7	40.8	4.7	39.43	3.54	10.25	0.78	0.5	3700
Rice Husk	11.8	63	15	10.2	37.54	4.65	34.8	0.29	0.02	3480
Press-mud	9.5	61.7	18.5	10.3	33.73	3.92	41.49	2.36	0.01	4051
Saw dust	12.8	72.7	3.6	10.9	41.9	5.24	38.21	0.08	0.07	4000

4.1 Experimental Procedure

Initially, a bed material (coal ash) of size ~2mm was fed into the reactor with a specific feed rate for building the bed inside the reactor using air as a fluidizing agent. The reactor temperature was raised by an external electric heating system (Patil-Shinde et al., 2014). Once the required temperature of ≈500°C was reached, the gasifying agents i.e. superheated steam (200-250°C) and preheated fluidization air (200-250°C), were charged into the gasifier column. The bottom ash was cooled to ≈40°C and discharged at a specific withdrawal rate in the ash bin. After reaching the desired gasifier temperature, the stream of blended feed was fed into the gasifier. Depending upon the reaction conditions and feed materials, the co-gasification process reached a steady state in time duration ranging between 15 and 30 minutes. For determining the product gas composition, gas samples were collected periodically in the stabilised gasification temperature range of 850-1014°C; the said stabilization was attained by fine tuning the fuel and air feed rates. The hot raw fuel gas containing entrained particulates and other contaminants was passed through a series of cleaning systems: (a) cyclone separator, (b) quench column and (c) venturi-scrubber. The purified gas samples collected in the glass pipettes was analysed using an offline gas chromatograph (GC) and the rest of the clean gas was flared from the flare stack (Patil-Shinde et al., 2014). The volume % of the different components of the product gas determined by the GC analysis is CO % (10.96-15.76); H_2 % (2.14-17.84); CO_2 % (8.01-14.74); CH_4 % (1-2.04); and N_2 % (54.71-72). Due care was taken in the air-blown FBG facility for maintaining an appropriate mass flow rate for ensuring a uniform temperature in the gasifier.

Based on the above-stated experimental and operating procedures, a total of 56 experiments were conducted by (i) varying the co-gasification operating parameters, namely, fuel feed rate and gasification temperature, (ii) variation in the biomass types, namely, rice husk, pressmud and sawdust, (iii) variation in the weight percentages of coal-biomass blends, that is coal 90% and biomass 10%, coal 80% and biomass 20%, coal 60% and biomass 40%, etc. The magnitudes of the operating parameters of the fluidized bed gasifier are listed in **Table 3**.

Table 3: Operating parameters of the fluidized bed gasifier

Operating Parameters	Variation Range
Fuel Feed rate	5.7-9.6 kg/h
Bottom Ash Discharge rate	2.8-4.6 kg/h
Gasifier Temperature	850-1014°C
Air feed rate	200±20 LPM
Steam feed rate	2.5±0.2 kg/h

5. Results and Discussion

Co-gasification adds flexibility to the energy systems by enabling the use of high-ash coal, solid biomass, and industrial/municipal/agricultural waste for several applications like power generation, transportation fuels and chemical production (Fermoso et al., 2010). This technique acts as an important "green" medium for the production of energy by co-employing the conventional and non-conventional fuels. It not only alleviates air pollution and release of volatile organic compounds but also diminishes soil and water pollutants that are emitted due to chemical constituents of coal (Emami-Taba et al., 2013). Co-gasification is a complex nonlinear process that is influenced by various factors, namely, the physical and chemical properties of feedstock, gasifier operating conditions (fuel feed rate (kg/h) and gasifier temperature (°C)) and gasifying medium (steam feed rate (kg/h) and air feed rate (kg/h)). Its performance is commonly assessed in terms of (i) *total gas yield* (TGY) (kg/kg fuel) (Chavan et al., 2012; Patil-Shinde et al., 2014), (ii) *carbon conversion efficiency* (CCE) (%), (iii) *heating value of product gas* (HV) (MJ/Nm^3), and (iv) *cold gas efficiency* (CGE) (%) (Higman and Van Der Burgt, 2008; Watanabe and Otaka, 2006). The theoretical expressions of the four performance variables, namely, TGY, CCE, HV and CGE are given below:

$$TGY\left(\frac{kg}{kg\ fuel}\right)=\frac{Total\ Product\ gas\ out\ through\ gasifier\ (kg/h)}{Fuel\ Feed\ rate\ (kg/h)} \tag{2}$$

$$CCE(\%)=\left(1-\left(\frac{Carbon\ in\ Bottom\ Ash+Carbon\ in\ Cyclone\ ash}{Carbon\ in\ Fuel\ Feed\ Material}\right)\right)\times 100 \tag{3}$$

$$HV\left(\frac{MJ}{Nm^3}\right)=\sum_{v=1}^{3}\frac{Product\ gas_v\%\times Calorific\ value\ of\ gas_v}{100} \tag{4}$$

where, 1 denotes for H_2, 2 for CO and 3 for CH_4.

$$CGE(\%)=\left(\frac{Total\ gas\ produced\left(\frac{Nm^3}{kg\ of\ feed}\right)\times Calorific\ Value\ of\ Product\ gas\left(\frac{Kcal}{Nm^3}\right)}{Calorific\ Value\ of\ Feed\left(Kcal/kg\ of\ feed\right)}\right)\times 100 \tag{5}$$

The main objectives of this study therefore are assessing the performance of a fluidized bed gasifier (FBG) pilot plant based gasification process using blends of high ash Indian coal and various biomasses as fuels.

To examine the performance of gasification in FBG, cross-plots were generated (see **Fig. 1**) using the experimental dataset. In the cross-plots, each of the four performance variables, namely *TGY*, *CCE*, *HV* and *CGE* are plotted vis-à-vis four important process operating parameters, namely, temperature (°C), air/fuel ratio (kg/kg fuel), steam/fuel ratio (kg/kg fuel) and fuel feed rate (kg/h). Following observations can be made from the cross plots of **Fig. 1**.

- Panels (*b*), and (*c*) indicates that TGY is approximately linearly related to air/fuel ratio, steam/fuel ratio. There also exists a significant scatter in the TGY versus temperature (panel *a*) as also fuel feed rate (panel *d*) plot indicating nonlinear relations between them.
- Panels (*e*) to (*p*) show highly scattered points indicating more or less nonlinear relationships between the operating parameters, namely, temperature, air/fuel ratio, steam fuel ratio and fuel feed rate and the three performance variables, CCE, HV and CGE.

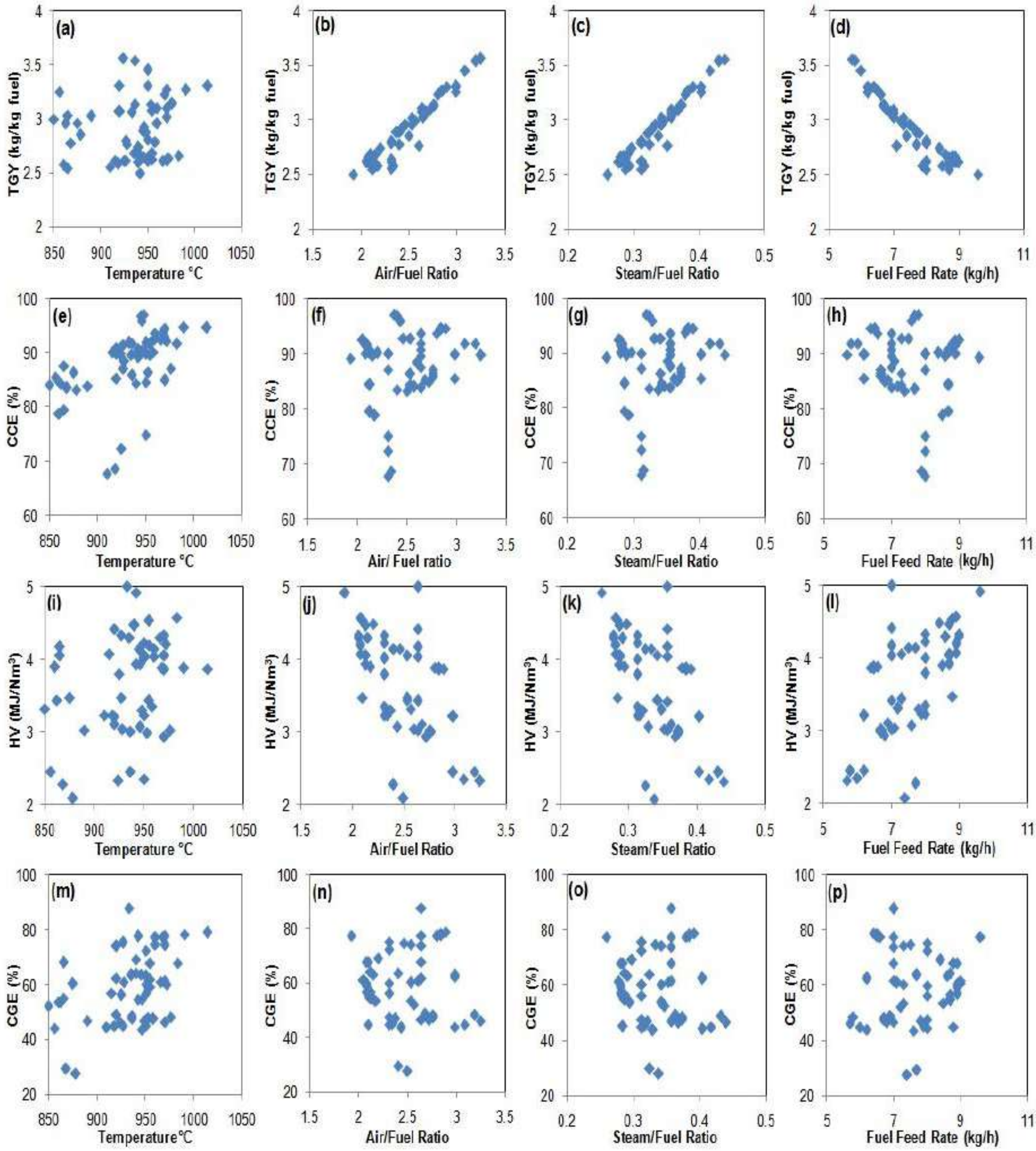


Figure 1: Cross plots of performance variables (TGY, CCE, HV and CGE) versus co-gasification process operating parameters (temperature, air/fuel ratio, steam/fuel ratio and fuel feed rate).

5.1. Effect of Biomass Content on Co-gasification Process

Andre et al. (2005) and Seo et al. (2010) have reported an increase in the total gas yield (TGY) with increasing biomass contents for fluidized bed systems. This could be due to the low ash, high carbonaceous mass and high hydrocarbons present in the biomass, or the synergistic effect between biomass and coal owing to which transfer of H radicals from biomass to coal causes more decomposition of coal. A similar trend was observed in the present study when the proportion of biomasses, namely, rice husk, pressmud and sawdust in the blended fuel was varied. As shown in **Fig. 2** (*a*), TGY increases with increasing content of rice husk, pressmud and sawdust in the binary blended fuel.

Demirbas (2004) reported that higher percentage of biomass in the binary blends of coal and biomass enhances the reactivity based on the fact that biomass feedstocks have a higher reactivity than the coal. The comparable trend was depicted in our study, shown in **Fig. 2** (*b*), where carbon conversion efficiency (CCE) increases with the increase of biomass content in the binary blends of coal and-rice husk, -pressmud and -sawdust, respectively. Also, as discussed above the synergistic effect between biomass and coal facilitates increase in the carbon conversion.

It has been observed that (see **Fig. 2** (*c*)) that heating value (HV) of product gas decreases with an increase in the biomass content of the individual coal blends with rice husk, pressmud and sawdust. This is primarily due to the decline in the generation of CO, H_2, and CH_4 in the product gas (Alzate et al., 2009). This decline can occur due to the limitation on the magnitude of the volumetric flow rate of the feedstock in the fluidized bed gasifier which correspondingly also leads to a decrease in the mass flow rate of the feedstock as biomass content in the binary feedstock increases.

For blends of rice husk and sawdust with coal, cold gas efficiency (CGE) increases with increasing content of the biomass (see **Fig. 2** (*d*)), while it decreases with increasing proportion of the pressmud blend (**Fig. 2** (*d*)). The CGE increase witnessed for rice husk and sawdust is likely due to the increase in the carbon conversion efficiency and total gas yield for their respective blends with coal. Possible reasons for the decrease in CGE, however, for coal-pressmud are: (i) pressmud has high oxygen content, and low carbon and hydrogen contents, (ii) the amount of air and steam supplied per kg of fuel was on the higher side for maintaining proper fluidization inside the reactor for high pressmud percentage blends; this resulted in generation of oxygen based non-fuel components in syngas (lean heating value syngas generation) thus leading to a decrease in CGE.

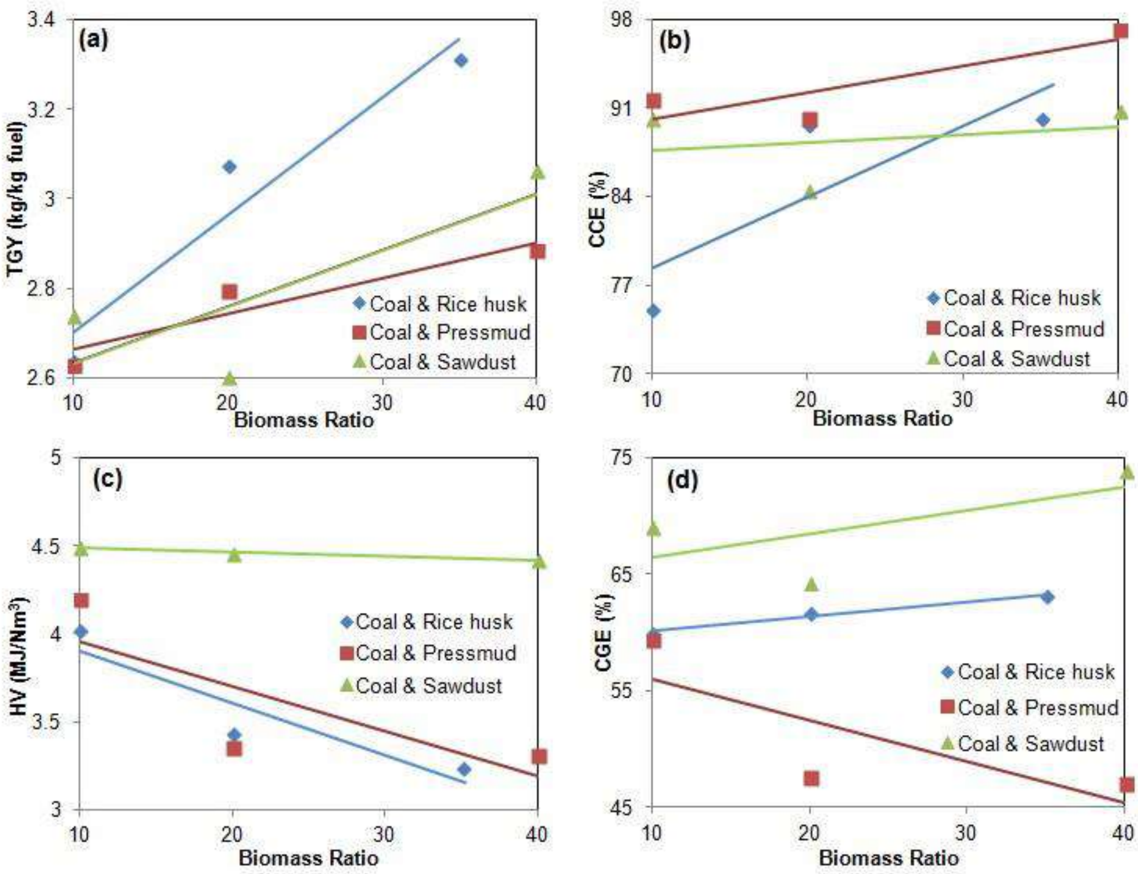


Figure 2: Effect of Biomass Content on the Co-gasification process

6. Conclusions

Among all the available gasifiers, FBG is most suitable to handle high ash Indian coals due to several inherent advantages. But presently FBG Technology is under developing stage. In India, numbers of stake holders are involved in the development of fluidized bed gasifier. However, some gaps need to be addressed for its commercial exploitation like, development of proper feeding and ash withdrawal systems for handling wide variety of feed stock, establishing proper hydrodynamics in side gasifier bed to minimize operational issues like agglomeration and clinker formation as well as to enhance the gasification performance. Further, establishing the suitable operational philosophy for gasification of different feed stock and their blends in FBG is necessary. Also, understanding the physico-chemical properties of feed stock and establishing its relevance with gasification performance parameters like carbon conversion, gas yield and heat value, etc. is necessary. In this direction, CSIR-CIMFR has developed FBG facility for high ash coals with feed rate 20 kg/h.

During experimentation in FBG, it was observed that high ash Indian coals can be successfully gasified without any operational problems like agglomeration and clinker formation with proper synchronization of different operating parameters. Further, it is also observed that blending of small quantity of biomass with coal improves its overall performance parameters. Considering the importance of co-gasification, three types of biomass such as rice husk, sawdust and press mud were taken with one high ash Indian coal in different proportions. It was observed that TGY as well as CCE increase with increase in biomass proportion in feed. On the contrary, heating value (HV) of product gas decreases with an increase in the biomass content of the individual coal blends with rice husk, pressmud and sawdust. Further, it was observed that for the blends of rice husk and sawdust with coal, cold gas efficiency (CGE) increases with increasing content of the biomass, while it decreases with increasing proportion of the pressmud blend.

Acknowledgement

The authors are thankful to Director, CSIR-Central Institute of Mining and Fuel Research for giving permission to present the paper in the International R&D Conclave on Emerging Opportunities & Challenges of R&D in Indian power.

References

Aigner, I., Pfeifer, C., Hofbauer, H., 2011. Co-gasification of coal and wood in a dual fluidized bed gasifier, Fuel. 90, 2404-2412. Doi: 10.1016/j.fuel.2011.03.024.

Alzate, C.A., Chejne, F., Valdes, C.F., Berrio, A., De La Cruz, J., Londono, C.A., 2009. Co-gasification of pelletized wood residues, Fuel. 88, 437-445. Doi: 10.1016/j.fuel.2008.10.017.

Andre, R.N., Pinto, F., Franco, C., Dias, M., Gulyurtlu, I., Matos, M.A.A., Cabrita, I., 2005. Fluidized bed co-gasification of coal and olive oil in industry wastes. Fuel. 84, 1635-1644. Doi: 10.1016/j.fuel.2005.02.018.

Aranda, G., Grootjes, A.J., van der Meijden, C.M., van der Drift, A., Gupta, D.F., Sonde, R.R., Poojari, S., Mitra, C.B., 2016. Conversion of high-ash coal under steam and CO_2 gasification conditions. Fuel Processing Technology. 141, 16-30.

Aznar, M.P., Caballero, M.A., Sancho, J.A., Frances, E., 2006. Plastic waste elimination by co-gasification with coal and biomass in fluidized bed with air in pilot plant. Fuel Process. Technol. 87, 409–420. Doi:10.1016/j.fuproc.2005.09.006.

Basu, P., 2006. Combustion and Gasification in Fluidized Beds, CRC Taylor and Francis Group. Doi: 0.1201/9781420005158.

Chavan, P.D., Sharma, T., Mall, B.K., Rajurkar, B.D., Tambe, S.S., Sharma, B.K., Kulkarni, B.D., 2012. Development of data-driven models for fluidized bed coal gasification process, Fuel. 93, 44–51. Doi:10.1016/j.fuel.2011.11.039.

De Jong, W., Andries, J., Hein, K.R.G., 1999. Coal/biomass co-gasification in a pressurized fluidized bed reactor. Renew. Energ. 16, 1110-1113. Doi: 10/1016/S0960-1481(98)00432-7.

Demirbas, A., 2004. Combustion characteristics of different biomass fuels, Prog. Energy Combust. Sci. 30, 219-230. Doi: 10.1016/j.pecs.2003.10.004.

Emami-Taba, L., Irfan, M.F., Wan Daud, W.M.A., Chakrabarti, M.H., 2013. Fuel blending effects on the co-gasification of coal and biomass - A review, Biomass Bioenergy. 57, 249–263. Doi:10.1016/j.biombioe.2013.02.043.

Engelbrecht, A. S., North, B. C., Oboirien, B. O., Everson, R. C., & Neomagus, H. W. P. J. 2011. Fluidised bed gasification of high-ash South African coals: An experimental and modelling study.

Fermoso, J., Arias, B., Plaza, M.G., Pevida, C., Ruberia, F., Pis, J.J., Garcia-Pena, F., Casero, P., 2009. High-pressure co-gasification of coal with biomass and petroleum coke. Fuel Process. Technol. 90, 926-932. Doi: 10.1016/j.fuproc.2009.02.006.

Fermoso, J., Arias, B., Gil, M.V., Plaza, M.G., Pevida, C., Pis, J.J., Rubiera, F., 2010. Co-gasification of different rank coals with biomass and petroleum coke in a high-pressure

reactor for H_2-rich gas protection, Bioresour. Technol. 101, 3230-3235. Doi: 10.1016/j.biortech.2009.12.035.
Higman, C., Van Der Burgt, M., 2008. Gasification, 2nd ed., Gulf Professional Publishing, Elsevier.
Li, K., Zhang, R., Bi, J., 2010. Experimental study on syngas production by co-gasification of coal and biomass in a fluidized bed, Int. J. Hydrogen Energy. 38, 2722–2726. Doi:10.1016/j.ijhydene.2009.04.046.
Mastellone, M.L., Zaccariello, L., Arena, U., 2010. Co-gasification of coal, plastic waste and wood in a bubbling fluidized bed reactor, Fuel. 89, 2991–3000. Doi:10.1016/j.fuel.2010.05.019.
McLendon, T.R., Lui, A.P., Pineault, R.L., Beer, S.K., Richardson, S.W., 2004. High-pressure co-gasification of coal and biomass in a fluidized bed. *Biomass Bioenergy*. 26, 377–388. Doi:10.1016/j.biombioe.2003.08.003.
Pan, Y.G., Velo, E., Roca, X., Manya, J.J., Puigjaner, L., 2000. Fluidized-bed co-gasification of residual biomass/poor coal blends for fuel gas production. Fuel. 79, 1317-1326. Doi: 10.1016/S0016-2361(99)00258-6.
Patil-Shinde, V., Kulkarni, T., Kulkarni, R., Chavan, P.D., Sharma, T., Sharma, B.K., Tambe, S.S., Kulkarni, B.D., 2014. Artificial Intelligence-based Modelling of High Ash Coal Gasification in a Pilot Plant Scale Fluidized Bed Gasifier, Ind. Eng. Chem. Res. 53, 18678–18689. Doi:10.1021/ie500593j.
Pinto, F., Franco, C., André, R.N., Tavares, C., Dias, M., Gulyurtlu, I., Cabrita, I., 2003. Effect of experimental conditions on co-gasification of coal, biomass and plastics wastes with air/steam mixtures in a fluidized bed system. Fuel. 82, 1967–1976. Doi:10.1016/S0016-2361(03)00160-1.
Pinto, Filomena; Andre, Rui Neto; Gulyurtlu, I. Innovation on Bimass Wastes Utilization Through Gasification and Co-Gasification. Stage of Deployment and Needs for Further R&D. In: Biomass Gasification: Chemistry, Processes and Applications. Nova Science Publishers, Inc., 2009
Saha, S., Sahu, G., Chavan, P.D., Datta, S. Gasification reactivity of high ash Indian coals in varying concentrations of CO_2. Int. J. Oil, Gas and Coal Technology. Article in Press.
Seo, M.Y., Goo, J.H., Kim, S.D., Lee, S.H., Choi, Y.C., 2010. Gasification characteristics of coal/biomass blend in a dual circulating fluidized bed reactor. Energ. Fuel. 24, 3108-3118. Doi: 10.1021/ef100204s.

Sjostrom, K., Chen, G., Yu, Q., Brage, C., Rosen, C., 1999. Promoted reactivity of char in co-gasification of biomass and coal: synergies in the thermochemical process. Fuel. 78, 1189-1194. Doi: 10.1016/S0016-2361(99)00032-0.

Stevens, C., 2011. Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power, Edited by Robert C Brown, John Wiley & Sons, Ltd, United Kingdom.

Velez, J.F., Chejne, F., Valdes, C.F., Emery, E.J., Londono, C.A., 2009. Co-gasification of Colombian coal and biomass in fluidized bed: An experimental study. Fuel. 88, 424–430. Doi:10.1016/j.fuel.2008.10.018.

Watanabe, H.,Otaka, M., 2006. Numerical Simulation of coal gasification in entrained flow coal gasifier. Fuel. 85, 1935-1943.

CV of Head Resaercher

Dr. Prakash D. Chavan

chavanpd@gmail.com

Dr. Prakash D Chavan is a Principal Scientist at Gasification and Liquefaction Research Group in CSIR-Central Institute of Mining & Fuel Research, Dhanbad, India. He has experience of more than 12 years in the area of coal, biomass and co-gasification of coal and biomass, development of fluidized bed gasifier & coal to liquid direct and indirect route. He has research interest in clean coal energy, coal and biomass gasification, liquefaction. He has several publications in various reputed national and international journals.

DESIGN & OPERATIONAL CHALLENGES IN FLEXIBILIZATION OF THERMAL POWER PLANTS

Authors: N Gopalakrishnan Unni and CP Tiwari; CTDS, Tata Power

Contact Details: gopalakrishnan.unni@tatapower.com - 9250008875

chandra.tiwari@tatapower.com - 9312072156

Table of contents

1.0 INTRODUCTION

For accommodating higher amounts of Non Dispatchable Renewable Energy (specially wind and solar) on the electric grid, Operators of Fossil Fuel Fired Plant needs to ramp down and ramp up or stop and start plants more frequently (a practice called cycling) for maintaining grid frequency.

Generally, Grid operators typically cycle power plants to accommodate fluctuations in electricity demand and / or abrupt outages at Fossil Fuel Fired Power Plants.

Variability and uncertainty of renewable generation will impact grid operation. Wind plant energy output tends to be higher during winter/spring seasons and during night hours, which is contrary to system peak load period. PV Solar produces energy during day time however output tends to decline in the late afternoon and morning hours when peak load will occur. For Concentrated Solar with thermal storage, maximum generation will be during the long summer days and the storage capability extends the energy output throughout the late afternoon and early evening hours when peak occurs. Impact of these known factors can be estimated with reasonable accuracy. However, uncertainty due to imperfect forecast of renewable resources may lead to greater impact on grid operation and will necessitate flexibilization of Thermal Power Plants.

This paper focuses on Design & Operational Challenges in flexibilization of Thermal Power Plants due to increased penetration of renewable energy.

2.0 OVERVIEW OF INDIAN POWER SECTOR

Renewable generation from wind and solar has increased substantially during past few years and forms a significant proportion of the total generation in the grid. This renewable generation is concentrated in a few states, to the extent that it cannot be called marginal generation and serious thought needs to be given to balance the variability of such generation and its impact on conventional power plants.

As per data from Ministry of Power, Government of India, total installed renewable capacity was 60,158 MW out of total installed capacity of 3,31,118 MW as on 30.10.2017. Generation from renewable sources in September 2017 was 7,516 BU out of total generation of 1,05,588 BU. By 2022, India is targeting for the installation of 175 GW renewable capacity and renewable energy share is expected to be 30% by 2022.

As can be seen, major capacity addition is planned in renewable segment which is non-dispatchable in nature, this will lead to flexibilization of thermal power plants.

3.0 VARIABILITY IN RENEWABLE GENERATION

Generation from Renewable Energy Sources depends on nature, i.e. wind velocity and sunshine. The variability of renewable power can be addressed through improved forecasting techniques, which are still evolving.

The peak wind generation occurs at different time as compared to the peak requirement of the States. Solar generation depends on solar irradiation and varies from morning till evening. Solar PV and CSP generation without storage is highest during noon time. Solar generation is affected due to appearance of cloud.

As mentioned above, renewable solar and wind generations are non-dispatchable in nature, varies on daily and hourly basis and cannot be predicted accurately.

India has a federal setup in respect of electricity wherein each state is responsible for maintaining its load-generation balance and complying with grid code (IEGC). As Renewable Energy Generation in India is concentrated in five states i.e. Gujarat, Rajasthan, Tamilnadu, Karnataka and Maharashtra, increased penetration & variability in Renewable Energy Generation will pose serious operational stresses on conventional power plants in these states. With present installed capacity of solar and wind, these renewable energy rich states need to follow different strategy for balancing and managing the variability like reduction of load of thermal units, balancing by hydro units or by use of pumped storage system.

In the larger interest of country and for reducing carbon foot print, it is suggested that wind and solar energy shall be given priority in generation scheduling and dispatch and balancing of renewable generation shall be at National level for reducing the operational stresses on conventional plants in renewable energy rich states. Further due to variability in Renewable Generation and consequently cycling of conventional units, cost of generation from conventional power plant will increase. Regulator should compensate the conventional generators for partial operation and start / stop cost so that it can perform balancing function without incurring financial losses.

4.0 FLEXIBILISATION OF THERMAL POWER PLANTS

Renewable energy injection from wind and solar affect the variability in residual electricity demand (total demand minus renewable generation) to be covered by conventional electricity generating system. To meet the variable residual demand, conventional thermal power plant is required to cycle, meaning that they have to change their output by ramping or switching on / off.

Most existing plants were designed for base load service, moderate load following and occasional on-off cycling. With the increased penetration of non-dispatchable renewable energy in the grid, these plants need to be cycled more frequently and over a wider range, causing accelerated fatigue loading and wear / tear to critical components.

With increased renewable penetration, unit load will increase or decrease, or unit may be required to shut down. Cycling & Flexibilization of large sized conventional power units may lead to the following issues:

- Damages to/ reduced life of equipment
- Decreased thermal efficiency at low loads.
- Increased fuel cost due to more frequent start-ups.
- Difficulties in maintaining water and steam chemistry.
- Impact on Environmental control equipment.
- Increased risk of human error in plant operation.

5.0 DESIGN CHALLANGES

In India, coal / lignite based conventional power plants are generally designed for the following start / stops and ramp-up rates in their life of 25 years:

- Hot Start (after 8 hrs of unit shutdown) : 4000
- Warm Start (After 36 hrs of unit shutdown) : 1000
- Cold Start (After 72 hrs of unit shutdown) : 400
- Step Load Change: +/- 10% per minute
- Ramp-up rate: +/- 3% per minutes (30% to 50% load)
- Ramp-up rate: +/- 5% per minutes (50% to 100% load)

Following are major design considerations which decide the life of power plant & its components:

- Parts and Components which are operating below creep range: Various code & standards specifies criteria for design and deciding the allowable stress values. Factor of safety considered in various codes & standards varies.
- Parts & Components which are operating in creep range: Various Codes and Standards specify design criteria and allowable stress values. Factor of safety considered in various codes & standards varies. Since the allowable stress for temperature above creep range is time dependent, this needs to be suitably considered in design of components. Generally, plant components are designed for creep life of 1,00,000 hrs. Many coal based plants in the world, designed for 1,00,000 hrs creep life are in operation beyond thirty (30) years. This was possible through well managed RLA studies and maintenance / repair / replacement activities apart from conservative design parameters and margins in the design codes.
- Certain components which are not operating at elevated temperature; wear and tear may be governing criteria like air and flue gas ducting, parts of Coal handling plant, ash handling plant and mill reject system. Design criteria for these components needs to be suitably modified for longer design life.
- Corrosion issue for components and parts which are operating in corrosive atmosphere is being usually taken care either by suitable material selection or painting / protective coating / lining etc. If we ensure proper material selection, select right painting / protective coating / lining, do in-service inspection, design life of these components can be suitably extended.

Design codes and standards presently being used for design of thermal power plant components specially components operating above creep temperatures does not considers combined creep fatigue effect. However, for flexibilization of thermal power plants, components operating in creep range shall be analysed for combined creep fatigue analysis as design code assumes that effect of fatigue were contained within the conservatism of the design stresses. These assumptions and considerations may be adequate for base load designed plants. Since ASME Section-VIII, Division 2 and other ASME sections used for design of Boiler and other power plant components does not include fatigue data at elevated temperatures applicable for supercritical units, we may have to use ASME Section-III, Sub Section NH (Nuclear Plant Design Code) for creep fatigue analysis.

6.0 OPERATIONAL CHALLANGES

6.1 Equipment & Component Failures

Failures in coal plant equipment caused by frequent cycling are not isolated events but often occur at unexpected times throughout the plant. Many of the failure modes and locations are not unexpected, but others may be surprising even to an experienced plant operator. Prevention of these failures or managing failure rates is key to success. Following systems and components within a typical coal-fired plant designed for base load operation are affected by cycling and load-following service:

6.1.1 Steam Turbine Generators

The life of a steam turbine is directly related to thermal transients experienced over time. In fact, the typical steam turbine startup ramp rate is well-defined by the manufacturer, as there are limits to the heating rates of the parts. Steam turbines require slow temperature changes to manage the thermal stress in their heavy metal components. Major failures are observed in:

- Castings such as turbine valves and casings.
- Rotor bore cracking is also observed in some cases.

As a preventive measure, an electric heated turbine blanket system may be beneficial during hot restarts to reduce thermal stress and distortion, ensuring a quicker start.

6.1.2 Boiler

- Superheater and Reheater tubes overheating and damage results from inadequate steam flow during start-up/ low load operation.
- Economizer tube failures are usually caused by thermal transients of the inlet header and tubing with relatively cold water, often during startup.
- Fire side corrosion may also occur in areas of the economizer where cold water reduces the metal temperature below the acid dew point of the flue gas during low-load operation.
- Poor boiler water chemistry during start-up is also a contributing cause for tube failures.

6.1.3 Fuel System

- Coal Pulverizers are prone to fireside explosions & require careful fuel purging and the addition of an inert gas blanket (inerting) when they are cycled off-line.
- Also, Pulverizers are prone to much increased mechanical wear when they are cycled or operated at the low end of their design minimum flow rates.

6.1.4 Air and Gas Systems

- FD, ID and PA fans on coal-fired units are equipped with HT Motors. Frequent starting and stopping of the fans motors will increase failure rates, inspection intervals, and maintenance.

  In some cases, fans need to be retrofitted with new drive systems for soft or low-stress starting and efficiency improvement.
- Additionally, air heaters are subject to wet gas corrosion, plugging, and damage caused by operating below the wet gas dew point during low-load operations.

6.1.5 Water Systems

- Makeup water consumption greatly increases for a cycling unit because of the large amounts of water used during startup.
- Feedwater heaters are subject to cool down and rapid heating during a hot or warm startup cycle, and this often leads to early tube failures.
- Boiler feed pumps are normally designed for full-load operation and experience accelerated wear when operated at low loads.
- Also, boiler feed pumps may be required to stop and start several times for one startup cycle, thus causing many frequent transients.

6.1.6 Environmental Control Equipment

Operation of large coal fired plants at low load can force the unit with SCR system to operate with lower flue gas temperature. Low temperatures create operational problems for SCR because of the formation of

Ammonium Bisulphate a sticky liquid that can fill catalyst pores, thus diminishing catalyst surface area and reducing reactivity.

6.2 Plant Efficiency

Flexibilization, cycling and part load operation of units will lead to loss in plant efficiency because at part load, heat rate and auxiliary power consumption will increase.

The major impact areas are listed below:

- Lower PLF due to ducking of load curve
- High ramping up/ down requirement
- Two shifting and cycling of plants
- Increased forced outage and O&M cost
- Equipment's life time reduction
- Poor heat rate and high Aux. Power
- Preservation costs and idle manpower cost
- Increased start-up cost
- More Carbon emissions per unit
- Increased cost of energy

6.3 Strategies to meet Cyclic Operation Challenge

6.3.1 Operation Philosophy Changes

- Review of Operation strategies to meet the demands of cyclic operation
- Prudent load distribution among units with the help of software for optimising heat rate & APC.
- Stopping of HT equipment when less loaded considering the impact on reliability. Additional provision of auto start.
- Sliding pressure operation
- VFD for main cycle and Aux. equipment
- Stringent water chemistry control
- Additional sensors/ probes for close process monitoring
- Control loop tuning for low load operation

6.3.2 Maintenance Strategy changes

- Identification of component reserves to be able to use higher stresses for a flexible operation
- Review of Maintenance scheduling: Delink from periodic maintenance and link with running hours, number of start/ stops
- Condition-based maintenance strategy involving modern condition monitoring systems to ensure a safe/ reliable operation at minimal maint. costs
- Maintenance based on opportunity
- Preparedness for maintenance in short notice
- Review periodicity of Residual Life Assessment

7.0 DAMAGE MECHANISMS

Various damage mechanisms are responsible for damage of components due to cyclic operation. The severity of the impact of these mechanisms can be mitigated to a certain extent through improved plant operation and process controls, but it is impossible to eliminate the reduction in major component life caused by cycling operation. Examples of these damage mechanisms are as mentioned below:

7.1 Thermal Fatigue

For metals that operate at temperature above their creep damage points, fatigue life deteriorates with creep damage. The components that have incurred a high degree of creep damage will have fewer fatigue cycle than a new one. Thermal Fatigue can produce cracking in thick-walled components, especially castings such as turbine valves and casings. Also affected components are boiler Superheater and Reheater headers, where ligament cracking is commonly seen between tube stubs.

7.2 Thermal Expansion

Several systems in a coal plant consist of components that undergo high thermal growth relative to surrounding components. The most important example of this phenomenon is the large movement of boiler parts relative to the boiler support structure. These parts include water wall sections, gas ductwork, and the ties used to support superheat and reheat tubing. These support ties are designed to accommodate growth but are subject to accelerated life consumption if the frequency of thermal cycling increases.

7.3 Corrosion-Related Issues

Cycling operation that challenges the ability of a plant to maintain water chemistry, can lead to increased corrosion and accelerated component failure. Increased levels of dissolved oxygen in condensate can be the result of condenser air in leakage, aggravated by more-frequent shutdowns. Other factors affecting chemistry include the increased need for make-up water and the interruption in operation of condensate polishers and Deaerators. Corrosion and fatigue can combine to accelerate damage to boiler tubing.

7.3 Fireside Corrosion

Cycling and relatively quick ramp rates will have a negative impact on both fireside corrosion and circumferential cracking.

7.4 Rotor Bore Cracking

When subjected to transients in the temperature of the admitted steam, the high-pressure and intermediate-pressure steam turbine rotors can suffer thermo-mechanical stress excursions, resulting in low-cycle fatigue damage. This damage can result either from introducing hot steam to a relatively cold rotor exterior, or the opposite. In both scenarios, the problem arises on the massive rotor forging due to the large time required for the metal temperature difference between the rotor exterior surface and the inner (bore) region to equilibrate.

8.0 COST OF CYCLING

EPRI has developed statistically based methodology for estimating the cycling cost. A regression model has been developed to predict the impact of cycling on operation and maintenance cost of steam based power plant mainly using coal as fuel. EPRI collected data from contributing utilities and public data bases and compiled into an analysis data base. The model produced an analysis tool to help utility users estimate the additional O&M cost associated with operating their plant in various cycling mode such as load following and on-off cycling

Total O&M cost shall be calculated by adding steam O&M cost and Electric O&M cost. EPRI has developed following equation for Steam O&M cost and Electric O&M cost:

Steam O&M1 = 0.860 x $(\text{Capacity Factor}_1/\text{Capacity Factor}_0)^{0.6119}$ $O\&M_0$ + $npmv^{0.8058}$ x (0.000268 x Δ Cold + 0.0000157 Δ Warm + 0.0000132 Δ Hot + 0.00000534 Δ n_{60} + cst)

Electric O&M1 = 0.606 x $(\text{Capacity Factor}_1/\text{Capacity Factor}_0)^{0.2306}$ $O\&M_0$ + $npmv^{0.7890}$ x (0.000104 x Δ Cold + 0.0000143 Δ Hot + 0.0000019 Δ n_{60} + 0.00107 (ramp $rate_1$/ ramp $rate_0$) + cst)

Where;

- Subscript on the variables refer to prediction year (1) and base year (0) which are consecutive years.
- Δ Cold is increased number of cold starts in year (1) with respect to year (0)
- Δ Warm is increased number of Warm starts in year (1) with respect to year (0)
- Δ Hot is increased number of Hot starts in year (1) with respect to year (0)
- Δ n_{60} is increased number of Hot starts in year (1) with respect to year (0)
- npmv is name plate rating of unit in MW.
- Ramp-up rate is in MW per hours
- Capacity factors are in %
- O&M cost in Million USD.
- cst is a constant and depends on plant design.

The effect of cycling variables depends on plant size and type of cycling. Cost increases with increase in unit size. Further cost of cold start is much higher than hot and warm start.

9.0 MITIGATING MEASURES FOR CYCLING OPERATION

New plants can be designed for cycling operation considering various aspects mentioned above. However, in India, where large thermal capacity designed for base load operation need to be operated in cycling, certain retrofit and changes in operational practices may be required to reduce the impact of cycling operation. These strategies should be generally assessed in terms of benefit-to-cost ratio when selecting action plans for specific units. Significant capital investment in improved design of boiler, turbine and control system may be required for mitigating the effect of cycling operation.

In older plants, the most cost-effective strategy from a life-cycle cost perspective may be to focus on improved operator performance and upgrade of control system. This approach may also include installation of additional process sensors (typically temperature), strategically located to guide operators during transients for minimizing temperature excursions. Increased attention to the location, operation, and capacity of drains is another cost-effective operation and maintenance strategy.

EPRI has undertaken many research efforts to better understand possible mitigation strategies. These includes:

9.1 Efficiency Improvements

One option for mitigating the effects of cycling operation is for plants to implement system modifications that recover plant efficiency lost to continuous cycling operation. However, many plants today do not have sufficient capital available to undertake major system modifications. To address this challenge, a recent EPRI study identified modification measures that have the potential to achieve the most impact for a reasonable investment. The options involve modifications to equipment and operating procedures that will be cost-effective for reducing heat rate under cycling operating conditions. Examples include sliding pressure operation, variable-speed drives for main cycle and auxiliary equipment, boiler draft control schemes, etc.

9.2 Cycle Chemistry Guidelines for Transient Operations

An area of concern for plants under cycling duty is following appropriate cycle chemistry guideline limits during plant startup, shutdown, and layup. Proper protection of the entire steam circuit (boiler, piping, feedwater, and turbine) is critical during these modes operation.

EPRI worked with the 40 members of the EPRI Cycle Chemistry Technical Advisors Group to develop cycle chemistry guidelines for all transient operations and shutdowns. The guidelines include specific procedures and advice for cycling, shutdown, startup, and layup for each boiler and feedwater treatment. The Guideline covers all major water and steam touched surfaces. Correct layup procedures, combined with appropriate chemical treatment during shutdown and startup, will significantly reduce corrosion and deposits in the steam cycle equipment, including the boiler, steam-touched tubing, and the turbine.

9.3 Thermal transients

Thermal transients can be avoided by carefully managing the unit when off-load and by adding engineered systems to alleviate the potential problems. In the United Kingdom, natural-circulation drum boilers have been fitted with off-load circulating systems to pump water slowly around the evaporative section to balance temperature variations. The aim is to eliminate flow stagnation and tube-to-tube temperature differences. In addition, interstage drains or vents have also been fitted to promote flow through the superheater stages and avoid quenching problems that may arise when cold condensate from platen elements is otherwise pushed into the relatively hot final superheater stages.

A primary constraint on ramping operation is matching steam and turbine metal temperatures. Sliding pressure offers advantages over throttle control during startup by establishing a flow to the turbine earlier in the sequence, with lower overall heat input and by retaining high temperatures on shutdown.

9.4 SCR Issues at Low Load

To avoid problems with SCR units during low-load operation, conventional design practice calls for a flue gas or water-side economizer bypass to elevate the flue gas temperature at low load to a level high enough to allow reagent injection. However, many units may not be equipped with economizer bypass capabilities. In these cases, operators have many options to comply with the minimum operating temperature:

- Evaluate actual SCR inlet operating conditions (NH_3 and SO_3 concentrations, and temperature distribution), and compare them with the SCR design conditions.
- Modify current operational practices (such as fuel sulfur content and NOx reduction levels at low load).
- Improve the SCR inlet temperature distribution by installing a static mixer.

10.0 CONCLUSION

Electricity consumption in India has been increasing at one of the fastest rates in the world due to population growth and economic development. India is planning to increase the renewable generation capacity to 175 GW by 2022. In terms of energy, renewable will have share of about 30% of total energy generation by 2022.

India has a federal setup in respect of electricity wherein each state is responsible for maintaining its load generation balance and complying with grid code (IEGC). As Renewable Energy Generation in India is concentrated in five states of India i.e. Gujarat, Rajasthan, Tamilnadu, Karnataka and Maharashtra, increased penetration & variability in Renewable Energy Generation will pose serious operational stresses on conventional power plants in these states.

Present renewable share in total generation at this stage may not have much impact on operation of conventional plants at National level. However, since these renewable generation is concentrated in five states of India, renewable share in these states will be much higher.

Increased renewable penetration in renewable rich states will result into reduced fossil fuel consumption, reduced carbon foot prints, reduced SOx and NOx emission and in turn may also lead to cycling operation of conventional power plants.

Cycling or varying the load levels of fossil unit including start/ stops, ramping or load following and operation at minimum load can create thermal and pressure stresses in the boiler, steam piping turbines and auxiliary components, and these stresses can accelerate wear and fatigue failures in various components. These wear and tear may result in increased forced outage, maintenance cost and reduced life expectancies of components. Additionally, varying the load level over prolonged periods typically degrades plant efficiency. Cycling of plant may lead to:

- Damages & reduced life of equipment
- Decreased thermal efficiency at low loads
- Increased fuel cost due to more frequent start-ups
- Difficulties in maintaining water and steam chemistry
- Impact on Environmental control equipment
- Increased risk of human error in plant operation

All the above issues will lead to increase in tariff of electricity generated through conventional sources and reduced equipment life.

Some of issues related to cycling of conventional plants can be mitigated by:

- Changes in Operation Philosophy and Maintenance Strategy.
- Efficiency improvement by sliding pressure operation & and other operational tweaking.
- APC improvement by providing Variable-speed drives for main cycle and auxiliary equipment.
- Compliance to chemistry guidelines for cyclic and transient operation.
- Upgrade of control systems. This approach may also include installation of additional process sensors (typically temperature), strategically located to guide operators during transients to avoid temperature excursions.
- Increased attention to the location, operation, and capacity of drains is another cost-effective operation and maintenance strategy.

However, these mitigation measures may not be adequate for eliminating complete risk & cost associate with Flexible operation of conventional power plants. A detailed analysis of cycling operation of conventional power plants with different share of energy from various sources is to be conducted and action plan needs to be worked out for mitigating and / or reducing the risk and cost associated with cycling operation. Further as most of the renewable capacity addition is non disptachable without storage, policy shall encourage installation of renewable energy projects with storage to meet the peak demand and reduce the stress of cycling operation on conventional power plants.

References:

1. Correlating cycle duty with cost at Fossil Fuel Power Plant by EPRI.
2. The Cost of Cycling Coal Fired Power Plant by Steven A Lefton & Phil Besuner of APTECH Engineering Services.
3. Mitigating the effect of flexible operation on Coal Fired Power Plants by Steve Hesler, EPRI
4. Make your Plant Ready for Cyclic Operation by Steve A. Lefton and Douglas Hilleman, PE Intertek Aptech.

Updates on R&D of IGCC in JAPAN

JCOAL Japan Coal Energy Center

Development of Next-Generation Coal-Fired Power Technologies

Power generation efficiency

60% · 55% · 50% · 45% · 40%

Integrated Coal Gasification Combined Cycle 1700 ℃ – class (IGCC)

Coal-fired thermal power generated through coal gasification, utilizing the combined cycle combining gas turbine and steam turbine

- Power generation efficiency: Approximately 46 to 50%
- CO_2 emissions: 650 g/kWh (1700 ℃ class)
- Technological establishment: Around 2020

Reduction of CO_2 by approximately 30%

Integrated Coal Gasification Fuel Cell Combined Cycle (IGFC)

Coal-fired thermal power utilizing the triple combined cycle combining IGCC with fuel cell

- Power generation efficiency: Approximately 55%
- CO_2 emissions: Approximately 590 g/kWh
- Technological establishment: Around 2025

Reduction of CO_2 by approximately 20%

IGCC

Completed verification by blowing air

- Power generation efficiency: Approximately 45%
- CO_2 emissions: Approximately 750 g/kWh

Advanced Ultra Super Critical (A-USC)

Pulverized coal thermal power utilizing high temperature and pressure steam turbine

- Power generation efficiency: Approximately 46%
- CO_2 emissions: Approximately 710 g/kWh
- Establishment of elemental technology: Around 2016

Ultra Super Critical (USC)

Pulverized coal thermal power utilizing steam power

- Power generation efficiency: Approximately 40%
- CO_2 emissions: Approximately 820 g/kWh

Present — Around 2020 — Around 2025

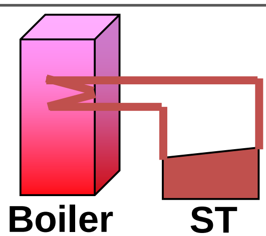
SOURCE : METI

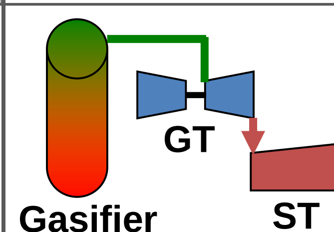
High-Efficient Coal Fired Power Plant

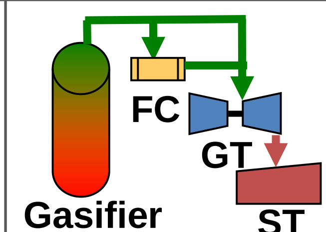
JCOAL Japan Coal Energy Center

Existing technologies → **Next generation technologies**

Pulverized coal-fired			Coal Gasification	
Subcritical	Ultra Supercritical (USC)	**Advanced-USC (A-USC)**	**Integrated Coal Gasification Combined Cycle (IGCC)**	**Integrated Coal Gasification Fuel Cell Combined Cycle (IGFC)**
36% （Efficiency; Net,HHV）	41%	46%	46% to 48%	55% or more
Steam temperature: approx. 560℃	Approx. 600℃	Approx. 700℃	Gas temperature: approx. 1500℃	Approx. 1500℃ or more







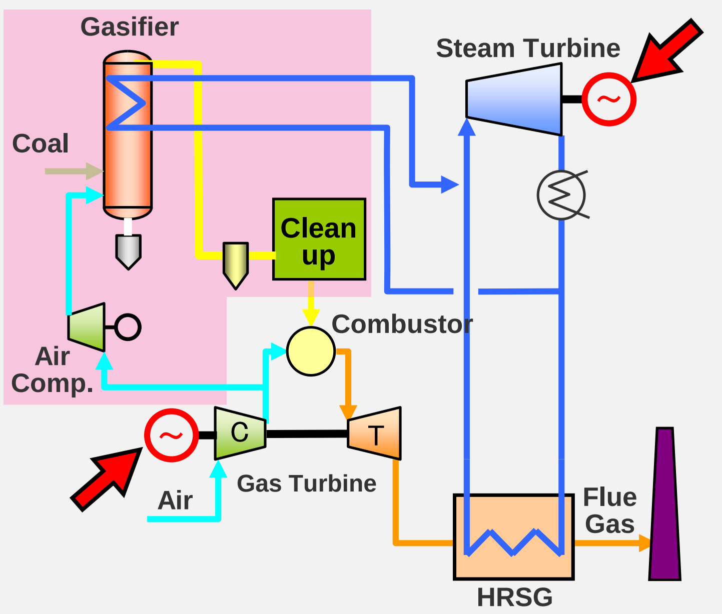
Further reduction of CO2 emission by technology developments: -approx.11% (A-USC), -approx.11 to 15% (IGCC), -approx.25% or more (IGFC)

Overview of IGCC Technology

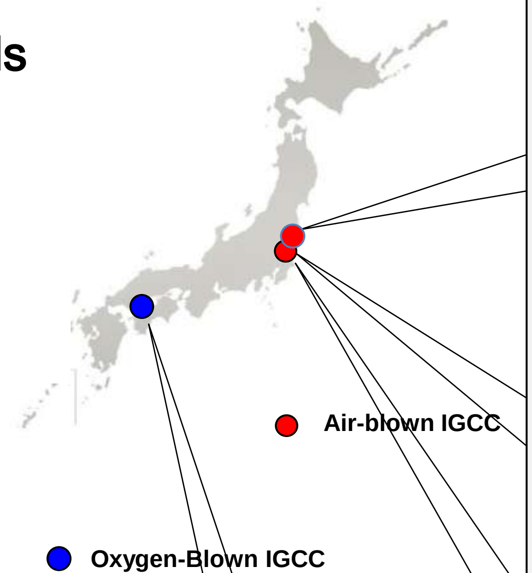
Features of IGCC

- High Thermal Efficiency
- Coal flexibility (Wider range of coals including low rank coals)
- High environmental performance (CO_2, NO_x, SO_x, Dust)
- Utilization of slag (Reduction of Ash Volume)

Combined Power Generation
(Combination of Brayton & Rankine Cycles)



Projects in Japan



Fukushima Revitalization Power

540MW Hirono (COD : Sep. 2021)

540MW Nakoso (COD : Sep. 2020)

Osaki CoolGen Corp.
Osaki CoolGen Project
166MW (Demo. 2017 -)

Joban Joint Power Co.
Nakoso #10, 250MW
(Demo. 2007 -, Commercial 2013 -)

SOURCE : MHPS, JOBAN JOINT POWER CO.,LTD.

Air-blown IGCC

Development of Air-blown IGCC in Japan

JCOAL Japan Coal Energy Center

Next Commercial plant
Joban Joint Power Nakoso 540MW (2020.9)
Tokyo Electric Power Hirono 540MW (2021.9)

Commercial plant
Joban Joint Power Co., Ltd.
Nakoso #10 250MW (2013-)

Demonstration plant
Clean Coal Power R&D Co., Ltd.
1700t/d 250MW (2007-2012)

Confirmation test plant
MHI Nagasaki 24t/d (1998-2002)

Pilot plant IGC Research Association
200t/d Equivalent to 25MW (1991-1996)

Process development unit
CRIEPI-MHI 2t/d(1983-1995)

SOURCE : MHPS, JOBAN JOINT POWER, TEPCO, METI

250MW IGCC Plant in Commercial Operation

Major Specification	
Output	250 MW (gross)
Gasifier	Air-blown Dry Feed
Gas Clean-Up	MDEA (Methyl-diethanol Amine)
Gas Turbine	M701DA GT (1 on 1)
Plant Efficiency	42% (LHV, net)
Project Schedule	
Operation Started	Sep. 2007
Commercial Operation	Jun. 2013

Nakoso 250MW IGCC Demonstration Plant achieved all the following target

- ✓Excellent Performance (High efficiency, Less environmental impact)
- ✓Higher Reliability (World record of continuous operation, 3,917hrs)
- ✓Fine Operability (Load change rate >3%/min)
- ✓Fuel Flexibility (Verified applicability to low-rank coal)

It is the first commercial IGCC plant in Japan as Joban Joint Power Co. Nakoso #10. Cumulative Operating Hours : 38,000 hrs.

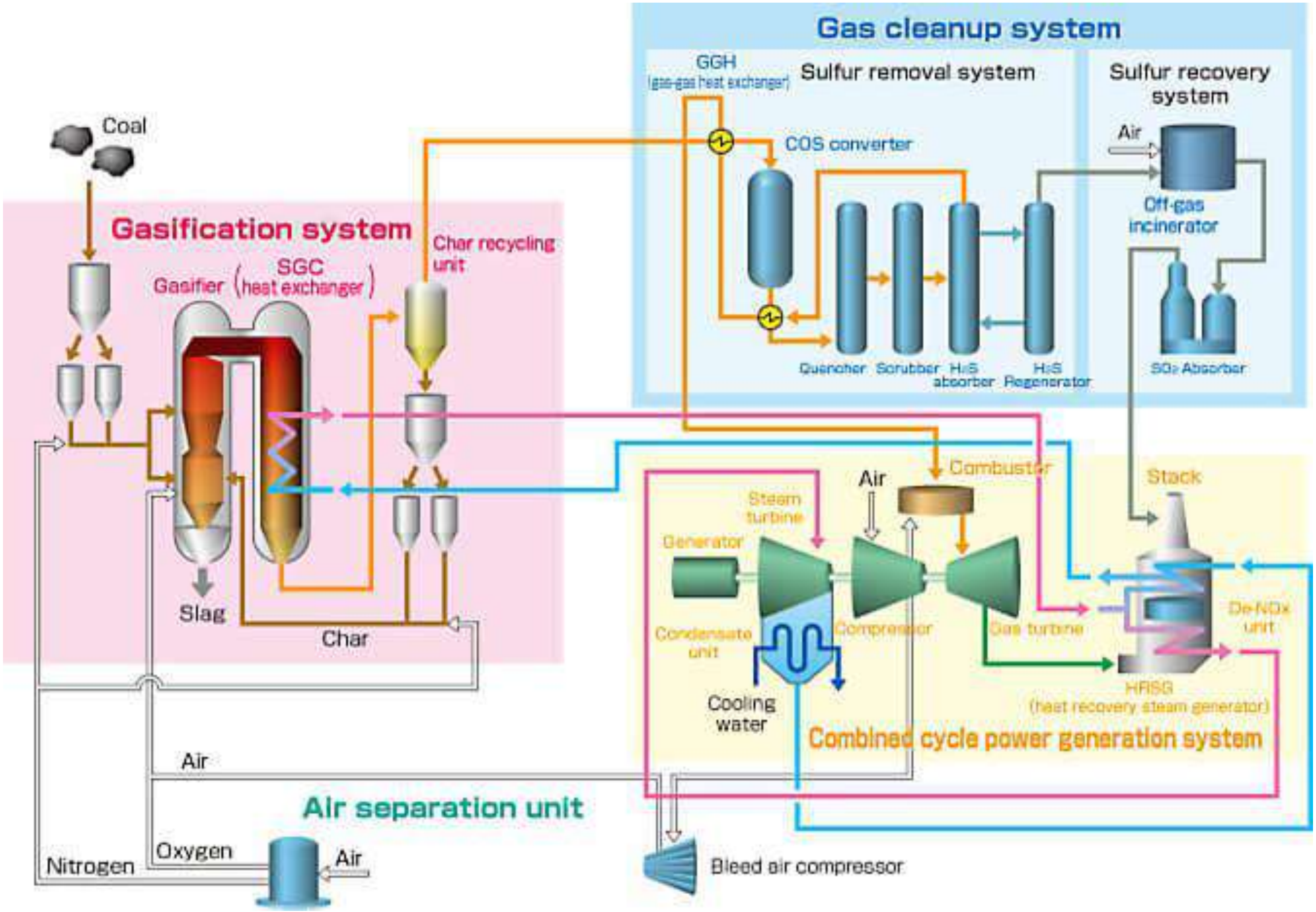
SOURCE : MHPS

Achievements of Nakoso 250MW IGCC Plant

		Targets	Achievements		Note
Performance	Output Gross Net	250MW 220MW	250MW 225MW		
	Efficiency (Net, LHV)	> 42.0%	42.9%		
	Carbon Conversion	> 99.9%	> 99.9%		
Emission (@dry, 16%O2)	SOx NOx Dust	< 8 ppm < 5 ppm < 4 mg/m^{3}N	1.0 ppm 3.4 ppm < 0.1 mg/m^{3}N	8.8 mg/m^{3}N(6%O2) 20.9 mg/m^{3}N(6%O2) <0.3 mg/m^{3}N(6%O2)	
Operational Flexibility	Coal Kinds	Bituminous Sub-bituminous	Chinese, Canadian 2 US (including PRB) 3 Indonesian (Adaro, etc.) Colombian, 2 Russian		10 kinds of coal 6 Sub-bituminous 4 Bituminous have been used.
	Start-up Time	< 18 hrs.	15 hrs.		
	Minimum Load	50%	36%		
	Ramping Rate	3%/min	3%/min		
Reliability	Long-term Continuous Operation	2,000 hrs.	3,917 hrs.		Cumulative operating hrs. approx. 38,000 hrs.

SOURCE : MHPS

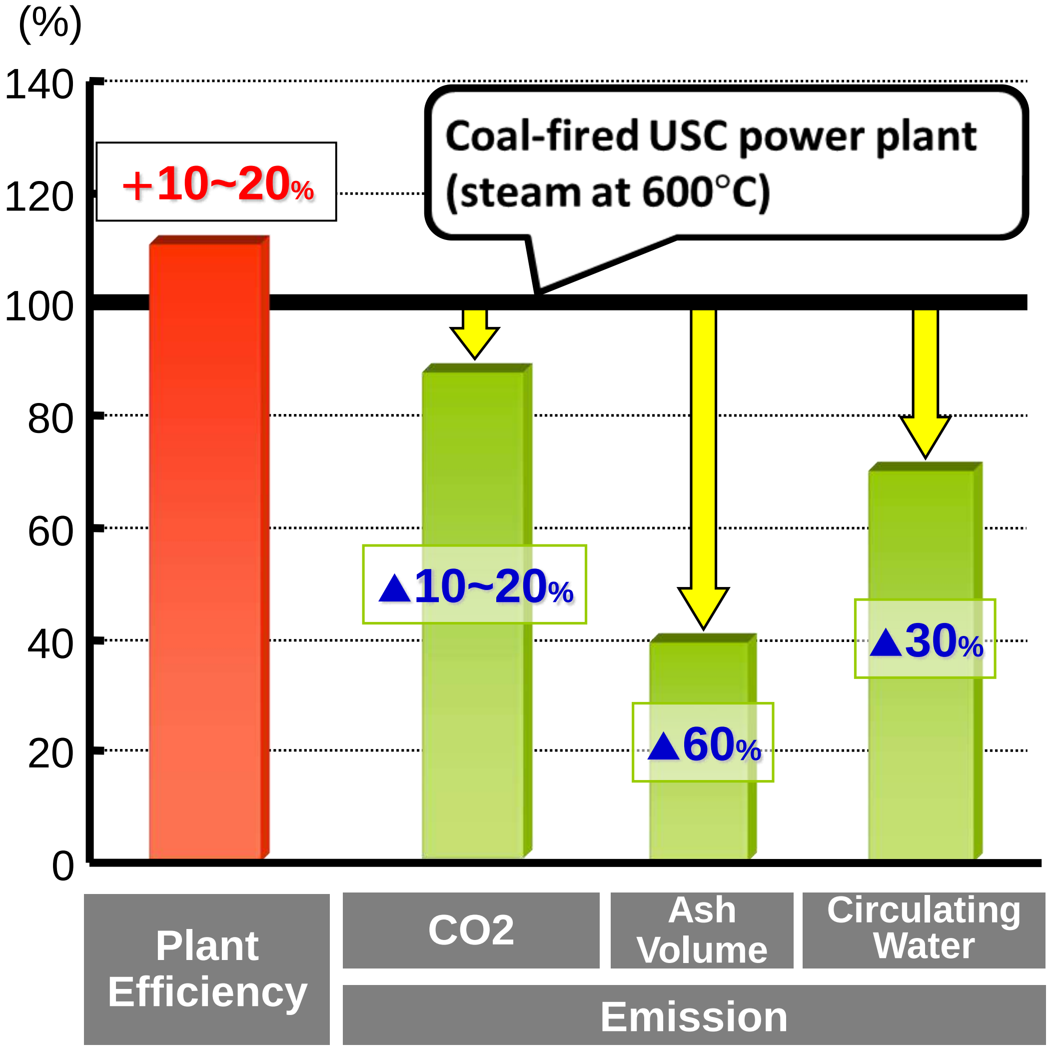
Schematic flow of Air-blown IGCC



SOURCE : JOBAN JOINT POWER CO.,LTD.

Environmental Performance

Higher Efficiency and Least Environmental Impact

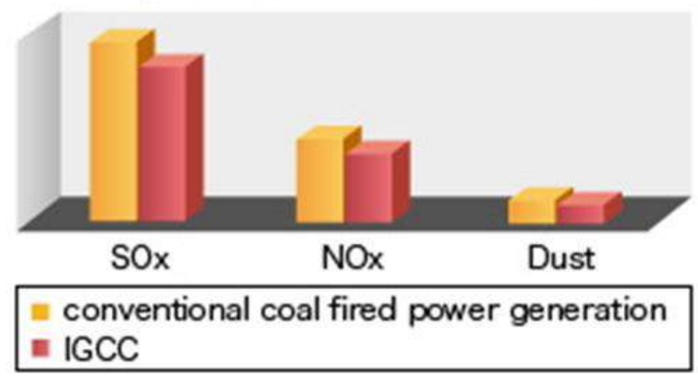


Fly-ash (Conventional Boiler)

Glassy Molten Slag (IGCC)

Approx. 60% decrease in volume

<Atmospheric Characteristics>

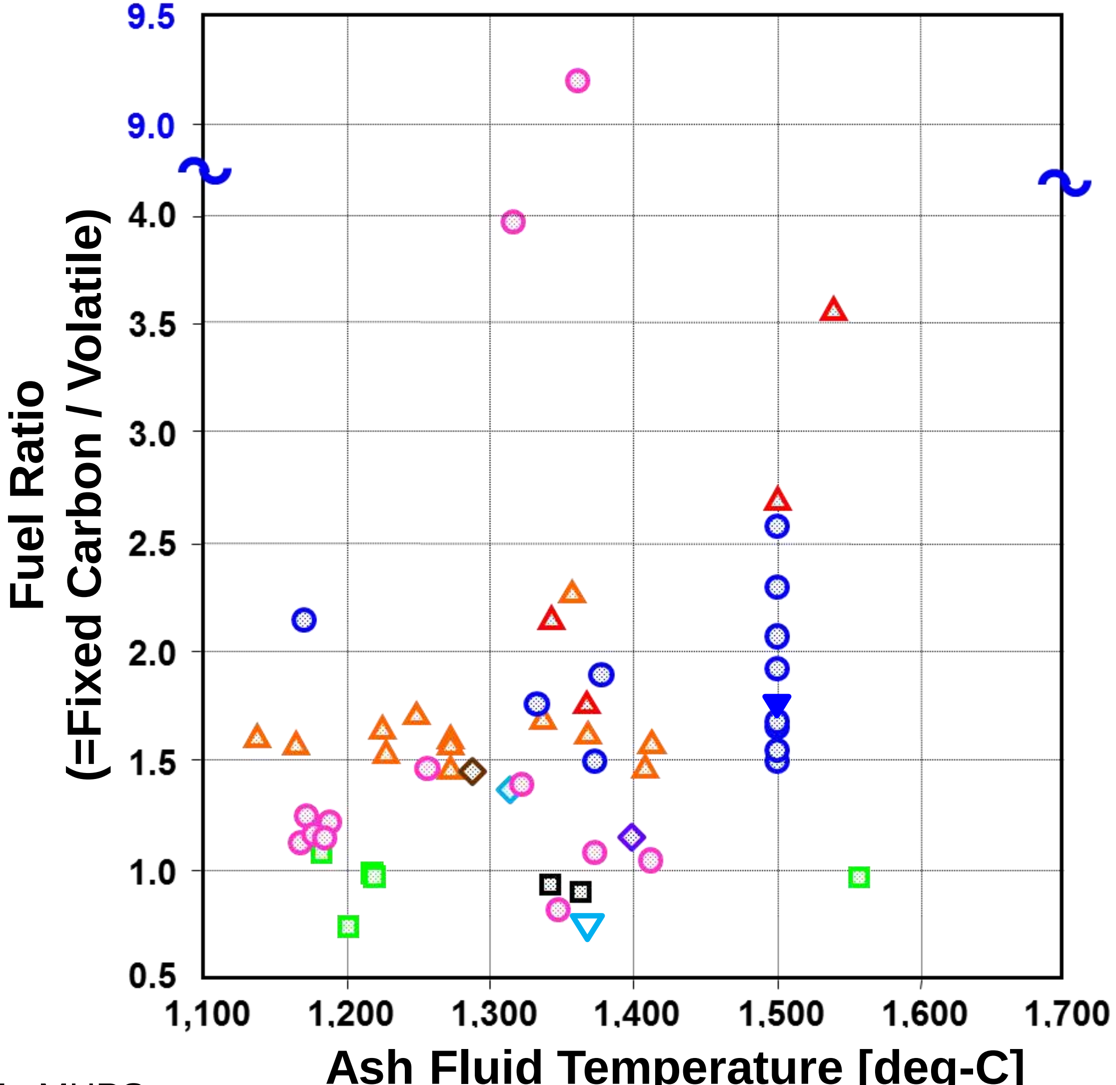


SOURCE : MHPS, JOBAN JOINT POWER, TEPCO, METI

Variety of Coal Experience and Capability

JCOAL Japan Coal Energy Center

IGCC has successfully operated in using world-wide variety of coal.



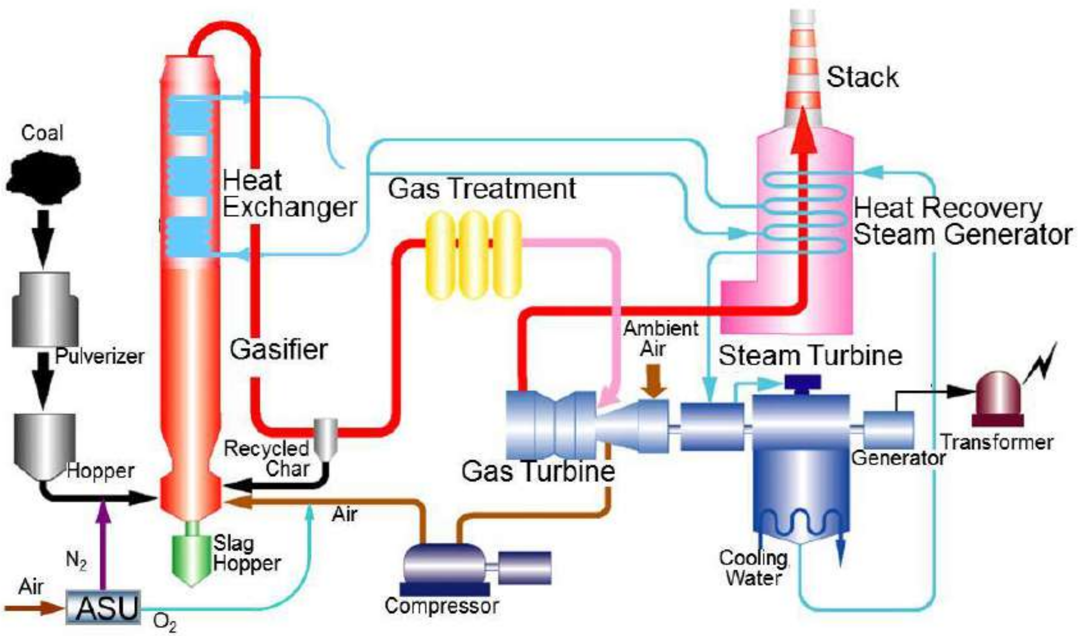
SOURCE : MHPS

Fukushima Revitalization Power IGCC Project

JCOAL Japan Coal Energy Center

Major Specification

Output	540 MW (gross) 480 MW (net)
Gasifier	Air-blown
Gas Clean-Up	MDEA (Methyl-diethanol Amine)
Gas Turbine	M701F GT (1 on 1)



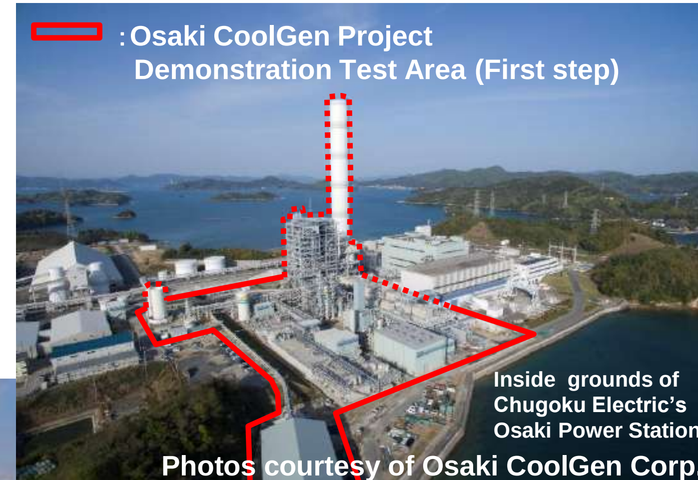
SOURCE : MHPS

Schedule

2014.8 Engineering Work Started
2016.10 Site Mobilization Started
2017.4 Construction Started
Commercial Operation (Scheduled)
2020.9 Nakoso IGCC
2021.9 Hirono IGCC

Oxygen-Blown IGCC

Development of Oxygen-blown IGCC in Japan



× 8
Scale-up

OCG Project (Osaki CoolGen)
(1,180t/d 2017～ Demo. Operation onward at Osakikamijima-cho)

× 3
Scale-up

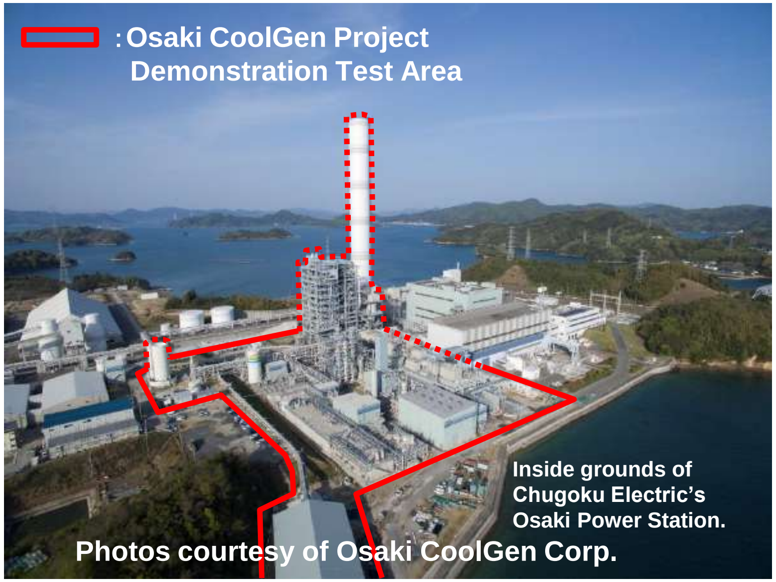
EAGLE pilot test
(Coal Energy Application for Gas, Liquid and Electricity)
(150t/d 2002～2013, 10t/d 2017- at Wakamatsu)

HYCOL pilot test (Hydrogen from Coal)
(50t/d 1990～1993 at Sodegaura)

PDU test(Process Development Unit)
(1t/d 1981～1985 at Katsuta)

SOURCE : MHPS

Osaki CoolGen Project

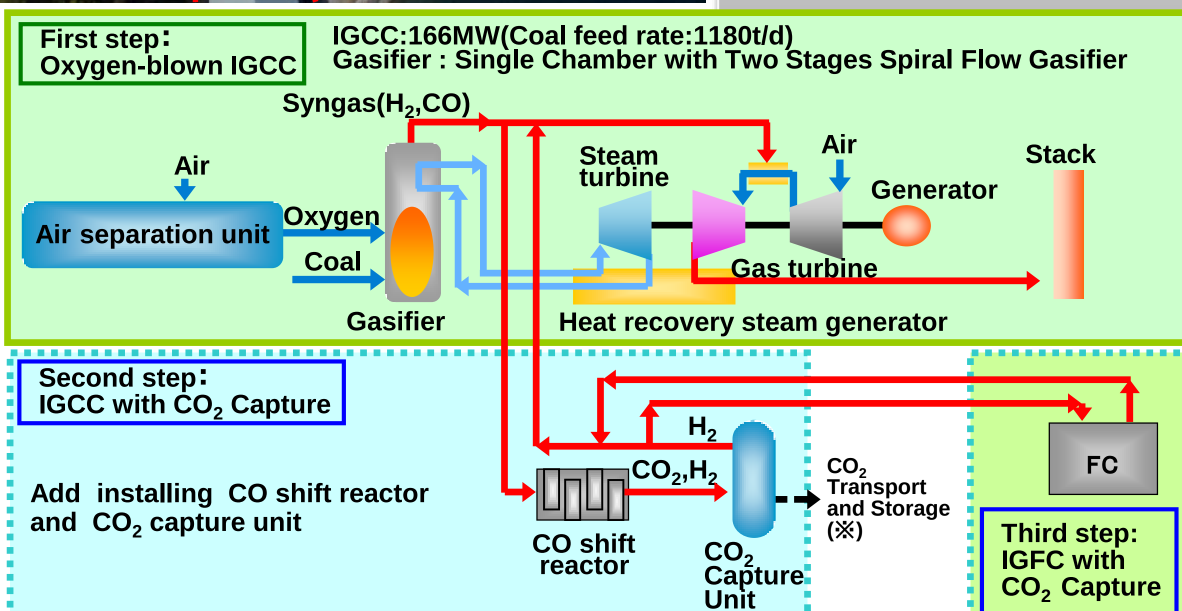


Major Specification

Output	166 MW (gross)
Gasifier	Oxygen-blown Single-chamber Two-stage Entrained-flow
Gas Clean-Up	MDEA (Methyldiethanol Amine)
Gas Turbine	H-100 GT (1 on 1)
Plant Efficiency	Target : 40.5% (HHV, net) <42.7% (LHV, net)>

Project Schedule

Construction	March 2013
Demo. Operation	March 2017 （First step）



First step : 2017-
Oxygen-blown IGCC
Second step : 2019-
IGCC with CO_2 Capture
Third step : 2021-
IGFC with CO_2 Capture
(*1)

(※) CO_2 transportation and storage are outside of the Osaki CoolGen Project.

SOURCE : MHPS

Title: - Flexible Operation of Thermal Power Plants in India

Author: - Sandeep Chittora
Siemens India

Abstract: -
With increase in Renewable Energy Integration to grid, conventional thermal power plants would be required to cycle. The plant would then be required to operate below current technical minimum load and require faster ramp up and ramp down rates. In such a scenario the life of critical components such as Boiler, Steam Turbine & Pumps gets affected. The increased fuel cost also presents the challenge to utility to achieve optimum efficiency. In order to achieve economic electricity, utility need to revisit the conventional operation and maintenance practices, optimize their operation with advanced digital solutions. In case of multiple units, it is further important to achieve the plant or fleet level optimization. OEMs like Siemens have prepared various solutions to address these requirements. At one hand on frequency control measures like condensate throttling and on other hand for plant monitoring and optimization like Thermodynamic Diagnostic (TDY) and Fatigue monitoring System (FMS) helps utilities and grid operator to benefit from new technologies. These solutions come on digital platform and are flexible to suit the requirements of utility. The present paper describes the challenges due to Renewable integration on conventional power plant and describes solutions from OEMs to improve the efficiency. The benefited power plants for adopting these solutions are Neurath, Altbach, Iskenderun, Luenen, NTPC Dadri and many more.

1. Volatile conditions

The typical operating modes of thermal power plants are undergoing changes both as a result of the liberalization of the power generation markets, but also especially as a result of the increasing percentage of renewable in electric power generation (see Figure 1). In some parts of the world these changes affect the conventional power plant operation mode significantly.

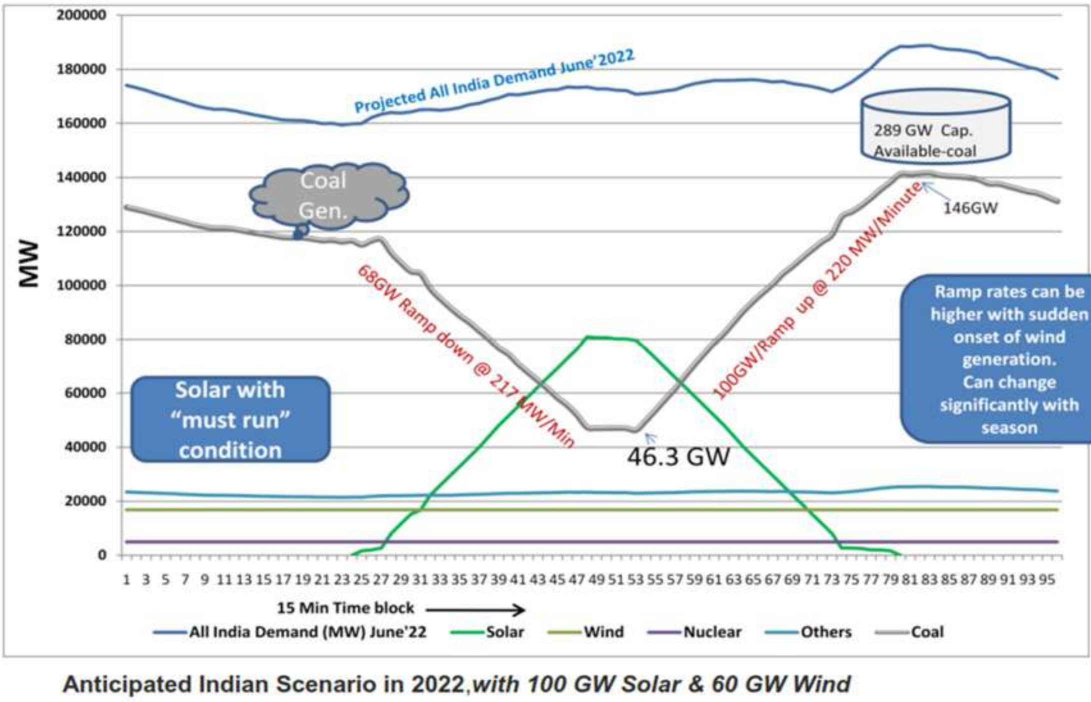


Figure 1: Future change in load demand of fossil fired power plants [1]

To push the expansion of renewable power generation, the technology and production, have been adapted to allow for mass production. For this reason, renewable power generation is not only financially subsidized, but also promoted as must feed-in to the electric power grid through administrative stipulations. Thereby the installed renewable power generation capacity increases by fluctuating sources of renewable energy. As a result renewable power generation queries the classical fractions. The former base load, intermediate load and peak load more and more split into renewable power generation and residual load. Minimizing carbon footprint by maximizing renewable power generation is the future trend, whilst residual load will be minimized by reasonable grid stability. The future trend comes along with expanding the grid, increasing power storage capacity, participation of renewable power generation in grid control and residual load generation by thermal power plants.

But residual load generation by thermal power plants means that thermal power plants will stand in for fluctuating renewable power generation. Main challenges are the fast start-ups, fast load change rates as well as efficient low load operation and high demand of primary frequency response.

This paper introduces various measures for coal-fired power plants that serve the aforementioned circumstances. Furthermore it is displayed what support in combining various measures Siemens can provide helping customers to optimize their plants for their specific requirements in a more and more volatile power market.

2. Increase swallowing capacity

Swallowing capacity is defined as the steam flow rate which can be processed by the steam turbine at specific inlet steam parameters - pressure and temperature.

The blading itself has a constant swallowing capacity. As a first approximation, at constant temperature, the mass flow rate which can flow through it is proportional to the inlet pressure. One possibility to enable fast load changes is to raise the swallowing capacity. At nearly constant pressure this increases the mass flow that is proportional to the turbine output. The load increase can be realized by using energy that is accumulated in the Boiler.

To increase the swallowing capacity there are various measures possible. One such measure is introduction of Last Main Steam Valve or also known as inter-stage admission.

The design of reaction turbines is categorized by a certain number of control valves that are directly connected to the ring chamber prior to the first stage of the HP-turbine. This first stage experiences a full arc admission. The order of opening of individual valves is that all but one valves open in parallel until they are fully open. In this situation at full pressure and temperature the rated output is reached. The last valve leads steam to a position in the HP blading a few stages downstream of the first stage. It is used to accomplish the valves wide open load point and is used for primary frequency response. The amount of additional swallowing capacity is regarded in design of the last HP valve.

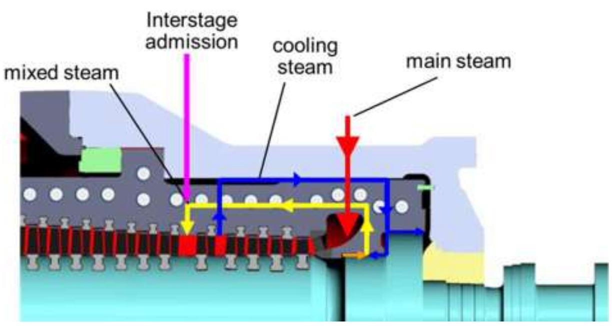


Figure 2: HP turbine with last main steam valve[1]

[1] The former so called „Over Load Valve“ or „HP stage bypass“ is now regarded as additional main steam valve by Siemens

Advantage of this method is that the amount of additional output can be designed over a relatively wide range. The turbine operates without throttling losses while being able to provide reserve power at any load point. Due to the full arc admission the stress to the blading of the first row is comparably low. The focus in designing these rows can be more targeted to optimized efficiency than to robustness meeting the same design life time targets.

3. Condensate throttling

Condensate throttling is a proven measure to enable fast increase of turbine power in case of high grid frequency decrease.

In this case the main condensate control valve is throttled to a calculated position allowing a reduced condensate mass flow flowing through the LP feed water heaters. Considering a certain response time the extraction steam mass flows of the LP feed water heaters and the deaerator/feed water tank are reduced. The surplus steam remains in the turbine and generates additional power. A principle system sketch of the related components is shown in Figure 3.

This condensate throttling compensates the transient time behavior of the boiler. The accumulated condensate is stored in the condenser hotwell or a separate condensate collecting tank. Parallel to the above mentioned measures the firing rate of the boiler has to be increased to meet the load requirements. The feeding of the boiler is continued and increased. Thus the level of the feed water storage tank is decreased accordingly.

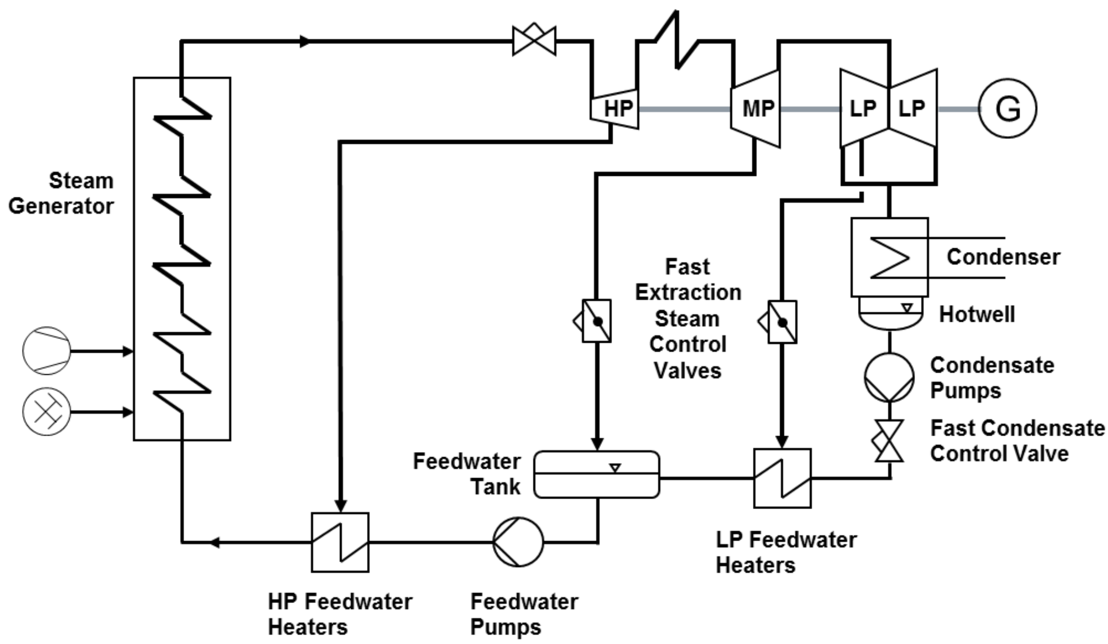


Figure 3: Principle sketch of condensate throttling

During this time the condensate flow reduction is gradually released and has reached steady state conditions again. Refilling of the feed water storage tank is initiated by releasing the condensate control valve to control the level of the hotwell or condensate collecting tank. The maximum allowable condensate mass flow is monitored and the refill flow is limited to a maximum value. Due to the increased condensate flow through the LP feed water heaters and into the deaerator the steam extraction from the affected turbine extractions is increased. The generator output decreases correspondingly. To compensate this influence the boiler-firing rate is increased. However, the maximum allowable superheater outlet flow is limited to 100 % BMCR (Boiler Maximum Continuous Rating).

The strategic effect of this method is to utilize the stored energy of the preheated feed water stored in a feed water storage tank. One benefit is that heat rate is not increased during normal plant operation. Furthermore no additional life time consumption is caused by usage of condensate throttling. Additional invest for extra buffer volumes and fast acting control valves is required.

3.1. Response time

The response time of condensate throttling depends on the time required for reduction of condensate mass flow. Therefore normally a fast acting main condensate control valve is used. By means of additional fast acting valves in the extraction steam lines the response time behavior can be optimized. The response time of 20s for 7% power at 100% load has been achieved through condensate throttling at NTPC Dadri.

3.2. Capacity

The resulting turbine power increase depends on the amount of throttling of the main condensate control valve and the actual unit load. The higher the unit load, the higher is the amount of additional turbine power which can be generated by condensate throttling.

3.3. Duration

Duration of condensate throttling operation depends on the amount of buffer volumes provided for condensate and feed water. The slower the boiler increases load, the larger the buffer volumes have to be.

4. Usage of HP feed water heaters

There are different types of HP feed water heater operation which can be used for provision of additional turbine output.

4.1. Partial bypass of HP feed water heaters

A planned increase in turbine power can be achieved by flexible setting of the preheat temperature according to demand by means of mixing partial flows of feed water.

To do this, the feed water is divided into a first partial flow being preheated and a second partial flow, which is routed in a bypass line to the HP feed water heaters and is then re-mixed with the preheated first partial flow (Figure 4). The remaining feed water still flowing through the preheating line, keeps the HP feed water heaters warm and thus prevents unwanted thermal stress. Switch over from normal to maximum overload operation is done slowly in respect to the allowable temperature gradient of the HP feed water heaters. Thereby the HP feed water heater design, U-type or header type or solutions with two parallel HP feed water heater lines influences the switch over capability.

By preheating only a partial flow, a smaller amount of heat is required compared with preheating the complete feed water. Thus, process heat in the form of a higher steam mass flow through the turbine is available to increase the turbine power as required, up to the boiler reserve of the steam power plant. In doing so the main steam mass flow is slightly reduced and plant efficiency decreases.

Siemens successfully installed this feature in the coal-fired power plant Kogan Creek, Australia.

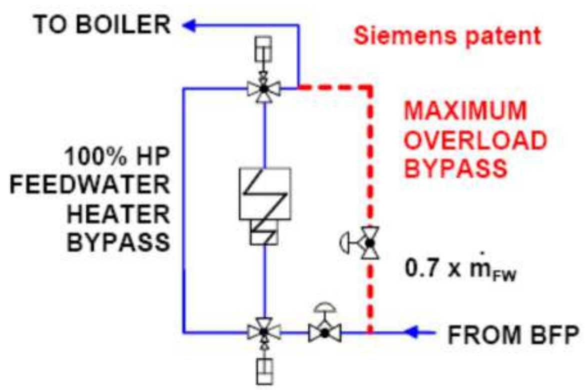


Figure 4 : Schematic of controlled (red) partial and full (blue) HP feed water heaters bypass

4.2. Full bypass of HP feed water heaters

A fast increase of turbine power can be achieved by using the usually provided full bypass around the HP feed water heaters. It is bypassing all feed water mass flow around the heaters (Figure 4). While the steam mass flow through the extraction of the steam turbine to the HP feed water heater is terminated the economizer feed water inlet temperature is significantly decreased. The surplus steam remains in the turbine and generates additional power. The resulting turbine power increase depends only on the actual unit load and cannot be controlled. Advantage is that no additional hardware is required. You have to keep into account that this measure causes a significant life time consumption of the components, in particular the HP feed water heaters and the boiler economizer. Therefore this measure should only be used a few times during lifetime of the plant.

4.3. Reduction of HP feed water heater extraction steam flows

In order to limit unallowable (life time consuming) stress in the components steam flows of the extractions can be partially reduced instead of bypassing the preheaters on the feed water side. Criteria are the maximum allowable reduction of feed water temperature upstream of the economizer and the selection of temperature transients for the HP feed water heaters

This can be realized by using control valves provided for the extraction lines or by closing HP heater extractions step wise, starting with the last HP heater stage.

In comparison to HP feed water heater bypass operation this measure limits life time consumption of the components, depending on amount of extraction steam flow reduction.

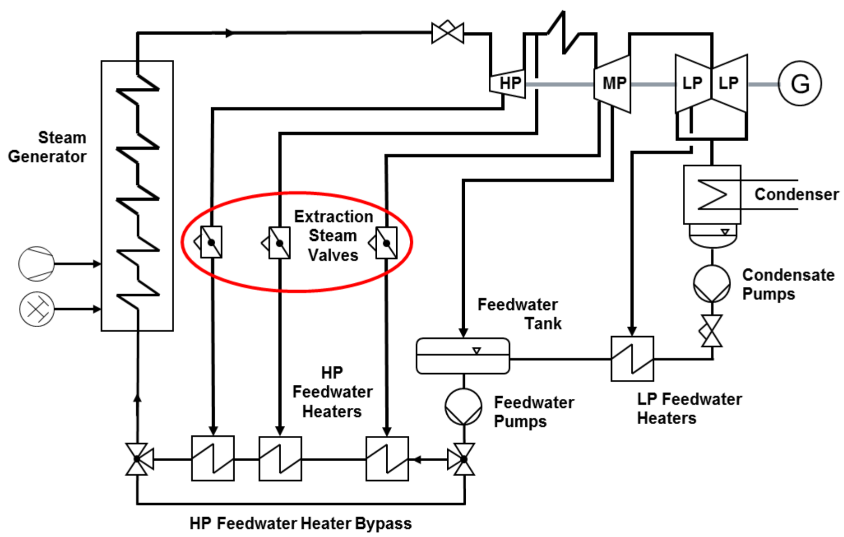


Figure 5: HP extraction control valves

5. Key parameters for selection of measures

The selection of measures which are the most beneficial for the individual project needs depends on a few key parameters.

5.1. Amount of load increase

The amount of increased power output is the key information and decides whether one measure is sufficient or a combination of various measures should be considered. So it would be sufficient for a 2% primary frequency response to operate with slightly throttled main steam valves. Whereas a 10% load jump would need a combination of several aforementioned measures

5.2. Number of load changes during life time

The number of expected load changes has an impact on what measures should be selected. If a rapid load change has to be conducted only a few times during life time e.g. a 100% HP feed water heater bypass operation might be the right selection. If rapid load changes are expected to occur frequently less life time consuming measures should be selected.

5.3. Required load transients

The required load transients (i.e. load change rates) are normally defined in the grid code but also grid specific circumstances have an influence on what measures should be selected or combined. For a scenario where a noon peek occurs frequently and foreseeable low load transients are feasible. In this case a partial bypass of the HP feed water heaters is a good solution. For high load transients main steam valves in combination with a condensate throttling including fast acting valves in the steam extractions are a proper solution.

6. Frequency response concept combining different measures

In order to fulfil challenging requirements in regards of frequency response it is necessary to combine several measures for fast load increase. Selection of measures has to consider project specific boundary conditions like stability of grid, local grid code requirements, plant specification and plant configuration.

The different measures are activated in a staggered way, depending on the amount of frequency deviation. The outcome is superimposed.

The higher the frequency decrease, the more measures are used in parallel to achieve the required increase of turbine output.

Thus the last measures are only activated in the very rare case of an extraordinary high frequency decrease. Therefore the measures with no impact on life time consumptions should be activated first, the measures with higher impact on life time consumption last.

7. Combustion Optimization under Static and Dynamic Operating Conditions

Combustion optimization by the means of control optimization is an effective measure for efficiency improvements and primary emission reductions because it directly influences the combustion process through the control of the air-fuel ratio.

The laser-based online measurement of the combustion gases provides vital information for the closed-loop balancing of the air-fuel distribution in the furnace. The effects of variations in the fuel quality, changing boiler load set-points, wear and tear as well as of control set-point corrections should be best measured directly since they are significant importance for the optimization process. The online measurement together with advanced control strategies forms the basis for the optimization under dynamically changing operating conditions. Anyway, even so called “static” conditions often appear to be subject to frequent changes of the boundary conditions so that a constant retuning of the combustion control parameters proved to be of high importance.

The combustion optimization solution comprises the following modules: laser-based measurement system, distribution calculations based on Computer-Aided Tomography (CAT) and closed-loop combustion optimization control logics.

The laser-based measurement system simultaneously maps the gas concentrations of oxygen (O2), carbon monoxide (CO), water steam (H2O) and the gas temperature in the upper combustion zone in real time. These constituents proved to be adequate for the optimization of the combustion process.

Each laser path measures the average gas concentrations and temperature at the same time. To generate a detailed two dimensional tomographic image of the measurement plane an ideally orthogonal grid configuration of 10 up to more than 20 lasers is typically used. The tomography algorithm is applied for the calculation of two-dimensional images from the laser path measurements. The tomographic images can be displayed directly in the control room and are used together with additional process information as an input for the closed-loop combustion optimization. With this input the combustion optimization calculates set-point corrections for all relevant and addressable combustion control loops in order to balance the combustion process in an optimized manner. The basic principle is shown in Figure 6.

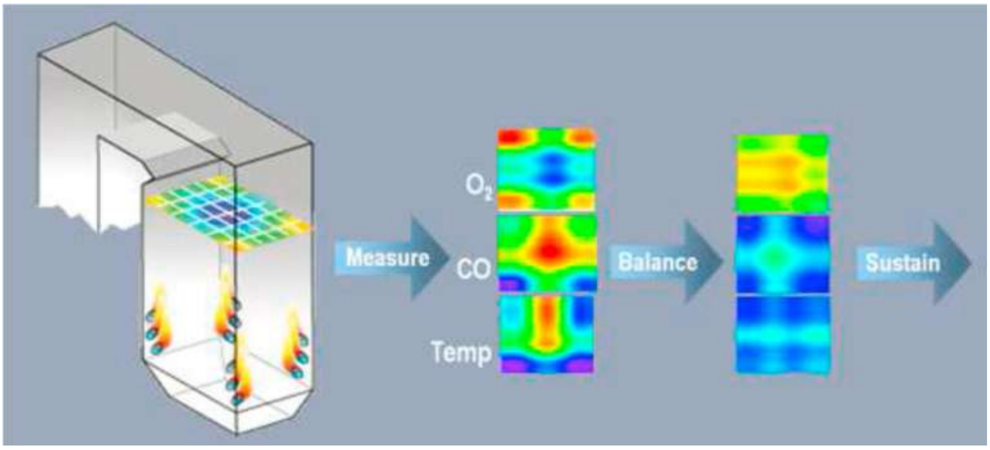


Figure 6: Laser–based measurements, tomography calculations and combustion balancing

8. Monitoring Systems such as Performance Monitoring (TDY and Fatigue Monitoring (FMS)

While working on part loads, it becomes apparent for utilities to make use of performance monitoring tools to assess the expected performance and compare them with actual performances. These tools help utilities to identify controllable losses. Per various studies, it is said that plants equipped with performance monitoring tools have 0.5% better operational performance than without.

Further with Fatigue monitoring, for every load cycle of ramp up and ramp down, utilities can now understand the consumption of life on various components of steam generator. On-line acquisition of cumulative boiler fatigue enables the optimization of operation with a view to residual life. In these tools, the theoretical life of the boiler is computed for a specific design loading. As a result of operating conditions outside the design parameters the lifetime that can be actually attained may be longer or shorter than that computed in advance. To be able to make the correct decisions on operation and maintenance, FMS computes impact the residual life based on the mode of plant operation.

9. Conclusion

There are many technical solutions to adapt coal-fired power plants to the upcoming volatile grid requirements. To get optimized economical result based on the project specific requirements it is necessary to have an early and close cooperation with the boiler, balance of plant and steam turbine generator supplier. None of them alone can provide a comprehensive optimized solution.

References:

[1] Presentation on "Effect of Renewable Energy on Grid" EEC National Seminar on Flexibilisation of Thermal Power Plants- Learning from German Experiences.

[2] Thomas Achter et.al, Upcoming Volatile Grid Requirements and Siemens' Answers for Flexible and Dynamic Operation of Large Coal-Fired Power Plants up to 1,000 MW.

[3] Max Starke, et.al, Control optimization solutions improve the combustion process under static and dynamic operating conditions and increase operational flexibility.

DAY 1: 20TH FEB 2018

SESSION 2:

Hydro GENERATION

First Filling of Water Conductor Systems- Challenges and mitigations with Specific reference to Rampur HEP-412 MW

L.M. Varma, Chief General Manager (Civil Design)
Rakesh Sehgal. Sr. Additional General Manager (Civil Design)
Jaswant Kapoor, Sr. Manager (Civil Design)

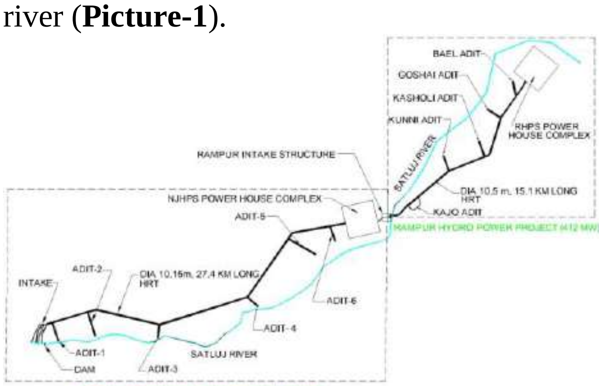
***Organization**: SJVN Ltd. (A Joint Venture of Govt. of India & Govt. of H.P.), Shakti Sadan Shanan Shimla, H.P., India*

Abstract

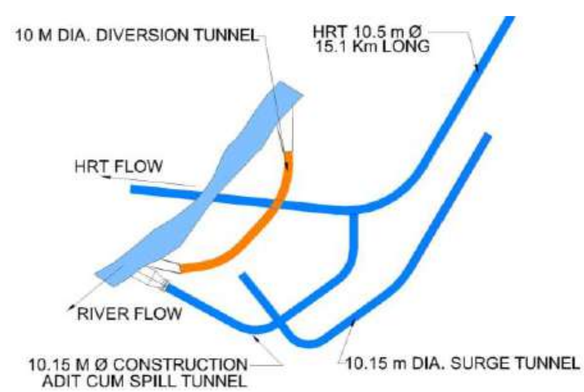
SJVN Limited successfully commissioned its Rampur HEP (412 MW) in 2014. The project has been planned to operate in tandem by directly utilizing the Tail Water of SJVN's prestigious Nathpa Jhakri Hydro Power Station 1500 MW located upstream. The initial filling of voluminous water conductor system of RHEP with 10.50 m diameter, 15 Kilometer long Head Race Tunnel, involved more than 1.5 million m3 of water. The filling operation of such a large diameter tunnel constructed in young folded Himalayas which always offer less ideal sites for tunnelling and their subsequent operations under pressurized conditions is worth sharing hydro power developers. The meticulous planning, execution, precautions taken, and performance monitoring during filling process keeping in view the fragile geology, low rock cover zones, shear zones in close vicinity of thickly inhabited areas, squeezing zones, hot water zones encountered during excavation has been discussed in the paper.

1. Rampur Hydro power station in brief:

Rampur Hydroelectric Project (412 MW), is located in Himachal Pradesh (India). This project is a downstream development of Nathpa Jhakri Hydro Power Station (1500 MW) constructed on river Satluj and commissioned during 2003. Both the projects today are now successfully working in tandem. The upstream NJHPS has been constructed on the left bank of the river while the downstream Rampur HPS is located on right bank of the river (**Picture-1**).



Picture 1: Combined Layout of NJHPS (1500 MW)



Picture 2: Rampur HRT Layout in initial reach

The major length of HRT of Rampur project lies on right bank of river before it crosses under the river in its initial reach (**Picture 2**). The main features of the project are as below:

- 10.50 m diameter 15 km long HRT ending in a 155.75 m deep, 38.00 m diameter surge shaft.
- 3 steel lined pressure shafts, 5.4 m dia, 211-220m long.
- Surface valve house 69 m long x 10.50 m wide x 23 m high housing 3 No. butterfly valves
- 3 No. surface penstocks 5.4m dia 368-382m long, bifurcating into six penstocks, each of 3.80 m dia. to feed six generating units of surface power house 158 m long x 24.50 m wide x 48 m high, with Francis turbines each of 68.67 MW capacity.

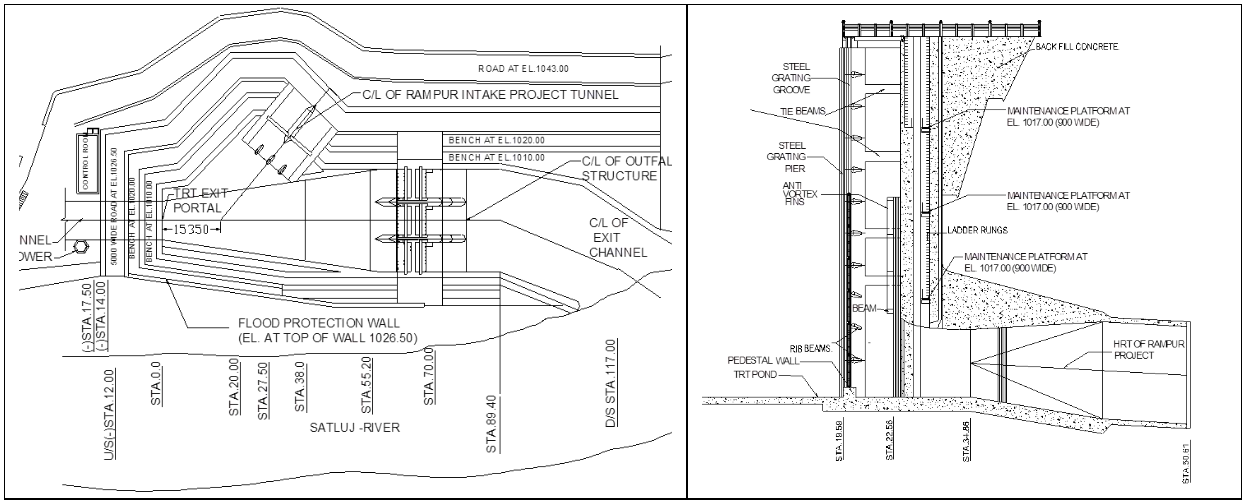
The discharge from the turbines is fed to a collection gallery and leads back to river Satluj through 10.15m horse shoe shaped 67.15m long tail race tunnel. The HRT construction has been completed using 5 no. construction adits at right bank and 1 no. construction adit cum spill tunnel at left bank of
the river. The spill tunnel has been provided to release the excess discharge in case of tripping of machine in RHPS. Since the Rampur Hydroelectric Project is directly utilizing the already desilted tailrace water of NJHPS, thereby major diversion and desilting components have not been provided. A gated intake structure for diverting 383.88 cumecs of flow emerging from Tail Race of NJHPS and HRT length of 50.61 m were already constructed in the tail pool of NJHPS before its commissioning.

The water after generating 1500 MW of power from Nathpa Jhakri Power Station comes out through a 982 m long tail race tunnel of 10.15 m diameter into the out fall structure 89 m long and 26.5 wide and is further lead to river Satluj through gated openings provided in the outfall structure (Picture-3) when Rampur HPS is not operating. Automatic regulating gates are provided at out fall to divert the water towards Rampur intake to meet the discharge requirements at Rampur HPS in downstream

Picture 3 :(TRT Out-Fall, Nathpa-Jhakri HEP)

Picture 4 : (Intake Structure, Rampur HEP)

A gate control for drawl of water for head race tunnel of Rampur HEP has been provided in the pond of TRT out fall structure (Picture-4). This Intake Structure comprises two intakes spaced at 8 m c/c. The center line of HRT of Rampur HEP has been aligned at an angle of 50° with the center line of TRT Outfall of NJHPS. The sill level of the gate has been kept at El. 989 m and the top of opening is at El. 996.54 m. The two rectangular gate openings of 6.0 m X 7.54 m, after a transition starting from Sta. 34.86m to Sta. 55.61 m, finally merge into a circular concrete lined HRT section of 10.5 m finished diameter (Picture5).



Picture -5

The two Intake gates of vertical lift wheel type have been provided. Each gate has been provided with upstream skin plate and upstream sealing. The gates have been designed to close under balance head conditions and are not intended for regulation purposes. The gates are designed to crack open under normal upstream water level and continue opening till balanced head condition is achieved.

2. First filling operation of RHEP

The first filling of RHPS was meticulously planned after a lot of desk study in such a way so as not to stop/interrupt the commercial generation of NJHPS even for a minute. The entire filling process was finalized keeping into consideration past experience, the safety of RHPS components, like HRT and surge shaft which passes through very adverse geological conditions and other control structures. Also the steep slopes with in HRT, High head at the Rampur Intake gates and the velocity restrictions for filling were kept in mind. As such the filling was taken up as a combination of filling through gates using Tail race Water of NJHPS & with pumps using the running river water at spill tunnel outfall. Adequate pauses were planned for slow filling along with regular checks at weak points like the adit plugs, low cover zones, surge shaft area , inhabited areas etc.

The total volume of water to be filled in the entire water conductor system was of the tune of 1.50 million m3. The breakup of the volume of water in various components has been tabulated below:-

Table -1
Volume of water in the Water Conductor System

Sr. No.	Component	Volume of Water (m3)
1.	Head Race Tunnel	1446046
2.	Pressure Shafts & Penstocks	25969
3.	Tail Race System	19023
Total		**1491038**

Due to several constraints in long Water Conductor System and for safety of structures against unbalanced head conditions likely to develop due to water filling and likely formation of hydraulic jumps at the points of changes in gradients, it was desirable to fill the system at a gradual, steady and slow rate with intermediate waiting period (saturation pause) during first filling operations. Keeping in view the type of rocks encountered in Head Race Tunnel, the filling was planned to be carried out with rate of increase of water head not exceeding 1m per hour. As such the maximum allowable velocity of flow at tunnel invert was limited to 6m/s. The velocity of flow was worked out for different invert slopes assuming open channel flow and maximum velocity was observed in the reach of HRT with steepest invert slope i.e. 1:15. This 95 m reach was located near the intake at RD 373.6 m and was prone to abrasion damage at higher velocity, since almost whole of the water volume was to pass through this reach. As such the maximum permissible discharge 3.85m3/s was worked out. However, in order to adhere to the rate of increase of water head of 1m per hour in the reaches having steep slopes, discharge much less than 3.85m3/s was required.
Bureau of Indian standard Guidelines for first filling of Pressure Tunnels were referred for safe initial filling of HRT. A comprehensive filling manual was prepared considering the following key points:

- A number of probable seepage observation points were identified.
- Filling rate was kept slow, so that the internal pressure increases gradually and surrounding conditions get sufficient time for stabilization and there is no scope for the air to get entrapped, compressed and then released.
- To avoid excessive tension in the lining the filling was carried out in pre-determined steps of water head based upon the known properties of the surrounding rock mass.
- HRT was planned to be filled initially up to the Surge shaft gates. The part of water conductor system between Surge shaft gates and Butterfly valves and MIV's was planned to be filled subsequently by operating Filling/Needle valves provided in Surge shaft gates/Butterfly valve.
- Filling of TRT up to minimum Tail water level was planned by pumping water from River Satluj.

Major Constraints and Challenges

Following were the major challenges and constraints in first filling operation:

- The construction of RHEP Intake and HRT up to station 50.61 m was completed with the commissioning of NJHPS in 2002-03. Since then the Intake Gates remained in dogged position. During the 10 years of operation of NJHPS, this reach of HRT (up to Sta. 50.61 m) remained filled with silted water resulting in heavy silt deposition at gate sill which hindered with lowering of gates. The final connection of HRT of RHEP with NJHPS Tail pond was only possible after lowering of Intake gates.
- Drawl of water for filling through Intake gates, from Tail pond of under operation NJHPS under High head (14-16 m) without depleting the Tail pond was a major constraint.
- Intake gates without Filling valves / stop logs, were designed to crack open 150 mm, which would have delivered very high discharge than permissible discharge of 3.85m3/s.
- Due to the variable invert slopes (1:15 to 1: 2555) in HRT, the required discharge for steady filling varied for every 1m head increment. Operation of Intake gates with different openings (10-150 mm) for regulation of the discharge was a big constraint.
- Damage to the invert concrete due to high velocity of water (about 12 m/s) near the crack opened Intake gates was anticipated.
- Water availability from NJHPS machines was not constant during the day because of lean season as the plant was producing peak power during part of a day as per grid requirements.

Measures taken to counter the Major Constraints and Challenges

- In order to connect the Rampur HRT with NJHPS Tail pool, Rampur intake gates were lowered in a planned manner, after removing the heavy silt deposits near the sill beam area. This 2.5 months long operation involved mapping of silt using RoV from gate groove and pond side and removal of silt by using agitator pumps for safe seating of intake gates. After lowering of intake gates, the Rock plug of HRT was removed and concrete lining was completed in this reach.
- Keeping in view the discharges required in HRT for 1m/hour rise in steep slopes, the operation of gates for very small openings was found risky as well as very tedious. Therefore, it was decided to fill the HRT by using pumps in very steep slopes where otherwise the required gate opening would have been 10 mm to 35 mm. A fleet of 10 pumps (150 lps capacity each), with total discharging capacity of 1.5 Cumecs was installed at the Spill Tunnel Portal lifting water from River Satluj
- For HRT reaches with medium and mild slopes, filling was planned to be carried out by operating Intake gates with Gate opening varying from 50 mm to 65 mm.
- In order to avoid the loss of generation at NJHPS, it was decided to go for filling at the same head (14-16 m) but with following precautions:-
    i. Providing High strength concrete (M:50) in invert near Intake gates to counter the effect of high velocities (12 m /sec) generating from orifice flow beneath intake gates.
    ii. Providing High strength concrete (M: 50) just downstream of Intake gates side walls to counter abrasion of concrete due to and Hydraulic Jump formation.

iii. Prior checking of Intake gates for lesser opening i.e. 50-60 mm using manual operation.

- The filling operation by virtue of the project completion fell in the lean season. In order to fulfill the water requirements during spinning /dry out tests for units of RHPS it was planned to operate one machine of NJHPS even at no load for shorter periods if required.

Risks involved

Following were the major risks foreseen in first filling operation:

- Majority of the HRT (62%) was having Q-value less than 0.1. In this reach the majority of rocks were phyllites/ carbonaceous phyllites. Filling in these geologically poor reaches was vulnerable to leakages, high stresses in lining leading to cracking.
- A number of cavities were encountered in HRT during construction stage. These patches were prone to non-uniform stressing of concrete lining and surrounding rock mass.
- Poor geology encountered at some of the HRT-Adit junctions was prone to leakages.
- HRT passing through thickly inhabited areas at various locations and zones having low rock cover.

Measures taken for Risk mitigation

- Keeping in view the very poor geology encountered in the HRT, consolidation grouting was done to strengthen the poor rock mass and to reduce the permeability to about 5 Lugeon. Apart from contact grouting in entire tunnel length, consolidation grouting in about 70% of length of HRT was carried out. The efficacy of grouting was ensured by following a set pattern of permeability tests. The reaches where required permeability values were not achieved were re-grouted and retested.
- The reaches where cavities were encountered during excavation, were thoroughly pre and post grouted and kept under observation both before and after lining. These reaches were provided with RCC lining irrespective of the rock class encountered during excavation.
- The vulnerable areas of Junction of HRT with construction adits were thoroughly grouted both from HRT and Adit side. Additional two rows of Curtain grouting 12 m long were provided near the junction.
- Since the HRT was passing in close vicinity of highly populated areas, it was ensured that the grouting of surrounding rock mass was thoroughly done. Prior to the start of the filling operation, reconnaissance survey was done a number of times to check and identify the vulnerable surface outcrops in these areas. These identified areas were constantly monitored during the filling operation. The natural water sources in these areas were identified, photographed and video graphed beforehand.
- Although as per the codal provisions, the rock covers (Horizontal-Vertical) along the entire HRT were sufficient, still keeping in view the geology encountered comparatively lower cover areas were grouted and no drainage holes were provided in these areas.

Keeping in view, the length of the water conductor system, probable seepage observations and filling requirements, the total time of about 20.5 days was estimated to complete the initial filling. This period included an observation period of 3 days after completion of filling. The process comprised of 23 Pressure steps to fill the system completely up to MIV level (EL. 856.4 m). However, the HRT filling was planned to be carried out in 13 pressure steps and rest were provided to fill the conductor downstream of the Surge shaft gates as a parallel activity taken up during saturation pause periods of HRT filling. Table-2 below shows the planned filling schedule for filling of Upstream Water Conductor System (HRT/Surge Shaft) only.

Table -2

Filling schedule for filling of Upstream Water Conductor System (HRT/Surge Shaft)

	Water Level		Volume per step	Cumulative volume	Filling Mode
	From	To			
	(m)	(m)	(Cum)	(Cum)	
HRT/Surge Shaft Pressure Step – 1	927.5	933.5	4768	4768	(Through Pumps)
HRT/Surge Shaft Pressure Step – 2	933.5	939.5	13250	18018	
HRT/Surge Shaft Pressure Step – 3	939.5	945.5	16120	34138	
HRT/Surge Shaft Pressure Step – 4	945.5	948.5	21733	55871	
HRT/Surge Shaft Pressure Step – 4	948.5	951.5	55608	111479	(Through INTAKE GATE)
HRT/Surge Shaft Pressure Step – 5	951.5	957.5	207692	319171	
HRT/Surge Shaft Pressure Step – 6	957.5	963.5	231895	551066	
HRT/Surge Shaft Pressure Step – 7	963.5	969.5	231706	782772	
HRT/Surge Shaft Pressure Step – 8	969.5	975.5	243718	1026490	
HRT/Surge Shaft Pressure Step – 9	975.5	981.5	248758	1275248	
HRT/Surge Shaft Pressure Step – 10	981.5	983.5	46200	1321448	
HRT/Surge Shaft Pressure Step – 10	983.5	987.5	28550	1349998	(Through Pumps)
HRT/Surge Shaft Pressure Step – 11	987.5	993.5	28437	1378435	
HRT/Surge Shaft Pressure Step – 12	993.5	999.5	30151	1408586	
HRT/Surge Shaft Pressure Step – 13	999.5	1005	37460	1446046	

3. Activities carried out before start of filling operation

The following were ensured before start of actual filling process:

Pre-fill checks

As the components after filling shall not be accessible, it was imperative that thorough inspection of all the components is carried out well before releasing water into the system. Their satisfactory completion and cleaning was ensured. Structural defects if any, noticed during various inspections were rectified under proper supervision. Entire length of all the tunnels and shafts of water conductor system of RHEP i.e. Head race tunnel, surge tunnel, spill tunnel, Surge shaft, Pressure shafts, Penstocks, Draft tube tunnels and Tail race tunnel etc. were thoroughly inspected and cleaned of all extraneous material.

Construction Defects i.e. cold joints, cracks and honey comb's etc. where ever present were spotted, properly treated and repaired. Contact and consolidation grouting in the prescribed reaches was completely ensured by the means of water permeability tests. Holes provided for grouting, were suitably plugged, ground flushed. Drifts and bore holes provided during Investigation stage were located and properly plugged. Drainage holes, where specified, were ensured as per the Construction Drawings.

All the gates i.e. Surge shaft gates, Draft tube gates and TRT gates were cleaned and ensured ready for water flow. The air vents at all the gates were checked and found clear of any obstruction. The access gate 2.5 m x 2.5 m provided in Goshai adit plug for future inspection of HRT was bolted/ locked properly and ensured for perfect sealing.

The pre-commissioning tests and inspections in the dry stage were completed in all respects and certified by the Manufacturer, Suppliers and Erector prior to filling operation. Proper functioning of all the air release valves, anti-vacuum valves and drainage valves was ensured. The drainage and dewatering pumps including spare pumps were checked and made in operational condition. The communication and control systems were checked and tested for proper operation.

Inspection of Intake Gates

It was ensured that all maintenance platforms provided in the RHEP Intake structure i.e. at El.999 m, El.1010 m and El.1017 m are clean and properly painted with anticorrosive paint. Weak members which had rusted with passage of time and after long submergence in the water were removed, replaced and repainted. Exposed parts of embedment except rust-resistant steel surfaces in the intake structure were painted as per relevant specifications. Wire ropes, electric installations, limit switches were thoroughly checked.

Location of observation points along the Water Conductor System

Before filling the Water Conductor System, the observation points were located at many places along the system such as near Spill Tunnel, near the tunnel plugs of all construction adits, in vicinity of Surge Shaft, near Valve chamber, along slopes of penstocks and near Main Inlet Valves in Power House.

In addition to above, observation points were located at existing nallahs, springs in low cover reaches. Minor leakage through the plug concrete was anticipated. Grouting equipment and material were kept handy for urgent requirements. A unique Unified Control Command Unit (U3C) was set up to avoid any grapevine communication.

Flushing of HRT

The entire water conductor system was ready for water filling except the Pressure Shaft no 3 which was further feeding the Unit No 5 and 6. The remaining part of surface penstock was planned to be completed on later date as this pressure shaft was being used for draining the seepage water from HRT after plugging of all the construction adits. Since the butterfly valve was about 40 m upstream of the open portion of the line no 3 of the Pressure Shafts, the entire water was planned to be stopped behind this valve to achieve the scheduled commissioning of the project. For the other 2 no lines of the pressure shafts, the valves were to be operated as and when required to feed the other 4 no. units ready for testing/commissioning. After various rounds of manual cleaning of

Water Conductor system and plugging of all the adits, the entire seepage of the HRT (abouts 80 Lps) was collected at the bottom of surge shaft. At the end of HRT near the Surge shaft Multi Junction, a temporary bund was created to prevent entry of any foreign material to multi junction area about 1.5 m lower in elevation than that of pressure shaft bell mouth entry. Further, a bulkhead at the open portion of the pressure shaft at EL 902 m was provided to divert the seepage water by gravity to the river through an opening of about 1 m dia. in the bulkhead and a temporary dewatering arrangement (Picture 6).

Picture 6

After completion of all activities in Multi Junction area, the entire HRT was flushed with water to ensure complete cleaning. During flushing of the HRT, Surge shaft gates/Butterfly valve no 1 & 2 were kept in closed position and 11 no. pumps installed at Spill Tunnel Portal were operated one by one. (Picture7)

Pumps installed for HRT filling at Spill tunnel portal

Start of flushing operation

View from Spill tunnel

Picture 7

The pumped water reached the temporary bund after about 4.5 to 5 hours, where the slush and gravel was checked and clean water was allowed to enter the multi junction area. When water started entering the Pressure Shaft no-3 after reaching EL 929.1 m, only one pump was kept in operation. At this stage, the collected foreign material and the temporary bund was removed through the surge shaft.

Cleaning of pressure shaft

Orifice as seen from Surge shaft Bottom

Surge Shaft viewed from orifice slab


Pressure shaft bifurcations seen from pressure shaft 3


Surge shaft bottom and rock trap seen in upstream


Butterfly valve in closed position

Picture 8

Thereafter the water started flowing out through the open part of Pressure shaft no-3. The silt contained in this water started settling in the horizontal reach of Pressure shaft no-3 near the Butterfly valve. Cleaning of the silt in this area and the perfect closure of the butterfly valve without excessive leakage was a very difficult job accomplished after a lot of trials and repeated efforts of the team (Picture 8).

4. Execution of water filling operation

4.1 Filling of TRT System

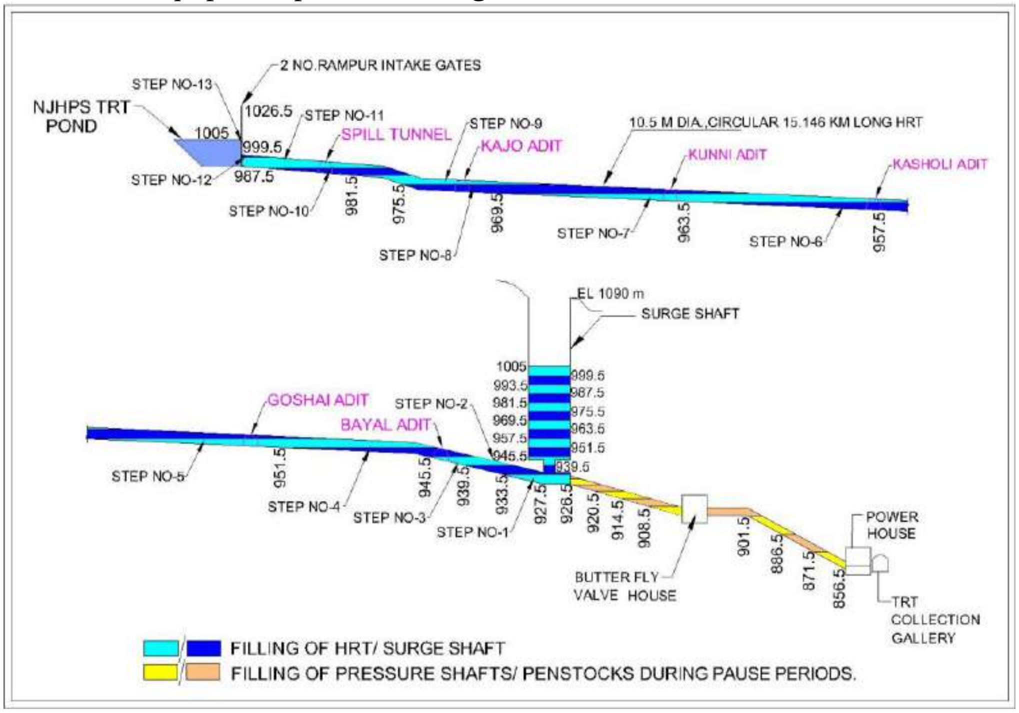
Before commencing the HRT filling, the filling of the TRT system between the Draft tube gates and the TRT Outfall gate was done. This was essential to maintain a water cushion downstream of the machines for wet spinning and to discharge the water of HRT at High Head into the water body avoiding the damage to the surrounding concrete/steel structure in case of emergency dewatering of HRT. The volume of 19023 m3 was filled in the TRT system with a head difference of 12 m. The filling of the TRT system was done in two pressure steps of 6 m each with an intermediate saturation pause of 1 day by deploying two pumps of 150 Lps capacity at the river bank near the TRT outfall. The draft tubes of units were filled up through filling valves of the draft tube gates of respective units. During this process, the water was allowed to rise above MIV into the penstock.

Table -3
Filling schedule for filling of Tail Race Tunnel

Description	Water Level		Volume per step	Cumulative volume	Filling Mode
	From	To			
	(m)	(m)	(Cum)	(Cum)	
TRT Pressure Step - 1	849.19	855.19	11192	11192	(Through Pumps)
TRT Pressure Step - 2	855.19	862	7831	19023	

4.2 Filling of Head Race Tunnel / Surge Shaft

During the 13 pressure steps of HRT filling shown in (Picture 9), an average rise of 6 m was taken followed by a suitable saturation pauses after each pressure step. The saturation pauses were given for gradual saturation of the surrounding rock mass. After complete filling of tunnel, intake gates were opened and kept in dogged position and water level was maintained at 1005 m which was monitored for 3 days. During this watch period of three days, the observation points along the Water Conductor System were closely monitored for any leakages and Slope destabilization. The pressure steps planned for filling of water conductor system down stream of surge shaft gates/butterfly valves were executed as per the requirement of machines. This involved wet testing of all the valves and other equipment provided along the lines.



Picture 9 - Schematic diagram showing pressure steps

Pressure Steps 1 to 3 -Filling from El 927.5 to 949.70 m

Keeping the surge shaft gates and all the three butterfly valves in closed the first three pressure steps were completed in four days by giving suitable pauses in between. A total rise of 22 m was achieved involving a volume of 75000 m^3. However, because of lesser unbalanced head acting on surge shaft gates, the leakages through the bottom and side seals of gates partially filled the 3 no. pressure shafts up to Butterfly Valves. Further, Gate no 1 & 2 of Rampur Intake were got inspected by the divers on the upstream side for accumulation of any foreign material. It was observed that the area upstream of Gate no 2 was comparatively cleaner than Gate no 1. Hence, Gate no 2 was operated for the filling operation.

Pressure Steps 4- Filling from El 949.7 to 951.3 m

On day 5 the filling operation was started after calibrating the gate opening w.r.t. no. of rotations required for lifting the gate. During this process the gate was lifted 10 mm and lowered down. This process was repeated with an incremental opening of 10mm till the desired 50 mm opening was achieved. Finally the gate was opened 50 mm and the water level at spill tunnel junction was observed. HRT was inspected through the spill tunnel after filling of 7 hrs up to elevation 951.3 m and No damage to invert concrete or increase in seepage near the downstream of the intake gate was observed.

Discharge of 1.23 cumecs was observed for 33033 cum volume of water filled in 7 hours which indicated the actual gate opening of about 20 mm instead of 50 mm. Therefore, the gate was recalibrated to achieve discharge corresponding to 50 mm opening.

Pressure Step No-5 to 7- Filling from El 951.3 m to 964.5 m

The pressure steps 5 to 7 were completed in 3 days with suitable intermediate pauses. Total Volume 425591 Cum. was filled resulting in a rise of 13.2 m up to elevation 964.5 m through gate no.2 with an opening of 50-60 mm. After this step of filling, the downstream side of intake gate was inspected and no signs of abrasion on the invert concrete were observed. After attaining the desired head on day 8, the initial wet spinning of unit no 1 was successfully taken up for 5 hrs .The filling process was continued during the spinning process so as to maintain the water level achieved so far.

Pressure Step No-8 Filling from El 964.5 to 967.6 m

After providing a pause of 15.5 hours, the filling was continued through gate no 2. The total volume filled during this operation was 119635 cum, with a total rise of 3.2 m up to elevation 967.6 m. Subsequently, initial wet spinning of unit no 2 was taken up till satisfactory completion for about 6.5 hrs. The rated RPM of the machine was achieved in first 2.5 hrs. The filling process was continued during the spinning process so as to maintain the water level achieved so far.

Pressure Step No-9 Filling from El 967.6 to 973.6 m

During this step the dry out spinning of unit no 1 was taken up. Before the start of dry out spinning the Intake Gate No-2 was opened 50 mm in order to maintain a constant water level during the dry out. The dry out spinning was completed to the satisfaction of the machine manufacturers in 28 hrs. Large variations in filling levels due to no load to part load operation of NJHPS were observed. With special permissions NJHPS could manage one machine generating during most of the day. During dry out test the pumps were again made operational to achieve the scheduled levels as filling operation could not be done effectively because of continuous outflow from unit no-1 of RHEP. The discharge drawn from NJHPS TRT pond was more or less same as that of released from Rampur unit. Further after the dry out test, the filling operation was continued and the final stabilized level of 973.6 m was achieved. A total rise during this pressure step was 6 m. The total volume filled during this operation was 231714 cum.

Pressure Step No-10 Filling from El 973.6 to 979.6 m

After providing a pause of 24.5 hrs the gate operation was again started and continued for about 11.5 hours. The total volume of 270800 cum was filled up to the level of 979.6 m and a total rise of 6.0 m was recorded during this step.

Pressure Step No-11 & 12 Filling from El 979.6 to 993.0 m

After a pause of 26.5 Hrs. gate no. 1 was operated for the first time with 25-30 mm gate opening. A total volume of 164972 cum was filled in two steps of 10 hours and 6 hours with an intermediate saturation pause of 24 Hrs. The water level of 993.0 m with a total rise of 13.4 m was recorded.

Pressure Step No-13 Filling from El 993.0 to 1002.3 m

After providing a pause of 18 hrs on day 16, the gate operation was again started from bay no 1. The gate operation was kept at 25-30 mm initially. At about 3 PM i.e. 5 hrs later the water level started to become constant at about 1000.6 m at spill tunnel. Now the increase in water level was very slow. As such at about 4:30 the lifting of gate no 1 (bay-1) was started initially with crack opening electrically and thereafter lifting the gate

electrically. At about 6 PM on 13.03.14 the gate no 1 was dogged at El 1026 m. During this process the water level in the pond and spill tunnel had stabilized at 1002.3 m.
The Chronology of Commissioning of Units after first filling water conductor system of RHEP is shown in Table-4. As of today both power houses (Picture 10) are operating in tandem and providing valuable power to Northern grid of the country.

Table -4
Chronology of Commissioning of Units

Sr. NO.	Unit No.	Synchronization	Commissioning of Unit
1	Unit-1	March 19, 2014	May 13, 2014
2	Unit-2	March 21, 2014	May 13, 2014
3	Unit-5	March 29, 2014	May 13, 2014
4	Unit-4	June 12, 2014	June 18, 2014
5	Unit-3	July 31, 2014	Aug. 8, 2014
6	Unit-6	Dec. 4, 2014	Dec.16,2014


Underground Power House NJHPS 1500 MW


Surface Power House RHPS 412 MW

Picture 10

5. Conclusion

Before the start of commercial generation from any hydroelectric scheme, the project passes through various stages and finally First Filling and testing. This phase i.e. first filling of the Water Conductor System is considered to be one of the most important of all the phases. During the process of initial filling, each and every underwater component and associated parts are tested for the first time under actual operational condition for which it has been designed. The response of the water conductor system and the surrounding rock mass under increasing water pressure during initial filling authenticates the design, construction & fabrication of every component on the way. In future more and more such underground passages would need to be built in Himalayan Mountains. In general, the Himalayas are young fold mountains offering very challenging sites. Apart from design and construction, the first filling of large diameter, long and voluminous water conductor systems will be a very challenging task keeping in view the geology, adjoining highways, infrastructure and habitations. Any abnormal seepage may lead to large scale erosions, danger to life and property in nearby areas. This may further lead to emptying and refilling of the system, causing risks, repair costs and huge loss of generation as well. After first filling of the water conductor system of Rampur HEP, the recorded seepages, only near plugs of underground construction adits are less than 5Lps.

This is a minute fraction of design discharge being carried through the tunnel i.e. 383.88 cumecs. At present, Rampur HPS 412 MW is successfully running in tandem with NJHPS 1500 MW and providing valuable power to the northern grid of the country. The experience gained in dealing with above mentioned issues can be utilized in other projects with similar conditions.

References:

1. Guidelines for first filling and emptying of pressure tunnels IS 12633:1984
2. Guidelines for first filling and emptying of HRT of NJHEP year 2001

Contact details of Authors:

Name of Author	Contact No.	Email id
L.M. Varma, Chief General Manager (Civil Design)	+91-9418001116	vlalit@hotmail.com
Rakesh Sehgal. Sr. Additional General Manager (Civil Design)	+91-9418071073	rakeshsag@gmail.com
Jaswant Kapoor, Sr. Manager (Civil Design)	+91-9418060858	jaswant_agrim@yahoo.com

Alternative Methods for Design of Support System for Underground Power House Caverns of JTHEP (108 MW): DPR Stage.

R.K. Vishnoi, ED (Design), T.S. Rautela, AGM (R&D), A.K. Badoni, Sr.Mgr. (R&D),
R&D Department, THDCIL, Rishikesh, Uttrakhand, India.

Abstract: The Jelam-Tamak Hydroelectric Project (JTHEP) is located in the upper reach of Dhauliganga in Chamoli district of Uttarakhand. Construction of underground power house complex of the project involves in excavation of underground caverns for Machine hall, Transformer hall and D/s Surge Tank etc. All the geological information was collected through the surface and subsurface mapping of the geological features. Apart from various geological and geotechnical parameters, in-situ stress at this location was also required to design appropriate support system for these caverns. A preliminary analysis of the stresses induced around the proposed Power house caverns shows that the stresses induced around the caverns are not exceeding the strength of the rock mass and the stability of the cavern is more structurally controlled rather than the stress controlled. Keeping in view the remote location of the project and that the machine hall & transformer hall caverns are proposed within massive rock mass with a vertical cover of about 220m, alternative methods are explored to determine the stress regime at this location rather than going for expensive in-situ stress measurement methods like Hydro-fracturing or Overcoring at the DPR stage of the project.

This paper provides an insight to the alternate techniques used to determine in-situ stresses at JTHEP power house location and assessing the support system during DPR stage of the project.

1. Introduction

The Jelam-Tamak Hydroelectric Project (JTHEP) is Run- Of- River (ROR) scheme with diurnal storage and is proposed to be developed as a 108MW (3X36MW) capacity, located in the upper reach of Dhauliganga river in Chamoli district of Uttarakhand. Dhauliganga is a largest head water tributary of Alakananda, originates from Kamet glacier. Kamet glacier lying above 6060 m is the source of this river. In the downstream, Dhauliganga river flows towards southwest. Dhauliganga confluences with Alaknanda river at Vishnuprayag on left bank (altitude 1440 m). Proposed barrage for JTHEP is located at 30^0 37’ 35.4”N latitude and 79º 49’39.5”E longitude while power house is located at 30º 36’ 45” N latitude and 79º 47’ 15” E longitude**.** The nearest rail head of the project site is Rishikesh (about 300 km away) and the nearest Airport is at Jollygrant, Dehradun. The project site is approachable from Rishikesh by National Highway-58 up to Joshimath (about 257 km) followed by Joshimath-Niti pass Border Road (57 km).

Jelem Tamak H.E. Project is proposed to tap hydropower potential of Dhauliganga between Jelam and Tamak villages. Water of Dhauliganga is proposed to be diverted by a water conductor system located on its right bank for power generation. Three units each of 36 MW (108 MW) located in underground powerhouse on the right bank of Dhauliganga have been proposed based on the feasibility study. Project involves a 28 m high and 83 m long barrage at altitude 2623.50 m, a horse shoe concrete lined head race tunnel of 4.40 km length, an underground power house and 308 m long trail race tunnel. The scheme envisages the utilization of design discharge of 57.58 m3 /sec and the drop of about 207.54 m for power generation. The annual energy generation in a 90% dependable year is 505.12 GWh.

2. Layout of Underground Power House & Description:

An underground Machine hall with dimension of 101.0m(L) X 19.5m(W) X 39.7m(H) and installed capacity of 108MW (3 units of 36MW each) is proposed in the right bank of river Dhauliganga in upstream of village Tamak. Other appurtenant structure to the machine hall are an underground 60m high surge shaft of 12m diameter, 245m steel lined pressure shaft of 4.0m diameter which trifurcates into 2.3m diameter penstocks and an underground transformer hall with dimension of 79m(L) X 13.5m(W) X 22m(H) etc.

Geological and Geotechnical parameters for analysis has been interpreted from the data recorded during 3-D Geological logging of the power house drift (Annexure I), bore hole logs and Surface Geological map of the area (Annexure II) and the field estimation of the UCS values of intact rock has been assessed with the help of Geological Hammer and Schmidt Hammer.

A 3D layout of the Power House Complex of Jelum Tamak HEP is shown in Fig-1.

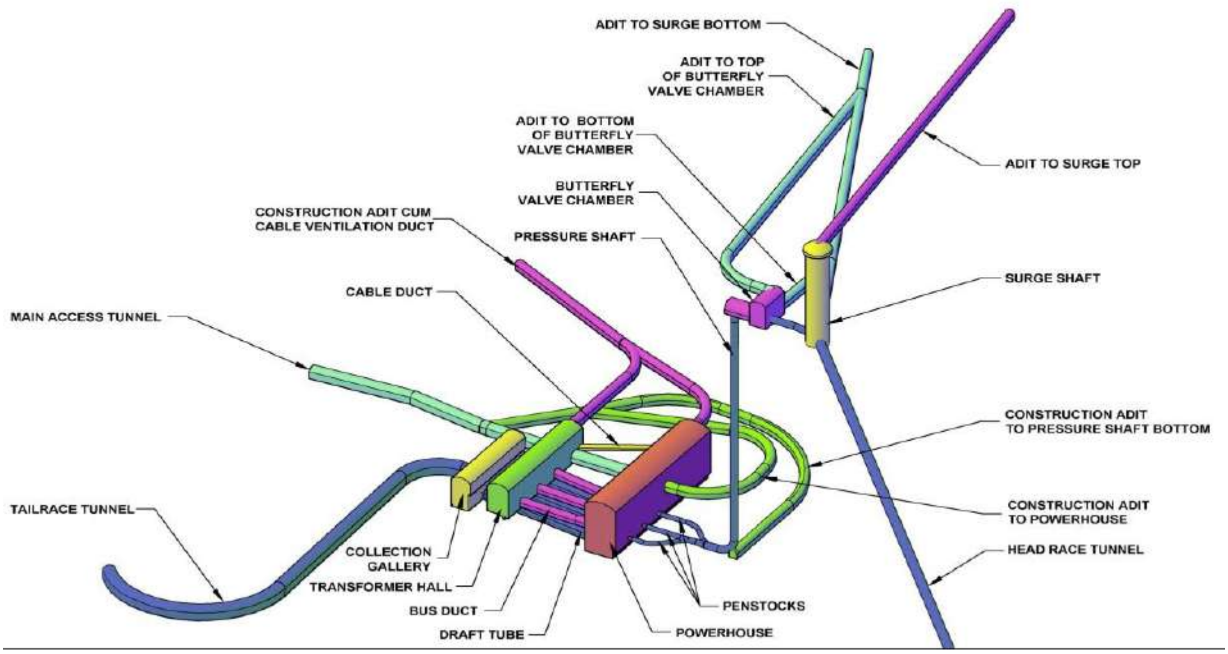


Fig 1: 3D Layout of Power House Complex of JT HEP.

3. Geological Setup at Power House Location

The power house is located on the right bank. The hill slope in the area exposes bedrock in the upstream portion whereas slopes in the downstream are covered extensively by slope wash deposits. It is observed that bedrock on both banks of the river comprises quartzite with thin bands of Schist and Gneiss. The bedrock comprising quartzite is foliated and jointed. The foliation in general, strikes in N03^{0}W-S03^{0}E and dips on an average by 39^0 towards east. The rockmass in the area is traversed by two major joint sets in addition to those parallel to foliation plane. The orientations of these major discontinuities are 64^0 / 196^0 and 76^0 /294^0 respectively.

The machine hall cavern and transformer hall cavern have been located within massive rock mass with a vertical cover of about 220m and lateral cover of bout 150m.

Surface and subsurface explorations carried out at the site includes detailed Geological mapping of power house complex area on 1:1000 scale and excavation of exploratory drift for exploring the site of underground powerhouse complex. Bedrock is exposed right from road level in the downstream part on this bank. Right bank in general is occupied by overburden between riverbed and Joshimath-Malari road. Deposition of fluvial terrace at road level is observed on right bank in the area. The right bank slope above the terrace rises moderately up to a height of about 30m and is relatively steep beyond it.

A 212m long exploratory drift at the proposed Power house location was excavated towards 345° with a cross cut at end. The drift encountered quartzite with occasional thin bands of Schist and Gneiss. The bedrock encountered is moderately jointed and traversed by three prominent joint sets of which the joints oriented parallel to foliation (S1) are more prominent having strike across the valley and dipping towards upstream. The strike of the joints belonging to this joint set (S1) is 178°-358° dipping at 20^0 to 65° towards 80°-120° direction, i.e. upstream. The joints belonging to this set are moderately spaced. The joints have undulating and rough surfaces in general. The joints belonging to set S2 strike across the river flow and dip steeply towards downstream. These are spaced at 20cm to 50cm. Joint's surfaces are rough and undulating in nature. It is also observed that the joints are tight and partly open all along the length of the drift with occasional infilling of rock flour. The joints belonging to set S3, strike askew to the river flow and dip steeply towards right abutment. These are spaced between at 20cm to 50cm. Joint surface is rough and undulating in nature. It is also observed that the joints are tight and partly open all along the length of the drift with occasional infilling of rock flour.

4. Objective:

Present study is intended to explore the alternative techniques to determine in-situ stresses and to assess Support system for underground Power house caverns of JTHEP proposed on the basis of well defined geology and similar in-situ stress data available in the nearby Hydro Power Projects in Himalayan region and thus avoiding expensive & cumbersome in-situ tests to determine the stress regime like Hydro fracture test, Over coring test at DPR stage of the Project.

5. Design Approach:

The Machine hall cavern is proposed to be oriented with its axis along N256 which is approximately parallel to the river course in this reach. As per the DPR, the rock cover over the MH Cavern is about 220 m leading to a vertical stress of about 5.94 MPa. A preliminary analysis of the stresses induced around the proposed Power house caverns shows that the stresses induced around the caverns are not exceeding the strength of the rock and therefore the in-situ measurement of stresses may not be required. Thus the stability of the cavern shall be structurally controlled rather than the stress controlled. Keeping in view the above following approach is adopted for the design of appropriate support system for the MH Cavern:

- Determination of Input parameter based on the geological investigations,
- Estimation of appropriate Stress regime,
- 3D stress analysis without support to compute the maximum possible deformations.

- 2D stress analysis & parametric study of Caverns w.r.t. to different stress scenario.
- Kinematic analysis for stability of wedges in the Machine hall Cavern,
- Based on the results of analyses finalization of Support system of Caverns.

6. Input Parameters:

a) Dominating Structural Discontinuities:

Based on the 3D-geological log of the exploratory drift, the structural discontinuities along with the physical properties are tabulated below:

Sl.No	Discontinuity	Dip Amount	Dip Direction	Remarks
1	Foliation joint, FJ/J1	35^{o} - 40^{o}	075^{o} - 090^{o}	-
2	Cross Joint, J2	70^{o} - 75^{o}	280^{o} - 300^{o}	Not Distinct as the rockmass is massive
3	Joint plane, J3	65^{o} - 70^{o}	180^{o} - 200^{o}	Low Persistence

Joint	Spacing (mm)	Aperture (mm)	Filling	Persistence (m)	Weathering *(ISRM, 1981)*	Water
FJ/J1	200-1000	1-2	Nil	1-5	W1-W2 (Fresh to Slightly Weathered	Dry
J2	200-1000	1-3	Nil-Clay	1-5		
J3	300-1000	1-3	Nil-Clay	1-5		

b) Geo-Physical & Geo-Mechanical Properties

The Geological and Geotechnical parameters have been inferred from the data recorded during 3-D geological logging of the power house drift, bore hole logs and surface geological map of the area available in respective volumes of DPR and further efforts were also made to collect UCS data from the field. It is an intact rock property from which the UCS for rock mass can be derived. It is generally either from tests carried out on intact core pieces in the laboratory or field estimates with the help of Schmidt Hammer &rebound hammer. In this case field estimate using Schmidt Hammer & rebound hammer has been adopted.

3-D Geological log of the Powerhouse drift (upto Ch.212m) was referred and according to the log the rock mass condition is good and the strength of the rock is strong for the whole stretch except weaker zones from Ch 8-11m and 15-19m. Based on the exposed rock near the drift portal area and 3-D Geological log of Powerhouse drift and with a conservative approach, value of **UCS as 90Mpa** is found to be appropriate for the present analysis.

The Geological Strength Index (GSI) is also an important input parameter. GSI can be obtained by using the published GSI chart directly or alternatively by calculating from Rock Mass Rating (RMR). The Rock Mass Rating (RMR) and Q-value calculated on the basis of joint characteristics during detailed logging of the drift. The average value of RMR is 67 and calculated value of **GSI is 62**.

The inputs for deriving rock mass properties are presented in Table no.1 along with the respective references.

Table: 1 Intact rock and rock mass properties			
Property	Unit	value	Reference
UCS(unconfined Compressive strength)	MPa	90	From the DPR – 3-D Geological log of the Powerhouse drift(upto Ch.212m)
GSI(Geological Strength Index)		62	Estimatedfrom3-DGeological log of the power House drift
Modulus ratio (MR)		375	Estimated form Rocscience programme RocLab
E_i (Elastic Modulus)	GPa	33.75	Calculated from Rocscience software RocLab for MR=375
Bulk density	MN/m^3	0.027	
Rock Cover Depth	Meter	220	JTHEP DPR
E_{rm}(Deformation Modulus)	GPa	10.23	Calculated with Rocscience software RocLab.
Cohesion (C)	MPa	1.6	Calculated with Rocscience software RocLab.
Friction Angle (ϕ)	Deg	52	Calculated with Rocscience software RocLab.
Global rock mass compressive strength (Sigcm)	Mpa	22.13	Calculated with Rocscience software RocLab.
D(Disturbance factor)	-	0.5	Assumed
mi(Quartzite)	-	20	Estimated with Rocscience software RocLab

c) Critical Strain for the Rockmass:

Critical strain for the rockmass using relation Er = σci *100/(Ei^0.63 * Etj^0.37) comes out to be 0.41% and using relation Er = 31.1 * σci^1.6/(Ei* Y^0.6 *Q^0.2) comes out to be 0.50%.

7. Estimation of Appropriate Stress Regime:

As per the DPR, the rock cover over the MH Cavern is about 220 m leading to a vertical stress of about 5.94 MPa. Based on a preliminary analysis, induced stresses around the proposed Power house caverns are around ±10.5 MPa and are not exceeding the Global rock mass compressive strength (Sigcm) value 22.13 MPa of the rockmass (Refer Table 1) and therefore the in-situ measurement of stresses may not be a necessary requirement.

Kumar et al[19] have provided details of stress measurements for hydro projects in the Himalayas. These tests were mostly done by hydro fracturing with some of the testing by overcoring. The results were in agreement with structural geological interpretations and can be roughly summarized as follows:

- Horizontal stress may be two to three times the vertical stress
- The average direction of maximum horizontal Tectonic stress in Himalayas is in the north eastern quadrant (normal to MCT).
- The minimum horizontal stress is often consistent with the vertical stress.

- The maximum Vertical stress is assumed to be equal to the weight of overlying strata and the horizontal stress is assumed to be multiplication of vertical stress and in-situ stress ratio.

The world stress map (WSM) is the Global repository for contemporary tectonic stress data from the earth's crust. The WSM is an open access database and can be accessed on the web. Fig 2 shows the stress map for the Himalayas as obtained from the WSM project. The stress map displays the maximum horizontal compressional stress S_H and it shows an orientation of maximum horizontal compressional stress roughly along N 60° - S240° (with a variance of ±20°) around the project area which is approximately along the major Caverns axis.

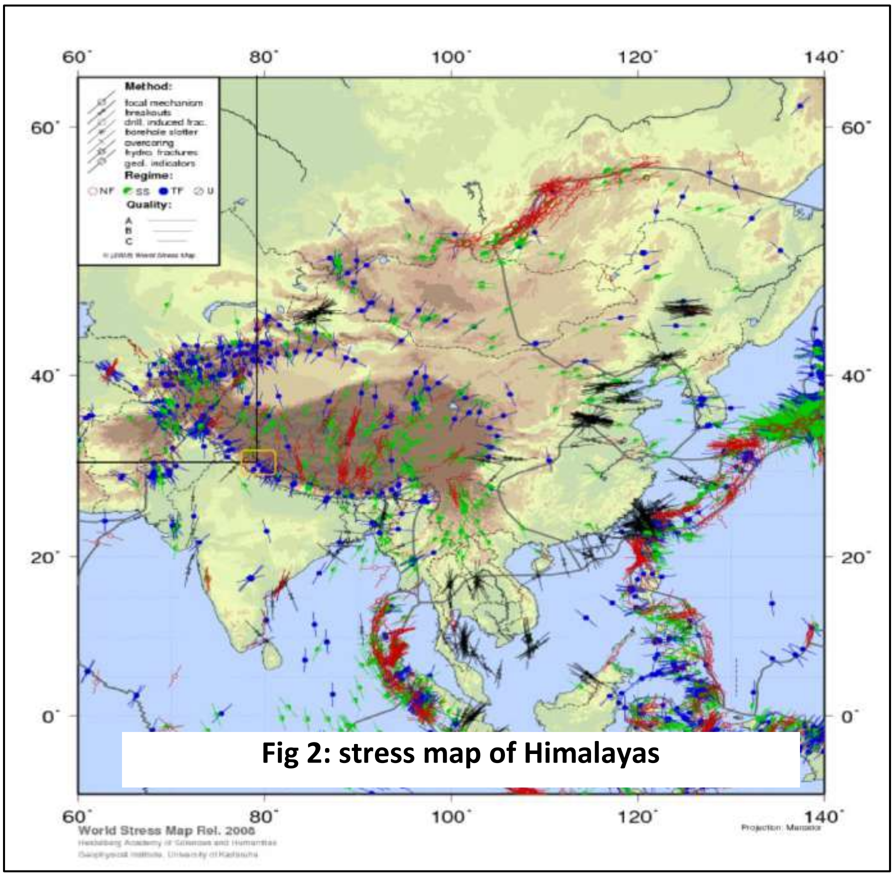


Fig 2: stress map of Himalayas

The values of in-situ stress ratio considered in the FEM analysis for different projects in similar tectonic setup as for JTHEP are as given in the Table 2.

Table 2: Stress ratio in different projects in similar tectonic setup of JTHEP

Project	Vertical Stress MPa	Ratio of Maximum Horizontal Stress to Vertical stress K H	Ratio of Minimum Horizontal Stress to Vertical stress K h
Tapovan vishnugad HEP	4.20	1.00	0.72
Lata tapovan HEP	5.48	1.20	0.79
Vishnugad Pipalkoti HEP	9.65	1.55	0.62
Tehri HPP	10	0.5	0.3
Tehri PSP	12.2	1.2	0.9

A more useful basis for estimating horizontal in situ stresses was proposed by Sheorey (1994). He developed an elasto-static thermal stress model of the earth. This model considers curvature of the crust and variations of elastic constants, density and thermal expansion coefficients through the crust and mantle. A plot of the ratio of horizontal to vertical stress predicted by Sheorey's analysis, for a range of horizontal rock mass deformation moduli, is given in Figure 3.

From the Fig-3, ratio of horizontal to vertical stress (k) at MH cavern location of JTHEP can be calculated as 1.56 for E=33.75 GPa and Rock cover of 220 m which is quite close to that for the d/s projects e.g. Vishnugad Pipalkoti HEP, Lata Tapon HEP.

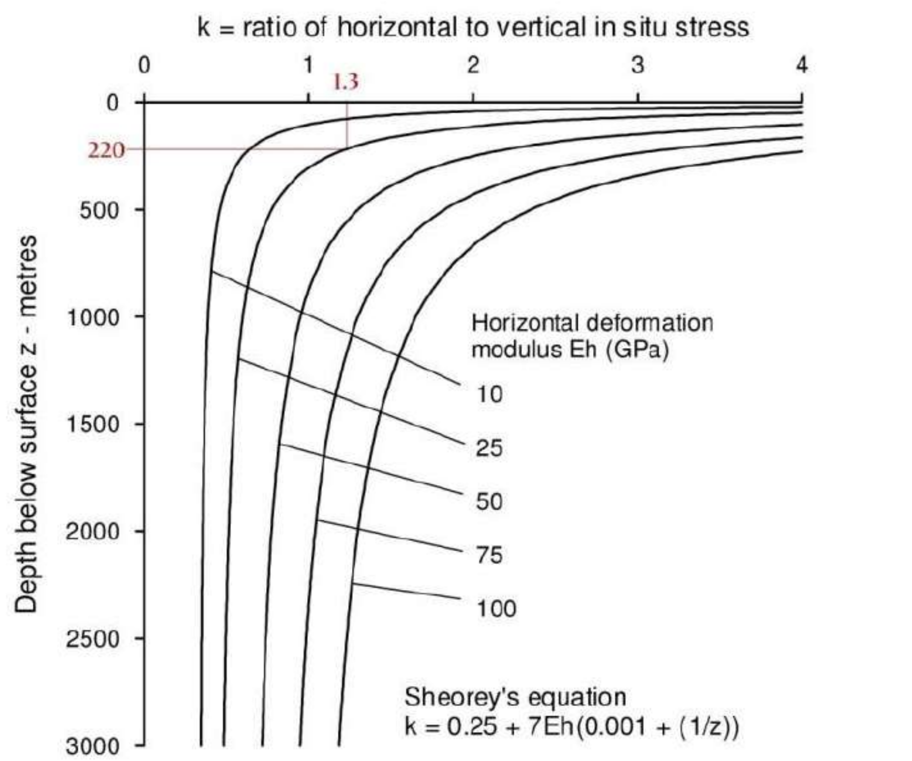


Fig-3: Ratio of horizontal to vertical in situ stress versus depth below surface. (Sheorey 1994)

Keeping in view the above, a parametric study, considering various values of horizontal to vertical stress ratio i.e. 2.5:1, 2:1, 1.5:1 and 1:1 has been attempted in 2D plain strain analysis to ascertain the adequacy of support system for PH caverns of JTHEP. The vertical and horizontal stresses have been calculated as:

Vertical stress $\sigma_v = \gamma * Z$; $\sigma_H = K_H * \sigma_v$ and $\sigma_h = K_h * \sigma_v$.

In all the cases (Case 1 to 4) direction of major horizontal principal stress (**σ_H**) has been considered N256/N76 i.e. parallel to the **axis** of MH Cavern except one more adverse case (Case-5) with stress ratio of 1:1.5 and major principal stress considered perpendicular to the caverns axis.

8. 3D Stress analysis by Boundary Element Method without Support:

3D stress analysis of Power house complex of Jelam Tamak HEP has been carried out by Rocscience programme Examine3D which is based on Boundary Element Method. The Examine3D model of the PH complex is shown in Fig-4. Stress analysis has been carried out considering the rock mass properties stipulated in Table 1 and stress ratio for major principal stress i.e. K_H as 1.5:1 has been considered in the analysis with major principal stress aligned with cavern axis. Ratio of Intermediate stress and vertical stress i.e. K_h has been taken as 1:1.

Total displacement contour computed by the programme is shown in Fig-5. As per the computed results maximum displacement is about 20 mm and the same is observed near junction of bus ducts and the walls of Machine Hall cavern.

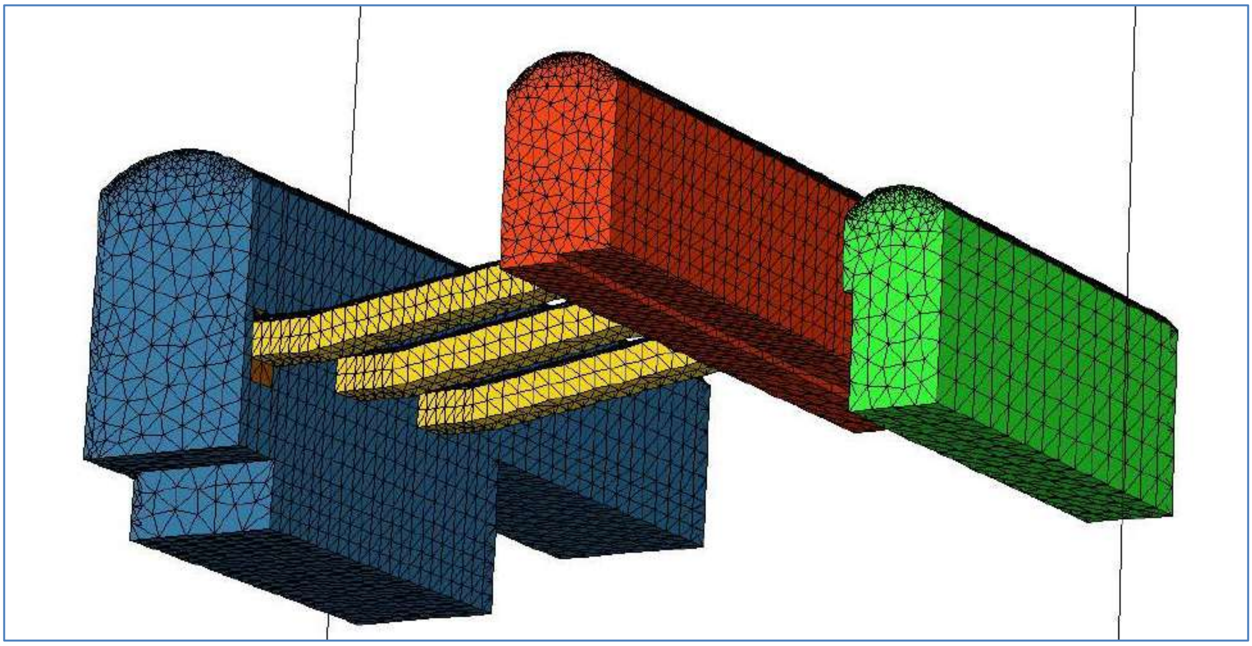


Fig 4: 3D Stress Model of PH complex by Examine3D

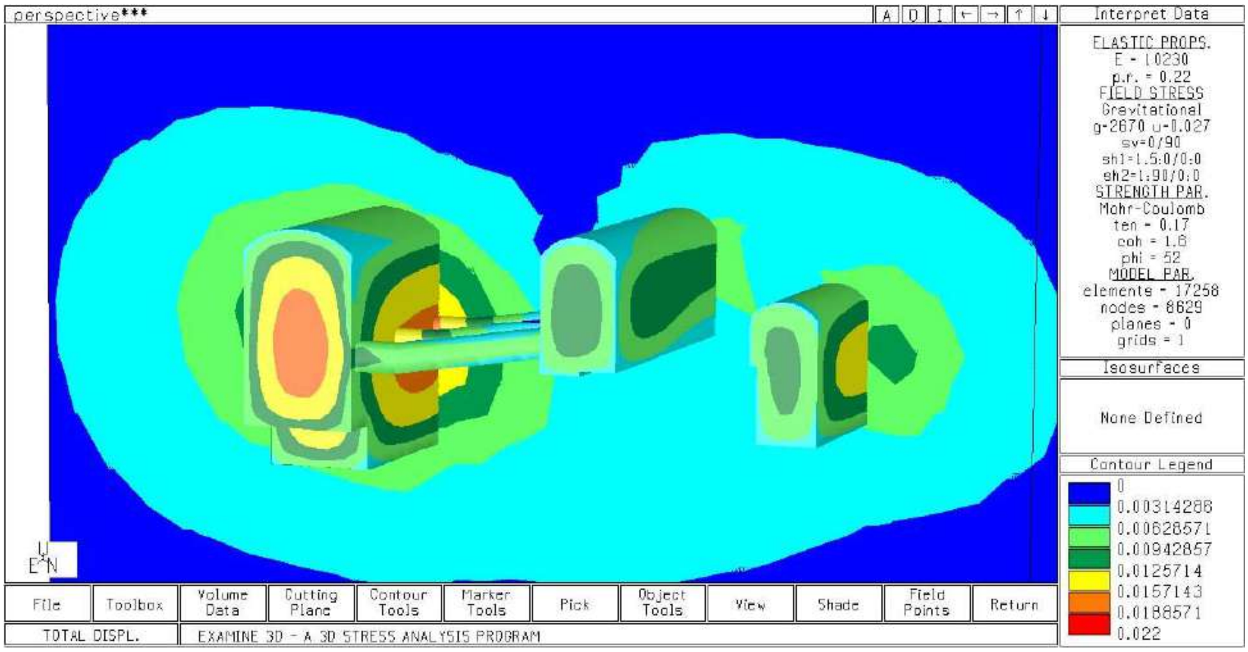


Fig 5: Total Displacement Contours in PH Complex computed by Examine3D

9. 2D stress analysis & parametric study:

2D plain strain analyses of the machine hall & transformer hall caverns of JTHEP have been carried out in-house by finite element method using Rocscience programme Phase2 v7.0 available with THDCIL. The parametric study for the various values of stress ratio has been done to envisage the worst possible scenario of stress regime.

a) Geometry and Support System for the Power House Complex

In the DPR stage,the dimensions of Machine hall was kept as 101m (L) X 19.5m(W) X 39.7m(H) and the dimensions of transformer hall was kept as 79m(L) X 13.5m(W) X 22m(H). The rock pillar width between machine hall and transformer hall was kept as 40m.

In the DPR drawings, support system for these cavities was described as below:

Machine Hall:

Rockbolts: 25mmdia, 8m long @ 1.5m c/c (crown) and 2.5m c/c(wall).

SFRS: 100-150mm thick.

Transformer Hall:

Rockbolts: 25mm dia, 8m long @ 1.5m c/c(crown)and 2.5m c/c(wall).

SFRS: 100-150mm thick.

Properties of Rock bolts with attached face plates:

Bolt modulus (E) =200000 MPa, out –of-plane spacing of bolts=1.5m, L=Shear strength of grout=1MPa, Bond length=30%, for resin grout G=1.0 GPa(Farmer 1975)

Bond Shear stiffness;K_{Bond}=2*pi()*G/(10*ln(1+2t/d))

Bond Strength;S_{Bond}=pi()*D*L

Where, t=annulus thickness,d=Bolt diameter & D=Bore hole diameter.

25mm dia bolt (Bore hole dia=38 mm): Tensile capacity=0.19 MN, K_{Bond}= 1500 MN/m/m & S_{Bond}=0.12 MN/m.

The tensile capacity of the rock bolts has been considered as 0.19MN.

Properties of Shotcrete Liner:

100-150mm thick SFRS layer has been adopted for machine hall and transformer hall cavern.

b) 2D Numerical Model of the Machine hall & Transformer Hall

2D stress analysis for various components of the power house complex e.g. Machine hall, Transformer hall has been done using Rocscience software Phase2 v7.0.In the analysis, phase wise excavation of these components has been simulated. The Phase2 model of the machine hall has been shown below in Fig- 6. The maximum rock cover over machine hall at this location is 220m and no structural discontinuities and shear zones have been modeled in the analysis of machine hall cavern.

Excavation of machine hall has been simulated by total 13 stages comprising of first equilibrium stage (without excavation) followed by 12 main excavation stages and two sub-stages (core softening method to simulate the effect of 3D excavation of each stage) corresponding to each main excavation stage and after first stage all the displacement in the model have been set to zero to bring the model into a equilibrium stage.

Among the various options of rock bolt type in Phase2 v7.0 “tie back” type rock bolt has been opted in the analysis. At the rock bolt installation sub stage of any excavation stage, it is assumed that only 30%length of the rock bolt is grouted and in the next sub stage balance 70% length of the rock bolt is grouted.

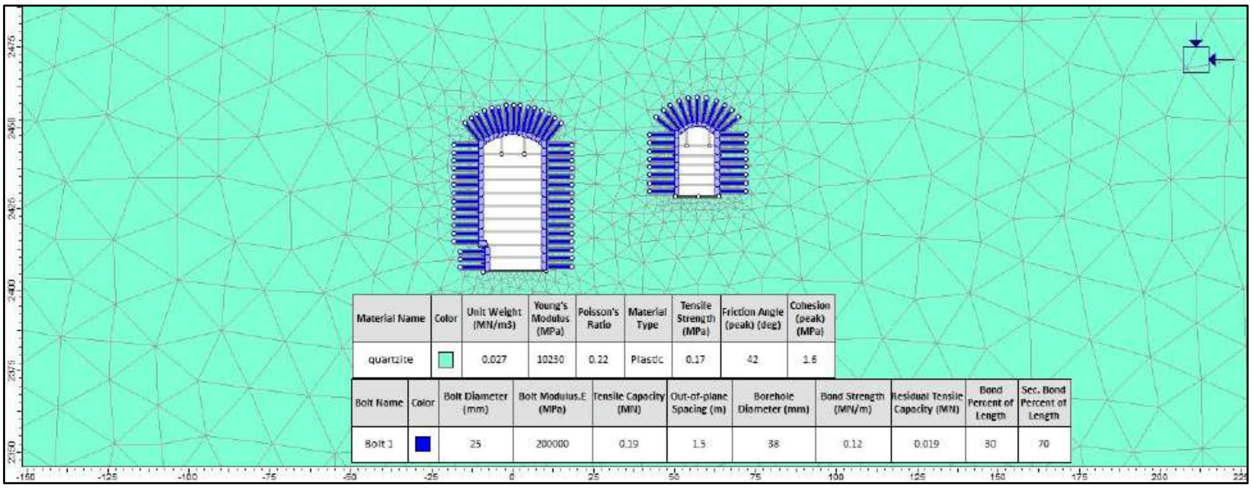


Fig 6: Phase Model JTHEP MH for Quartzite ground (core softening model)

c) Excavation of Power House Complex with support:

Parametric study of the machine hall & Transformer Hall caverns of JTHEP has also been done using different stress ratios as given below in Table-3 and input parameters discussed in preceding sections. The ratio of minor horizontal stress to vertical stress (Kh) in all cases has been kept as 1 to be little bit in conservative side.

Table-3: Stress Ratio Considered in the 2D Stress Analysis

K_H	K_h	Vertical displacement (mm)	Horizontal displacement (mm)	Max Strain %
2.5	1	-9 (crown) & 16 (Floor)	28 (U/s) & 26 (D/s) walls	0.26
2	1	-8 (crown) & 14 (Floor)	26 (U/s) & 24 (D/s) walls	0.24
1.5	1	-8 (crown) & 14 (Floor)	25 (U/s) & 23 (D/s) walls	0.23
1	1	-8 (crown) & 13 (Floor)	25 (U/s) & 23 (D/s) walls	0.23
1	1.5	-8 (crown) & 15 (Floor)	40 (U/s) & 36 (D/s) walls	0.37

d) Analyses Results:

Case 1: K_H=2.5 & K_h=1 (Cavern Axis aligned with σ_H):

As per the analysis results, total displacements of 9 & 16 mm are observed at the crown & floor of MH and total displacements of 28 mm & 26 mm are observed on the u/s wall & d/s wall of the cavern, thus leading to a maximum strain of 0.26% which is well within the critical strain of 0.5% for the surrounding rock mass. Maximum axial force of 0.18 MN observed in the rock bolt is also within the Yield strength 0.19 MN assigned to the rock bolts.

Strength factor for the pillar between Machine hall and Transformer hall cavities is also >1. Major induced stress around the cavern is 8.94 MN.

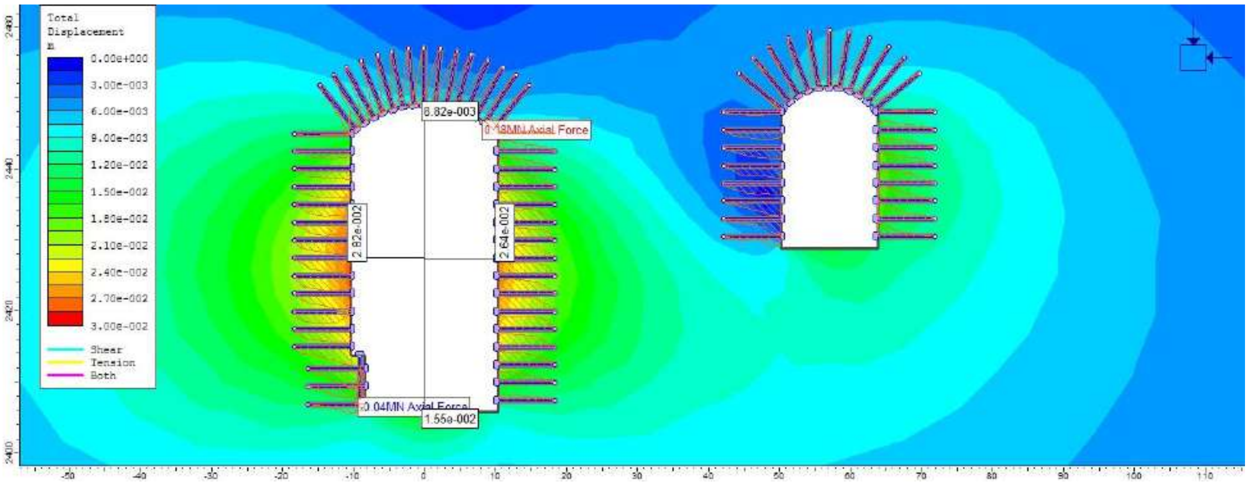


Fig 7: Total Displacement Contour for K_H=2.5:1

Case 2: KH=2 & Kh=1 (Cavern Axis aligned with σ_H):

As per the analysis results, total displacements of 8 & 14 mm are observed at the crown & floor of MH and total displacements of 26 mm & 24 mm are observed on the u/s wall & d/s wall of the cavern, thus leading to a maximum strain of 0.24% which is well within the critical strain of 0.5% for the surrounding rock mass. Maximum axial force of 0.16 MN observed in the rock bolt is also within the Yield strength 0.19 MN assigned to the rock bolts. Strength factor for the pillar between Machine hall and Transformer hall cavities is also >1

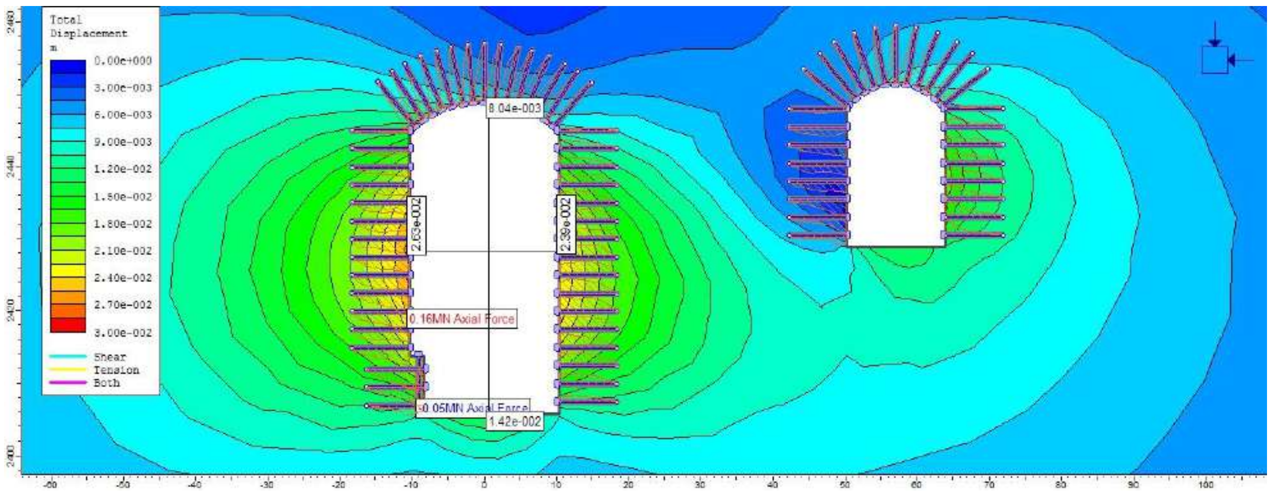


Fig 8: Total Displacement Contour for K_H=2:1

Case 3: KH=1.5 & Kh=1(Cavern Axis aligned with σ_H):

As per the analysis results, total displacements of 8 & 14 mm are observed at the crown & floor of MH and total displacements of 25 mm & 23 mm are observed on the u/s wall & d/s wall of the cavern, thus leading to a maximum strain of 0.23% which is well within the critical strain of 0.5% for the surrounding rock mass.

Maximum axial force of 0.15 MN observed in the rock bolt is also within the Yield strength 0.19 MN assigned to the rock bolts. Strength factor for the pillar between Machine hall and Transformer hall cavities is also >1.

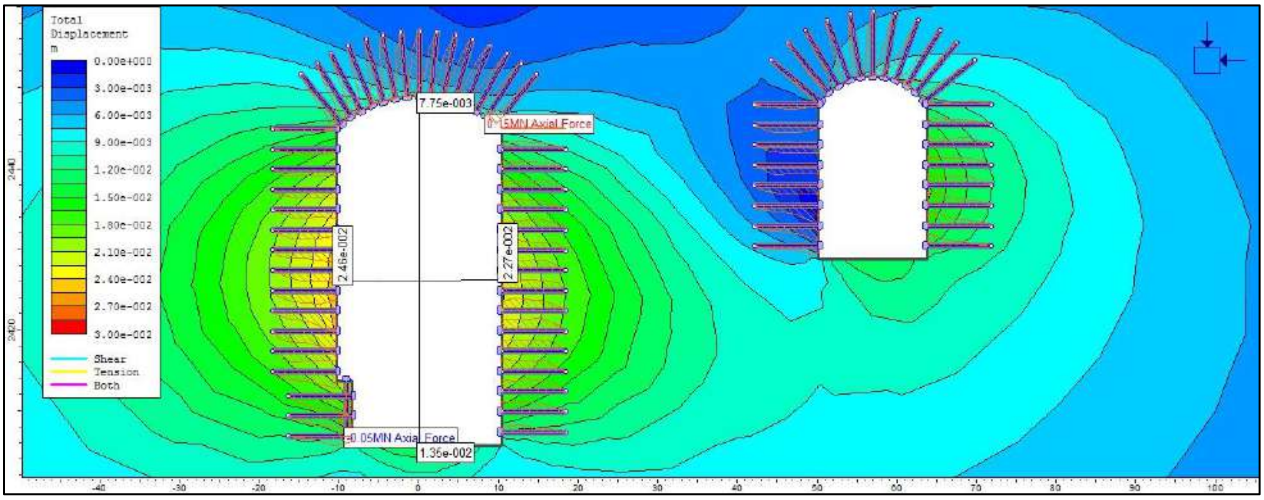


Fig 9: Total Displacement Contour for K_H=1.5:1

Case 4: KH=1 & Kh=1(Cavern Axis aligned with σ_H):

As per the analysis results, total displacements of 8 & 13 mm are observed at the crown & floor of MH and total displacements of 25 mm & 23 mm are observed on the u/s wall & d/s wall of the cavern, thus leading to a maximum strain of 0.23% which is well within the critical strain of 0.5% for the surrounding rock mass. Maximum axial force of 0.15 MN observed in the rock bolt is also within the Yield strength 0.19 MN assigned to the rock bolts. Strength factor for the pillar between Machine hall and Transformer hall cavities is also >1.

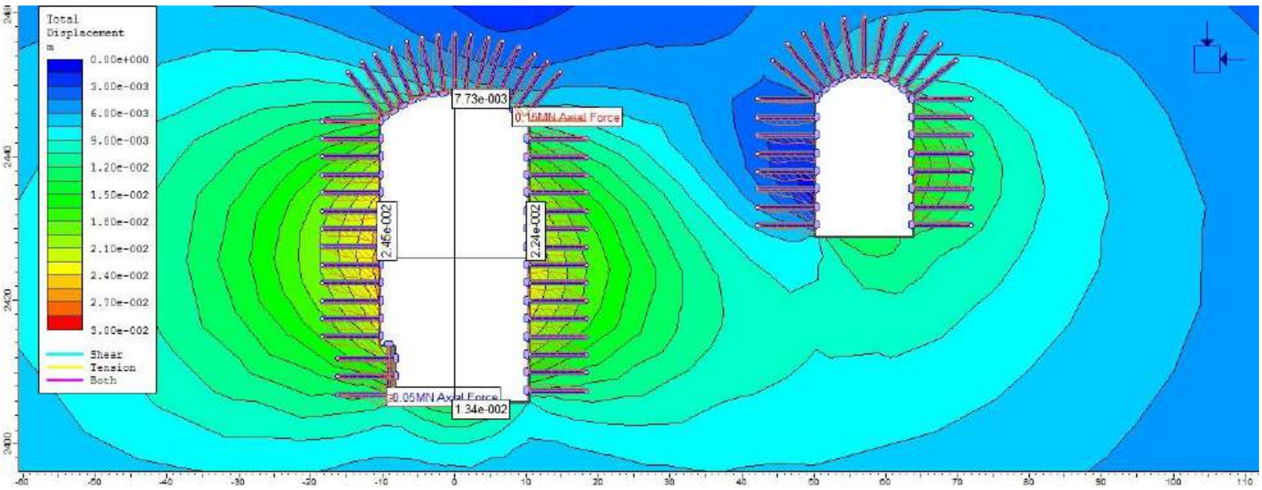


Fig 10: Total Displacement Contour for K_H=1:1

Case 5: KH=1 & Kh=1.5 (Cavern Axis perpendicular with σ_H):

As per the analysis results Vertical displacement of 8 mm & 15 mm are observed at the crown & floor of MH, maximum total displacement of 40 mm and 36 mm are observed on the u/s wall & d/s wall of MH cavern.

This leads to a maximum strain of 0.37% which is well within the critical strain of 0.5% for the surrounding rock mass. Maximum axial force of 0.19 MN observed in the rock bolt is also within the Yield strength 0.19 MN assigned to the rock bolts. Major induced stress around the cavern as computed by the programme is 9.8 MN.

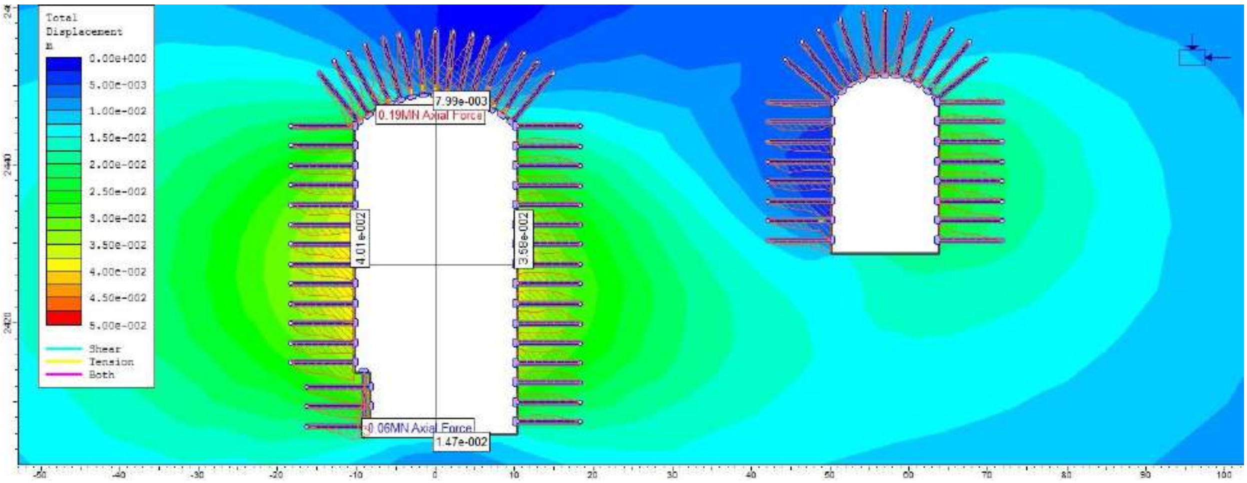


Fig 11: Total Displacement Contour for K_H=1:1.5 (σ_H perpendicular to Cavern axis)

10. Kinematic analysis for the MH Cavern

From the 2D plain strain analysis it is evident that maximum displacements are likely to be on the u/s and d/s walls of Machine Hall cavern. Maximum strain observed is well within the critical strain 0.5% of the surrounding rock mass and hence the possibility of stress induced failure is very remote.

In order to check the structurally controlled failure and adequacy of support system given in DPR for machine hall cavern, a kinematic analysis of MH cavern has been performed using rocscience programme Unwedge v3.0. Based on the exploratory drill holes and 3D logs of the exploratory drifts 03 sets of prominent structural discontinuities are traversing through the rockmass and the details of these discontinuities are given above under para 6 (a). In the kinematic analysis, following parameters have been considered for the 03 prominent joint sets:

Sl.No	Discontinuity	Dip Amount	Dip Direction	Friction	Cohesion (t/sqm)
1	Foliation joint, FJ/J1	39^o	90^o	35	5
2	Cross Joint, J2	76^o	294^o	35	5
3	Joint plane, J3	64^o	196^o	35	5

Sterionet plot of the above joint sets, the maximum size wedges that can be formed with the given geometry of the machine hall cavern and the support system to stabilize the wedges are shown below in Fig 12.

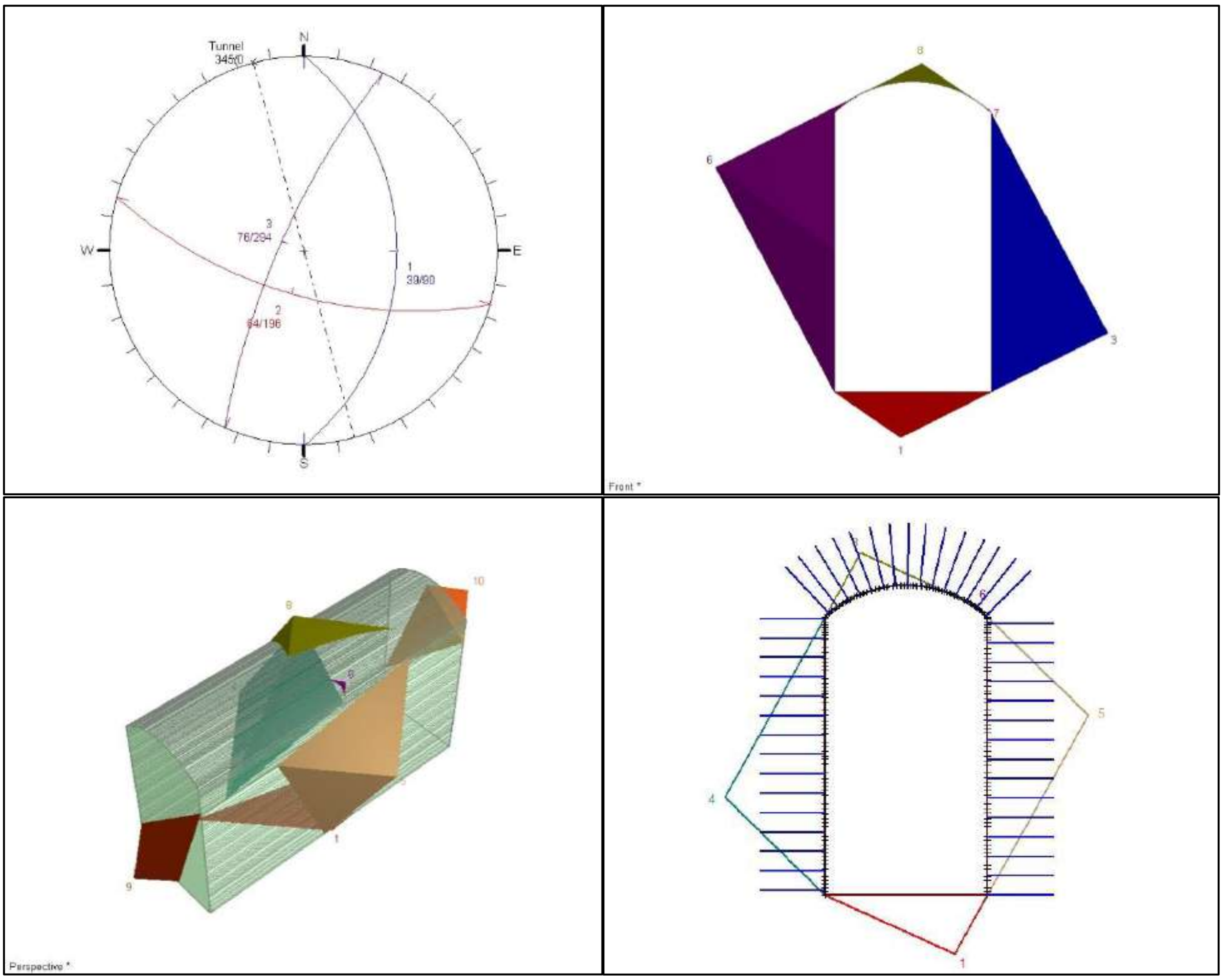


Fig 12: Sterionet Plot and Details of Maximum Size Wedges in Machine Hall

a. Pre-Support Results:

It can be seen that the unsupported wedge (8) on the roof has factor of safety =0 and is likely to fall under gravity.

Following is the details of the wedges formed around the periphery of the MH Cavern. :

- Floor wedge [1]: FS: stable, Weight: 1402.606 tonnes
- Lower Left wedge [4]: FS: 1.224, Weight: 5566.976 tonnes
- Upper Right wedge [5] FS: 1.162, Weight: 5543.270 tonnes
- Roof wedge [6]: FS: 3.793, Weight: 0.362 tonnes
- Roof wedge [8]: FS: 0.000, Weight: 312.484 tonnes

b. Post Support Results:

The Unwedge analysis has again been performed with the support system and the factor of safety of different supported wedges are given below:

Floor wedge [1]: FS: stable, Weight: 13.766 MN

Lower Left wedge [4]: FS: 1.797, Weight: 54.639 MN

Upper Right wedge [5]: FS: 1.459, Weight: 54.406 MN

Roof wedge [6]: FS: 3.858, Weight: 0.004 MN

Roof wedge [8]: FS: 2.024, Weight: 3.067 MN

11. CONCLUSION

Based on parametric study (for different in-situ stress ratios) carried out with the help of Rocscience software Phase2 v7.0 (2D plain strain analysis; FEM), 3D stress analysis carried out using Rocscience software Examine 3D & Kinematic analysis carried out using Rocscicene software Unwedge 3.0, following computation results are drawn:

- Even for the worst conditions of In-situ stresses i.e **k_H=1.5 (**perpendicular to cavern axis) **& k_h=1,** the maximum convergence in the MH cavern is 0.37% which is less than 0.5% (critical Strain for the surrounding rock mass)**.**
- 3D Boundary Element Analysis also reveal max total displacement of 20 mm (for maximum stress ratio K_H =1.5) with cavern axis parallel to σ_H.
- Maximum induced stress around the cavern i.e. approx. 10.5 MPa is less than the strength (22 MPa) of the surrounding rock mass as computed with Roclab programe.
- The proposed length of the rockbolts extends beyond the yielded zone around the caverns.
- The maximum axial tension on any of the rockbolts of the crown and wall do not exceed its yield strength capacity i.e. 19 tonnes, hence safe.
- The kinematic analysis reveals that the unstable roof wedge is having factor of safety greater than 1.5 with the proposed support system.

In view of the above parametric study, it may be concluded:

1. The rock support system proposed for machine hall & transformer hall caverns of JTHEP and as discussed above under para 9 (a) are adequate at DPR stage of the project.

2. In remotely located projects, for underground caverns in competent rock a parameteric study as discussed above may be considered adequate rather than directly carrying out expensive & cumbersome in-situ stress measurements at DPR stage of project.

3. During execution and detailed design stage of a project more subsurface data is likely to be available and any suitable descrete element analyses (DEM) may also be carried out to further optimize the support system for underground caverns.

Innovations Implemented in 720MW Mangdechhu Hydro-Electric Project, Bhutan

A.K. Mishra

Mangdechhu Hydroelectric Project Authority, Bhutan
(e.mail: md.mhpa@gmail.com, Contact no: +97517111501)

ABSTRACT: The under construction 720 MW Mangdechhu Hydro-Electric Project (MHEP) is scheduled for commissioning by June 2018. The project is being completed within the given schedule as per Detailed Project Report (DPR) in 84 months and at an approved cost of Rs. 4672.38 Cr, with construction cost of Rs 6.5 Cr. per Mega Watt. While almost all the hydroelectric projects in Indian sub continent are facing cost and time overruns, MHEP is scheduled for commissioning in approved cost and time, which is being achieved by following an innovative project management and advance construction methodology, comprising of adopting a transparent biding document with minimum ambiguity, project monitoring from a common platform, timely and correct technical decisions making and maintaining adequate cash flow to the contractor for maintaining smooth and steady progress and proper documentation.

INTRODUCTION:

The 720 MW Mangdechhu Hydro-Electric Project (MHEP) is under construction on Mangdechhu River in Trongsa district of central Bhutan. With 94% of the works being completed the project is scheduled for commissioning by June 2018 at a cost of Rs. 4672.38 Cr. With economic cost of construction (Rs. 6.5 Cr per Mega Watt) and timely completion within schedule of six years, the project is being looked upon as a model hydro electric project in entire SAARC Region. For ensuring timely commissioning of the project within the approved cost numerous efforts and innovative approach was adopted by the Management, write from selecting the biding document, project management, decision making process, construction of the project components and documentation. Various efforts of the innovative and continuously evolving approach implemented by the Management of the project are briefly discussed below.

TENDERING:

Mangdechhu Hydroelectric Project Authority (MHPA) adopted Standard Bidding Document (SBD) for contracting purpose. SBD incorporates Risk Matrix i.e. sharing of time & cost impacts between Employer/Owner and Contractor. This has brought the clarity on contractual aspects resulting in minimization of the claims of the contractor. Insurance policies are obtained in Bhutan which helped in speedier settlement of insurance claims. Adjudication/arbitration jurisdiction has been kept within Bhutan. In case of idling of equipment/manpower due to forced majeure/adverse geological conditions, the payment mechanism incorporated in the contract minimized the disputes/claims.

INFRASTRUCTURE DEVELOPMENT AND INDUCTION OF KEY CONSTRUCTION EQUIPMENT:

All access roads leading to the major components of the project were constructed by MHPA before the award of the major works. Construction power was provided at the door step of the major components of the project by installing DG sets (7.5 MW capacities for the entire project). In addition to this, a sub-station was commissioned independently by MHPA at Yurmu and the construction power was tapped from the grid power. As a record, construction power did not go off even for a blink of eye. New key construction equipment were purchased by MHPA in advance and were handed over to the contractors instead of giving the equipment advances. The cost of the equipment was recovered from the monthly running bills of contractors. All these efforts helped in expediting the Physical Progress from the very first day. A state of art quality testing laboratory was established at project site, for assuring the quality of the end product.

PROCUREMENT AND PROJECT MONITORING:

All procurements at the project level are through e-purchasing. SAP software was installed right in the beginning, which helped the project in monitoring the procurement processes on daily basis. Progress monitoring software (Primavera version 7) was made mandatory for the contractors and also installed at MHPA to monitor the physical and financial progress through a common platform.

IMPORTANT TECHNICAL DECISIONS:

Major technical decisions were taken by the MHPA in time which captured the construction schedule of the project and also reduced financial deviations. The important technical decisions/ change in design and/or construction methodology of the project components include replacement of permeation grouting by cut-off wall along upstream coffer dam to prevent seepage into the main dam foundation pit, providing additional construction adits to expedite the excavation of underground structures, shifting the location of the surge shaft and adopting the modified excavation methodology, modification in excavation methodology of vertical limbs of pressure shafts, insitu treatment of the shear zone encountered in power house caverns.

Replacement of Permeation Grouting by Cut-off Wall along Upstream Coffer Dam

Treatment of the upstream coffer dam to arrest seepage of water into the main dam foundation pit with by permeation grouting was suggested. However the sub-surface investigations during DPR stage revealed the presence of a sand horizon of undulating width, spanning the river channel, of thickness ranging between 5m to 10m. In view of uncertainty associated with penetration of grout in sand horizon and chances of higher seepage through it, which may result in piping action and failure of the coffer dam, MHPA carried out additional sub-surface investigation by drilling 9 number of drill holes to confirm the extension and behavior of this sand horizon. Sub-surface data from additional drill holes and earlier ones confirmed the longitudinal as well as lateral extension of the sand horizons throughout the dam foundation exhibiting a pinching and swelling nature and ranging in depth from 1m to 12m (figure 1). Gradational analysis of material from this horizon as per Indian Standard code IS: 2720, Part – 4 (1985, 2006), revealed that the dominant constituent of this horizon is fine grained sand (43.13% to 94.29%) with some silt and clay content. This horizon exhibited marginally higher permeability values ($3x10^{-3}$ to $10x10^{-3}$ cm/sec) compared to the surrounding river borne material whose permeability was observed in the range of 1.6×10^{-3} to 5.1×10^{-3} cm/sec.
Geotechnical evaluation of the river bed material form sand horizon, revealed that it could not be made water tight by permeation grouting as grout would not penetrate through this fine sand horizon (Raffel and Greenwood, 1961, Kazemian and Huat, 2009, Kim et.al., 2009, Indian Standard Code IS: 14343, 1996). Impenetrability of grout may consequently result in failure of the grout curtain against seepage and entail extremely high cost of dewatering in the main dam

pit while having a negative impact on the dam concreting. Further in view of the high head anticipated at upstream of the coffer dam and higher permeability of sand horizon, possibility of "piping action" which could de-stabilize the coffer dam itself, were also high (Mishra et. al., 2017). Accordingly the project authority appropriately decided that in view of its effectiveness in terms of seepage control for such foundation condition, it would be prudent to provide a cut-off wall across this horizon at the upstream coffer dam, up to bed rock level as against adoption of permeation grouting technique.

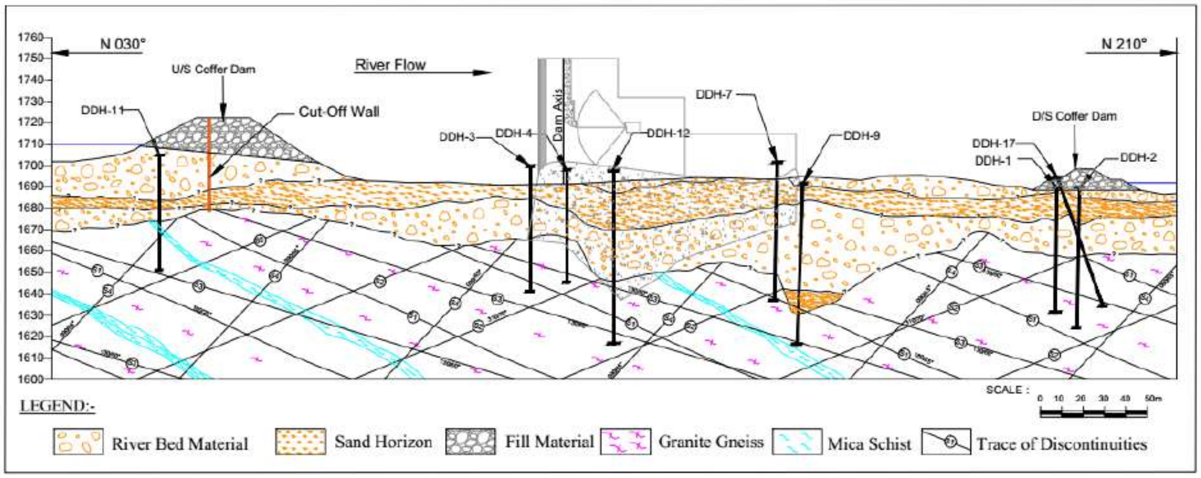


Figure 1: Geological section along river showing disposition of different horizons of river bed material.

The placement of concrete cut-off wall in the upstream coffer dam was executed by BAUER, (Germany). By placing the cut-off wall in the upstream coffer dam, excavation of 60m deep dam foundation pit in riverbed was carried out without any seepage problem, whereby only two pumps, working intermittently were sufficient to provide a dry foundation condition instead of 15 pumps running continuously for dewatering of the pit as envisaged in the DPR with treatment of upstream coffer dam foundation by permeation grouting. Due to negligible seepage in the dam pit the cleaning of the foundation and placing of the foundation concrete was of excellent quality, which is generally not achieved if seepages are high into the dam foundation pit.

Change in Alignment of Diversion Tunnel

A 574m long diversion tunnel was proposed on the right bank of the river. The outlet portal was located in slope wash/slide debris material, hence to delineate the bed rock profile a drill hole was drilled at the portal location. The data from the exploratory drill hole revealed presence of 19.5m thick overburden. Due to presence of thick overburden the quantities of the excavation were apprehended to increase substantially. Seepage of water was also observed along the road cut section around the outlet portal area. Further during the bench developments for access road to dam area about 0.5 to 1m wide cracks were observed at El. 1800m above the proposed portal area. Seepage of water and development of cracks implied that during the excavation of the portal area during the monsoon may charge the overburden mass inducing the pore pressure which may trigger its failure in form of slides. Geological mapping of the area revealed presence of exposed bed rock about 85m downstream of the original portal location where the portal of the diversion tunnel could be located to ensure the stability of the outlet structure and minimize surface excavation. Accordingly MHPA decided to relocate the outlet portal by 87m, downstream of the original location. Relocation of the outlet portal increased the length of the tunnel by 107.89m to 681.89m.To expedite the excavation of the diversion tunnel an additional adit of 43m was also provided. With four fronts available for excavation the diversion of the river for dam works was achieved in 10 months.

Change in location and excavation methodology of Surge Shaft

The excavation of the back slopes of the surge shaft started in April 2012 and as per the construction drawings issued by the consultant. However during the excavation of back slopes of the structure, rock exposures were noticed towards upstream. As such the structure was shifted marginally by about 20m towards the hill to accommodate the entire structure within bed rock.
The shifting in centerline of the surge shaft by 20m resulted in increase of height of back cut slopes which in tender drawings were envisaged between El.1802 to El. 1836m, by 36m i.e. upto El. 1872m. As per the construction drawing for surface works, 3 numbers of berms at interval of 15m height and slope of 1(V):1(H) between two berms was envisaged. But during execution, cracks were observed along unexcavated slope (figure 2a & b) and the slopes of 15m height appeared to be unstable. In view of this gradient of slope was changed from 1(V):1(H) to 1(V):1.25(H) and height between two berms was reduced to 9m from 15m, thereby increasing the number of berms from 3 to 6.

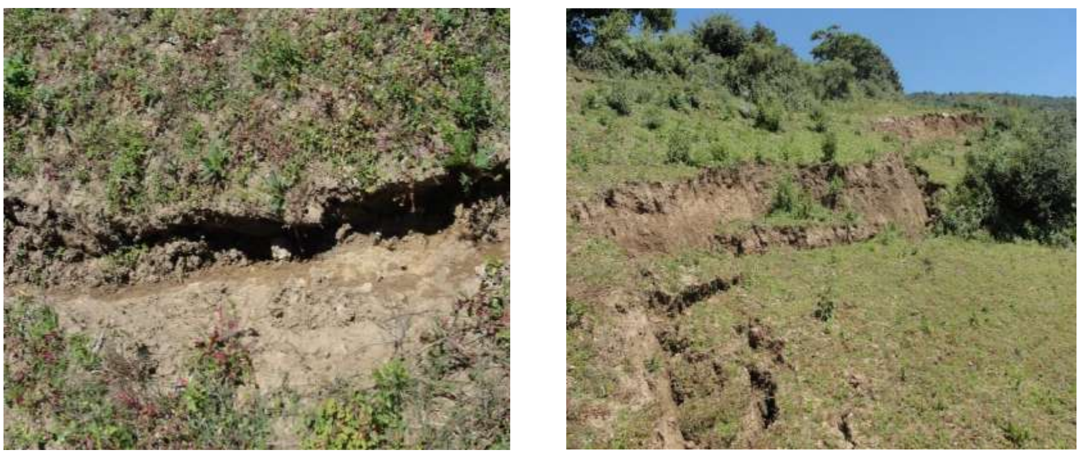


Figure 2: Photographs showing (a) cracks & sliding of unexcavated surface above El. 1832m observed when the height between the two berms was 15m and slope 1:1.

As per Contract document excavation of the surge shaft was proposed to be done by Raise Borer, by first making a pilot hole of 300mm diameter from top to bottom (El. 1796 – El. 1656.5m). After drilling the pilot hole, its reaming to about 2m diameter, pilot shaft was to be taken up by Raise Borer itself, starting from bottom to top, followed by widening of the shaft from top to bottom by drill and blast method, allowing the muck to be dropped through pilot shaft to the bottom, while the muck was to be removed from bottom of the shaft through Adit V to HRT. However in view of the poor geological conditions encountered during the excavation of the back slopes and along adit –V and adit to pressure shaft-I where weathering had deteoriated the rock mass to the depth of 180 to 200m it was inferred that the poor geological conditions might be prevailing along the entire length of the shaft. As such chances of raiser borer being getting stuck were very high. Further owing to poor geological conditions encountered along adit-V its excavation was delayed thereby making it impossible to do mucking from the bottom of the shaft through it. Hence in view of the aforesaid geological conditions, excavation of surge shaft by raise boring appeared unsuitable and excavation of surge shaft by full face sinking method was adopted instead.

Excavation of surge shaft by full face sinking was carried out by mechanical means using excavator and limited use of explosive was resorted to which was mainly restricted to below El.1680m, where rock strength was considerably greater. To facilitate excavation by sinking method, two cranes were erected at working platform at El. 1802m (figure 3a). The excavation methodology comprised of excavating the shaft by advancing to 2.5m depth by mechanical means using excavator (figure 3b) and removal of the muck by tower and goliath crane with the help of 3 and 8 cum. buckets respectively, followed by installation of primary support in the form of shotcrete and rock anchors. After installation of primary support, secondary support in the form of steel ribs was installed. Extensive strengthening of the rock mass strata by aid of 6 to 8m deep grout holes spaced 1 to 1.5m apart and radiating outwards at an angle of 15^{o} was also undertaken before advancing the shaft excavation after every stage.

Figure 3: (a): Panoramic view of Surge shaft showing installed cranes. (b) Excavation being carried out by excavator (mechanical means).

To further ensure the stability of the shaft, extensive grouting was carried out along the periphery of the shaft by aid of 125mm diameter, 100m deep holes in two rows placed in the concentric rings at 4m and 7m from the excavated shaft boundary (figure 4), for consolidating the rock mass and allowing it to participate in load distribution. Grouting was also expected to be helpful in preventing seepage during charging of water conductor system. First row of the grout holes was located at a distance of 4m from the shaft periphery wherein 37 nos. of primary grout holes at spacing of 2m c/c were initially grouted. After the evaluation of the grouting by aid of check drill holes further 37 nos. of secondary grout holes were drilled and grouted. Second row of grout holes was located at a distance of 7m from the shaft periphery and the hole to hole spacing was kept as 2m. Total no of holes in second row were 47. It is pertinent to mention that grout intake in secondary holes of first row was only about 25% of the primary holes, average intake per meter length of grout hole for primary holes of first row was 7.56 bags, while that for secondary holes it was 1.84 bags only (figure 5a). Similarly average grout intake per meter length of grout hole of second row was 2.94 bags which is just one third of the primary holes of first row (figure 5 b).

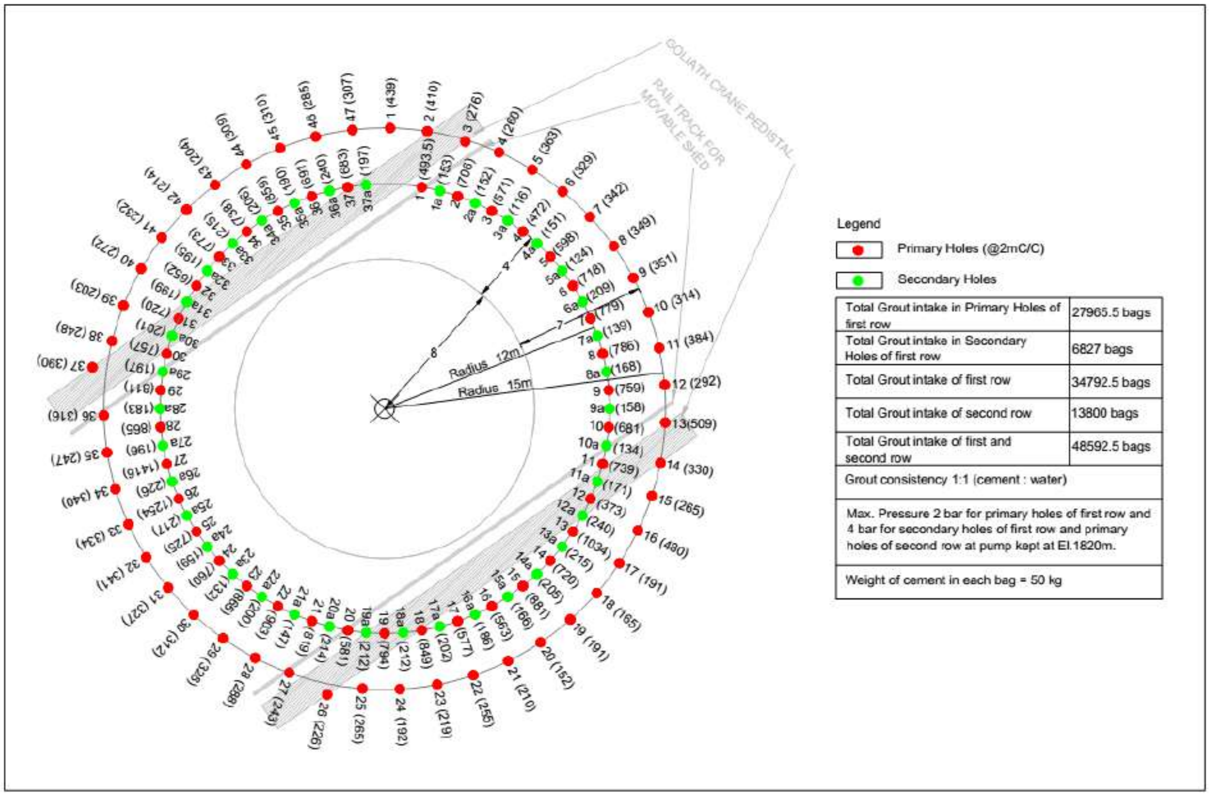


Figure 4: Schematic plan showing grout intake in bags in each hole of first and second row.

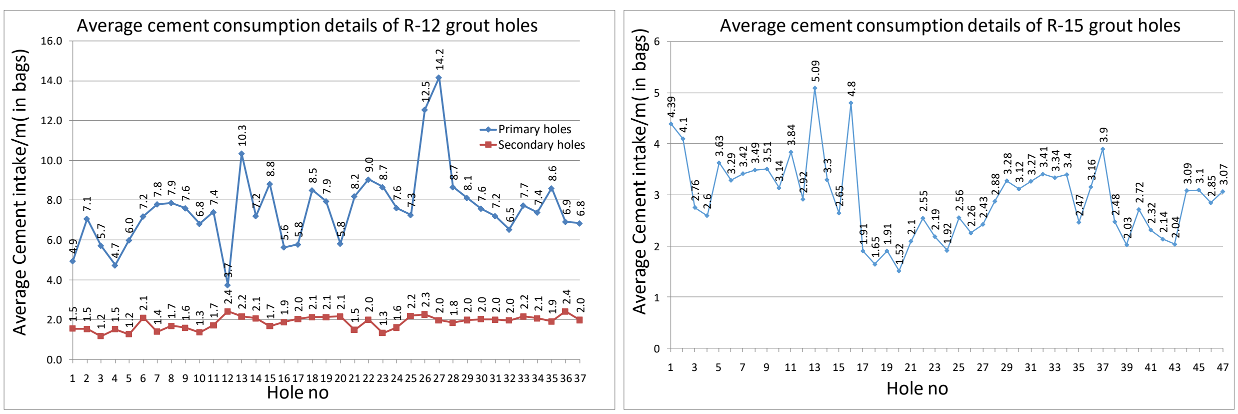


Figure 5 a & b: Graph showing average grout intake per hole per meter length in (a) first row (b) second row.

Insitu Treatment of Shear Zone in Power House Caverns

During the excavation of central gullet of power house cavern and transformer cavern, a 1.5 m thick shear zone with associated fracture zone of 2 to 6m thickness with attitude of the N30°E–S30°W dipping 10 to 24° due N60°W was intercepted between RD 125m to 155m (between EL 1052m to 1044m) and RD 70 to 90m (EL: 1056.50 1048.50m) respectively. The disposition of shear zone was such that it was cutting along the entire length of the caverns and also bisecting the intermediate rock pillar between both the caverns (figure 6 a to e).

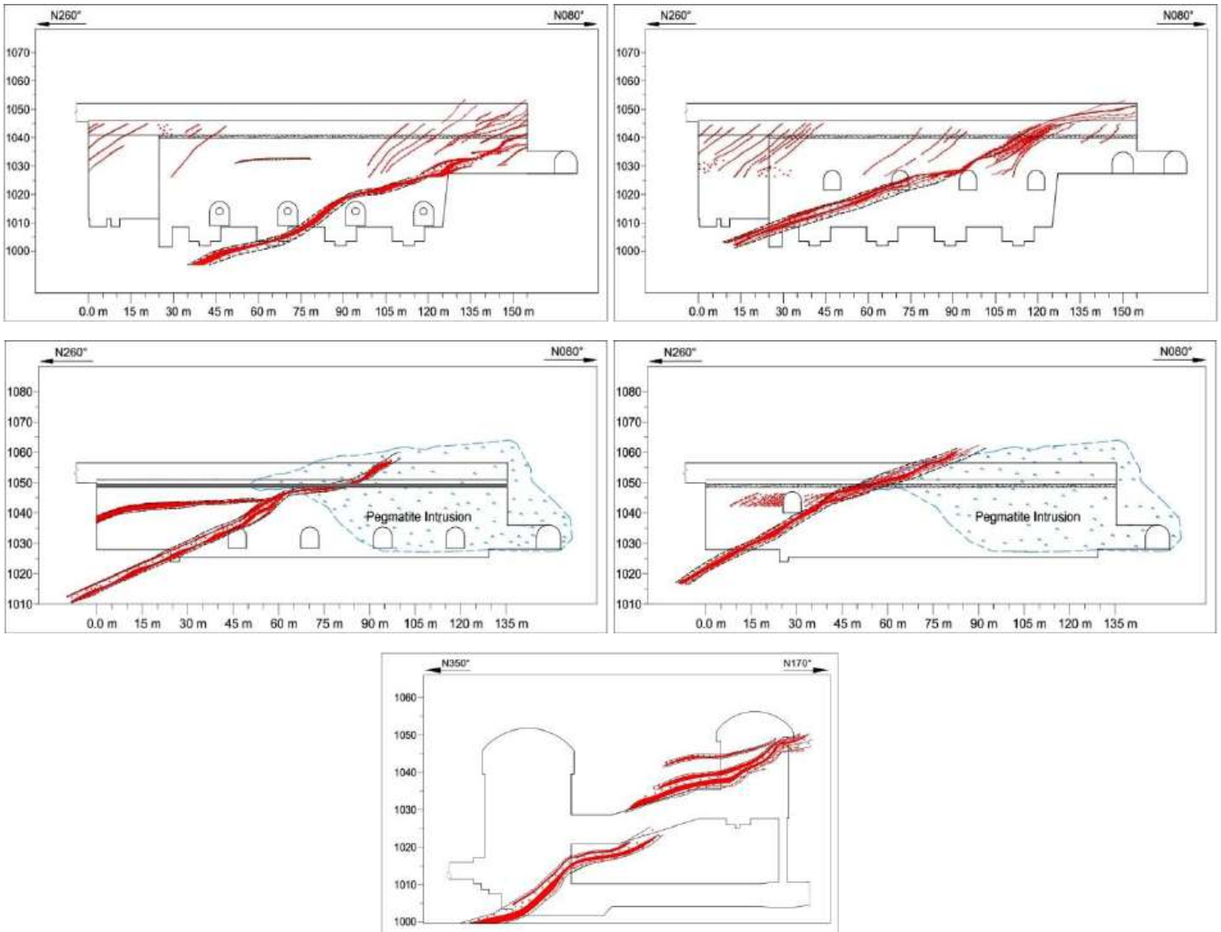


Figure 6: Geological section showing disposition of shear zone along (a) upstream wall (b) downstream wall of power house cavern (c) upstream wall (d) downstream wall of transformer hall cavern (e) across the caverns.

Presence of previously un-envisaged shear/ fracture zone of 2 to 8 m thickness appeared detrimental for the stability of the caverns; as such reassessment of stability of both the caverns, while also revalidating the rock support and excavation methodology, was undertaken. The consultant suggested shifting the caverns about 40m laterally toward valley side whereby the crown of the caverns could be relatively free from the affect of the shear zone. However this would have resulted in the shear/fractured zone intersecting the turbine foundation and its continuity along the walls and rock column between the caverns would have still not been avoided, further this would necessitate re-alignment of pressure shafts, which were excavated for a considerable length, along with realignment of main access tunnel, involving considerable time and financial losses. Therefore MHPA decided for insitu treatment of the shear/fracture zone.

To ensure long term stability of the crown reaches affected by shear/fractured zones, formation of cavity and observed rising deformation trends, steel ribs support comprising of ISMB 350 steel ribs, spaced 0.5m c/c between RD 0 to 35 and RD 100 to 155m in the power house cavern and between RD 0 to 20 and RD 60 to 120m in the transformer hall cavern were provided, followed by extensive contact and consolidation grouting to the depth of 6m into the rock mass. Longer rock bolts of 12m length at spacing of 3m c/c were also provided along the crown of both the caverns in addition to 7.5 and 9m long rock bolts as proposed in construction drawings. To assess the behavior of the rock mass during benching down of the caverns and to optimize support system, progressive three dimensional numerical modeling studies of the caverns, were undertaken, and based on the results of the progressive modeling analysis; excavation methodology and sequence were optimized while simultaneously revalidating the support system.

While the crown affected by shear zone of both the caverns was strengthened by steel ribs support and grouting, the shear/fractured zone along the walls was treated progressively during course of excavation of caverns. The shear/fractured rock mass was manually scooped out upto a depth of 2 to 3m, followed by cleaning of the void and filling it with reinforced concrete of M30 grade. The concrete cladding was stitched with bed rock by 18m long rock bolts spaced 1.5m c/c. Consolidation grouting to a depth of 20m with ultrafine cement with grout consistency ranging from 5:1 to 0.8:1 (water cement ratio by weight) and maximum pressure of upto 14 kg/cm^2 and spacing of 1.5m was also carried out.

To monitor the behavior of the rock mass during the course of excavation an extensive and systematic geotechnical instrumentation monitoring program was implemented wherein the change in stress conditions were monitored by load cells, displacement of rock mass at different depth inside the excavated periphery of the structures by single and multi point bore hole extensometers to the depth of 20m, while surface deformations were monitored by aid of tape extensor-meter and survey target points. The data was regularly collected and analyzed on daily basis. The anticipated deformations as obtained by numerical modeling analysis were regularly compared with the observed deformations to ensure safe excavation and optimize excavation methodology. The deformations recorded at site during excavation were much less than those anticipated from 3DEC numerical modeling analysis (figure 7 and 8).

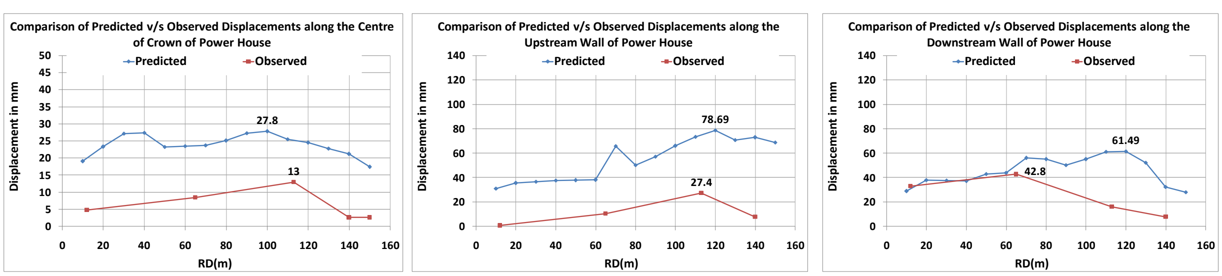


Figure 7. Comparison of anticipated and observed deformations along crown and walls of power house cavern.

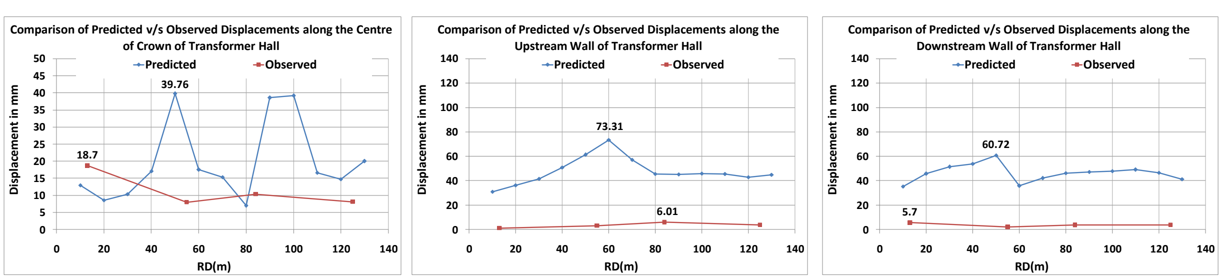


Figure 8. Comparison of anticipated and observed deformations along crown and walls of transformer hall cavern.

Change in excavation methodology of Vertical Limbs of Pressure Shaft

As per tender document all the vertical limbs were proposed to be excavated after the completion of the bottom horizontal limbs, Raise Borer was to be placed appropriately over the top of the respective centre of the vertical limbs in penstock erection galleries. First, a pilot hole of 300mm dia. was to be drilled from top to bottom. Thereafter, widening of this pilot hole was to undertaken by riming 2.0m dia. from bottom to top. After excavation of 2.0m dia. Pilot shaft, further widening of the shaft upto 5.1m dia. was to be carried out proceeding from top to bottom. However in view of the poor geology and seepage conditions as encountered during excavation of adits and as inferred from sub-surface investigations it was observed that excavation by method suggested in contract document would not be prudent as chances of raise bores getting stucked are very high and excavation of pilot shaft from bottom will also be difficult and full of uncertainties as such excavation of vertical limbs was planned to be carried out by conventional full face sinking method from top and was accordingly executed for excavation of all the three vertical limbs of both the pressure shafts. Further to expedite the excavation of the vertical limbs of the pressure shafts excavation by employing raise climber from bottom of the shafts (vertical limb - 2 and 3) and by providing additional face for excavation for vertical limb-1 by an additional adit from horizontal limb-2 was undertaken. MHPA also decided to erect longer ferules of six and five meter lengths in place of three meter as suggested in tender drawings this saved enormous time as number of welding joints at site reduced to half. For erection of longer ferules, the height of the erection galleries was increased to 12.5m in place of 8m as envisaged in construction drawings.

Introduction of Additional Adits

To ensure scheduled completion of the project additional adits for expediting the excavation of underground structures were introduced as and when required. A total of seven additional adits totaling a length of 1214m were provided during course of project construction. These adits not only expedited the excavation works but also helped in taking two different works as parallel activities, thereby saving enormous time. Apart from saving time additional isolate the works of different contractors to avoid any interference between them. The details of the additional adits provided during the project execution are tabulated in table 1

Table 1: Details of additional adits provided during course of project construction

S. No	Adit Location	Length (m)
1	Additional Adit to Diversion Tunnel	43
2	Additional Adit to Power Intake Tunnels	211.16
3	Additional Adit to Head Race Tunnel	185.12
4	Additional Adit to Bottom of Vertical Limb - 1	244
5	Additional Adit to Bottom of Vertical Limb - 3	210.5
6	Additional Adit to Tail Race Tunnel	275.8
7	Connecting tunnel between PS-1 and 2 , HL-3	44.5

Additional Adit to Diversion Tunnel

With increase in length of diversion tunnel due to shifting of the outlet portal and to expedite the excavation of the tunnel to divert the river before onset of the monsoon an additional adit of 43m length was provided to double the excavation fronts from two to four. With four fronts of excavation the diversion of the river was successfully achieved by June 2013.

Additional Adit to Power Intake Tunnels

The excavation of power intake tunnels of 165.29m and 212.68m length was planned to be carried out adit to desilting chambers. It was proposed that from adit to desilting chambers excavation of desilting chamber in first stage will be carried out upto the invert level of power intake tunnels, followed by excavation of power intake tunnels. Benching down of the chambers was planned to be carried out after completion of power intake tunnel works. This excavation methodology appeared to be time consuming and may result in delays in project completion. To ensure timely completion of the construction of desilting chambers and power intake tunnels, an additional adit of 211.16m length was provide to intake tunnels. The adit branched from adit to desilting chambers as such no surface excavation for portal development was envisaged. With provision of this adit excavation of desilting chambers and power intake tunnels was carried out as independent activity, saving considerable construction time and hence ensuring scheduled commissioning of the project.

Additional Adit to Head Race Tunnel

In contract document for excavation of HRT face 1 and branch tunnel1 and 2 of HRT from desilting chamber was proposed to be executed from single adit (Adit-1 to HRT). Face-1 of HRT was part of Contract Package-2 (C-2) awarded to m/s Gammon India Limited, while both the branch tunnels were part of Contract Package-1 (C-1) awarded to m/s Jai Prakash Associate Limited. Single access for two different work agencies would have arisen a lot of interference issues, which might have hampered work progress. To avoid any interference disputes between two different contractors an additional adit of 185.12m length was provided from adit to gate operation chambers of desilting chambers, which intersected HRT at the limit of C1 and C2 contract packages. This additional adit isolated excavation of branch tunnels and HRT Face-1, thereby avoiding any interference disputes between two contractors.

Additional Adit to Tail Race Tunnel

As per contract document excavation of 1333.55m long Tail Race Tunnel, 105.54m long TRT manifold main Tunnel and four Draft tubes of length varying from 100 to 157m were proposed to be excavated from a single face, from TRT outlet Portal even the mucking of turbine pit excavation was to be carried out from TRT. Lining of the entire tail water structure was to be taken up after complete excavation of the machine hall and gate shafts. This enormous excavation from single excess might have delayed the scheduled completion of the powerhouse works, as such an additional adit of 2753.8m was provided from adit to Pressure Shaft bottom to TRT which intersected TRT at RD 1333m, thereby isolating main TRT for benching down and lining. The excavation of the TRT manifold Tunnel, all four draft tubes and mucking of the turbine pit excavation was carried out from this adit, while benching down of TRT and Lining of the tunnel was taken up as an independent and parallel activity. By providing an additional adit excavation and lining works of entire tail water structure and excavation of turbine pits was timely completed.

Additional Adit to Vertical Limb -3 Bottom

Excavation of both the pressure shaft of vertical limb-3 was taken up by full face sinking method from Penstock Erection Gallery – 3. Heavy ingress of water was encountered during the excavation of the shafts, which hampered the progress. In view of the slow progress excavation of shafts was expedited by taking up excavation of pilot shaft from bottom of the shafts by Raise Climber. For employing raise climber and also to take up ferule erection along the horizontal limb – 4 of the pressure shafts as a parallel activity an additional adit of 210.5m was provided from pressure shaft- 2 of HL-4. From this adit excavation of pilot shaft of 2m diameter was taken up by raise climber as a parallel activity and pilot excavation of 80m length along PS-1 and 90m along PS-2 was carried out. The widening of the shaft was taken up from top and mucking was taken up from the bottom of the shafts through the additional adit. Widening of the shafts from top was completed in three months, while excavation of this stretch by full face sinking from top would have required at least 8 months, thereby saving excavation time by five months.

Additional Adit to Vertical Limb – 1

Excavation of both the pressure shafts of VL-1 was taken up from Penstock Erection Gallery -1 by full face sinking method. Heavy ingress of water along with poor geological conditions were encountered during the excavation. The delay in excavation of PEG-1 due to adverse geological conditions along Adit-5, Adit to PEG-1 and PEG-1 already delayed the excavation schedule of the VL-1, which was further getting delayed owing to prevailing poor geological strata along with heavy ingress of water. To expedite the excavation of the shafts additional face for excavation was provided by introducing a 244m long additional adit from pressure shaft – 2 of HL-2. From this adit excavation of both the shafts was undertaken by full face sinking method as a parallel activity along with erection of steel liner along the lower bend portion of the shafts. This compressed the construction schedule of the shafts by almost six month, three months saving in excavation and three months saving in erection of steel liner in bend portion of the shafts which were taken up as parallel activity along with sinking of the shafts from PEG-1.

Connecting Tunnel between PS-1 and PS-2 of HL-3

To expedite excavation of both the pressure shafts of Vertical Limb-2, excavation of pilot shaft by aid of raise climbers was undertaken from the bottom of the shafts. To facilitate excavation by raise borer and simultaneously erection of ferules along pressure shaft 1 of horizontal limb 2 a connecting tunnel of 44.5m length was excavated between both the pressure shafts of Horizontal Limb-2. Pilot excavation of 99m was done along pressure shaft 1 and that of 51m was done along pressure shaft-2 by raise climber as a parallel activity along with full face sinking of the shafts from top. Mucking of pilot shaft excavation of both the vertical shafts was undertaken through pressure shaft-2. Erection of ferules downstream of the junction of connecting tunnel and pressure shaft 1 was also taken up as a parallel activity. Widening of the pressure shaft-1 from top took three months against 10 months required for excavation from top by full face sinking. Similarly widening of 51m length along pressure shaft-2 was completed in one and half month against five months required for full face sinking from top.

DECISION MAKING AND DOCUMENTATION:

MHPA follows a more informal and interactive mode of functioning. The Technical & Financial decision making process always followed the laid down procedures/methods having the established sound base within India and Bhutan. MHPA Management is also relied upon the feedback system wherein the assessment is made before the decisions are taken. Continuous corrections in the processes are made to bring them near to absolute clarity at all levels. The paper work is minimized for seeking Administrative and Financial approvals. Till date MHPA has faced five yearly Audits (combined CAG & RAA) and no serious observations are outstanding in MHPA. MHPA has also documented the project completion report, pertaining to construction of various components of Mangdechhu Project, for a period from 27th August 2010 to 31st December 2015. MHPA is also actively involved in writing technical papers for various journals and conferences, for disseminating the knowledge generated within the project for further references.

CASH FLOW AND RATE ANALYSIS:

Inadequate liquidity with the contractors affects the progress of the works. MHPA always ensured smooth cash flow to the contractors by releasing 75% payment of the monthly running bills within 24 hours of the submission while balance 25% is released within a week's time. MHPA has also placed in position, a strong base for analysis/finalization of rates of items requiring rate revision and cost analysis. Two level committees examine the rates and filter out the short comings of the rate analysis.

CONCLUSION:

Construction of Hydro-Electric Projects is associated with a lot of uncertainties arising due to geological conditions, contractual ambiguity, and design aspects with reference to site constraints, which results in schedule delays and cost overruns primarily associated with delay in decision making. MHPA addressed all these issues write from beginning of the projects by selecting a most appropriate tendering process, development of infrastructure prior to award of contract. Delay that may have arose due to adverse geological conditions or those associated with design with reference to site constraints were minimized by taking appropriate and timely decisions. Delays which might have cropped up due to break down of equipments brought by contractors were minimized by ensuring induction of new and advance construction equipment, which were procured by MHPA and handed over to the contractors. Addressing the problems right in the beginning, timely decision making and transparent working style at all levels helped MHPA in ensuring timely completion of the project within the approved cost. In Indian subcontinent where almost all the hydro-electric projects are facing time and cost overrun, commissioning of MHEP in approved cost and within schedule is a major achievement in development of hydro-electric project, which may open way for boosting development of hydro-electric projects in this sub-continent.

REFERENCES:

IS: 2720 (Part – 4), 1985 (Reaffirmed 2006), "Indian Standard method of test for soils, part – 4, Grain size analysis (second revision", Bureau of Indian Standards, New Delhi, pp. 1 – 38.

Raffle, J.F., Greenwood, D.A., 1961. The relation between the rheological characteristics of grouts and their capacity to penetrate soil. Proc. The 5th Int. Conf. of Soil Mechanics and Foundation Engineering, Paris. Vol. 2. pp 789.

Kazemian, S., Hout, BBK., 2009. Assessment and comparision of grouting nd injection methods in geotechnical engineering. Eur. Jour. of Sci. Res. Vol. 27 (2), pp. 234 – 247.

Kim, J.S., Lee, I.M., Jang, J.H., Choe, H., 2009. Groutability of cement-based grouts with consideration of viscosity and filtration phenomenon. Int. Jour. for Numerical and Analytical Methods in Geomechanics. Vol 33 (16), pp. 1771 – 1797.

IS: 14343, 1985 (Reaffirmed 2001), "Indian Standard – Choice of grouting materials for alluvial grouting – Guidelines", Bureau of Indian Standards, New Delhi, pp. 1 – 9.

Mishra, A.K., Chaudhary, R.K., Punetha, P., Ahmed, I., 2017. Cut-off Wall a Boon for Deep Dam Foundation Pits: A Case Study of Mangdechhu Hydro-electric Project, Bhutan. Proc. INDOROCK 2017: 7th Indian Rock Conference, New Delhi, pp.596-603.

Biography:

***A.K. Mishra**: Graduated in Civil Engineering in 1977, thereafter completed M. Tech from IIT, Delhi in 1989. He has contributed extensively in the planning, design & engineering, contracts, execution and monitoring of hydroelectric projects in India and Bhutan. He has taken over as Managing Director, Mangdechhu Hydroelectric Project Authority, Bhutan, on 27 August, 2010. He got superannuated from NHPC Ltd on 31st December 2015 as Executive Director. Thereafter, reappointed as Managing Director, MHPA for a period of another 2 years. He is also working at the risk mitigation model for hydroelectric power projects for his research work.*

TOPIC: TARGETED SOLUTION THROUGH EMERGING GEOPHYSICAL TECHNOLOGY IN RESISTIVITY IMAGING, SEISMIC TOMOGRAPHY & GROUND PENETRATION RADAR (GPR) FOR OPTIMIZATION OF GEOLOGICAL UNCERTAINTIES IN HYDROPOWER PROJECTS.

Head Researcher: S.L. Kapil, General Manager

Associate Researchers: Jyotirmoy, Manager (Geophysics), Mohinder Pal Singh, Manager (Geophysics) & S. S. Barhia, Manager (Geology)

Affiliation: Hydro Sector, NHPC Limited, Sector-33, Faridabad-121003, Haryana

ABSTRACT:

Investigation in Hydroelectric Project plays a very vital role and is of great importance for construction of project in optimum time and cost effective manner. Although serious efforts are being made for investigation utilizing geological mapping, drilling and limited geophysical studies, but still geological uncertainties comes into picture during execution of hydropower schemes and projects are delayed, leading to time and cost overrun. It is to mention that there is ample scope to utilize geophysical investigation tools to achieve targeted solutions during investigation and construction of Hydropower schemes.

The proposed project proposal “Targeted Solution through Emerging Geophysical Technology in Resistivity Imaging, Seismic Tomography, & Ground Penetration Radar for Optimization of Geological Uncertainties in Hydropower Projects” which is under submission encompasses application of geophysical tools of Resistivity Imaging, Seismic Tomography, and Ground Penetration Radar (GPR) with latest available technology for investigation in hydro power schemes.

Resistivity Imaging technique uses the contrast in electrical properties of the material for subsurface mapping, seismic tomography is based on the elastic properties of the material and GPR uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum to map the subsurface structures.

This paper deliberates on an initiative towards utilization of 2D high resolution resistivity imaging for successfully assessing and delineating geological uncertainties in cost and time effective manner without drilling along HRT and Adit with cumulative length of about 4km at Sengulam Augmentation Scheme, Kerala. Based on the highly encouraging results of resistivity technique, it is proposed to extend its usage in hydro power investigation for generating 3-Dimensional subsurface information of subsurface. It is also proposed that seismic tomography and GPR will also be integrated with resistivity imaging for achieving desired resolution and targeted solution for investigation of HRT, dam, powerhouse area and other appurtenant structures.

KEYWORDS: 2D high resolution Resistivity Imaging, Seismic Tomography, Ground Penetration Radar

INTRODUTION

Kerala State Electricity Board Limited (KSEB) is involved in construction of Sengulam Augmentation Scheme (85Mu) located in Idukki District of Kerala. The project envisages construction of a diversion weir of 12m high and 80m long across Western Kallar stream of Periyar Basin for diverting water through a 3.5m dia unlined, 6.7Km long Diversion tunnel to the existing Sengulam Reservoir to increase the storage and power generation (Fig.1). The construction of the project commenced in the year 2010 wherein at present almost 60% Diversion tunnelling works has been completed by drilling and blasting method and balance of 2620m length is under halt due to adverse geological conditions encountered during tunnelling.

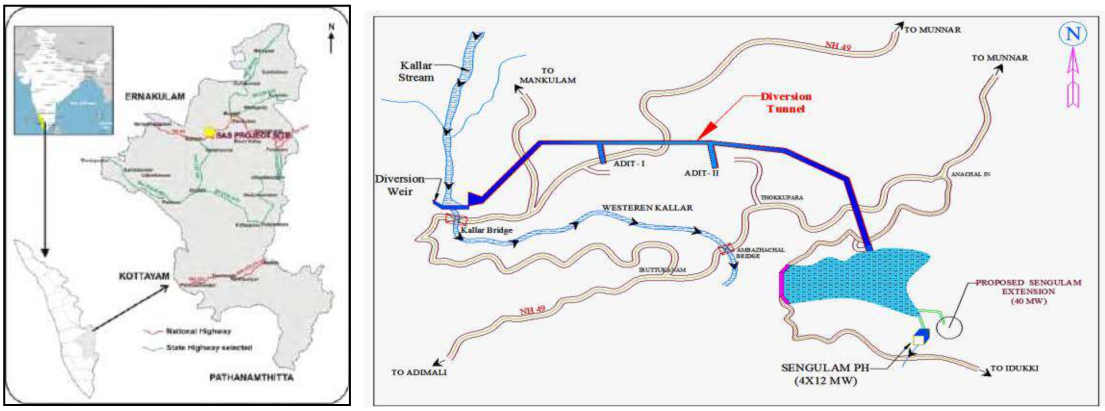


Fig. 1: Project Location & Layout Plan

Initially, survey & investigation along the Diversion tunnel alignment / adit area was carried out by Geological Survey of India (GSI) through extensive drilling and about 2Km exploratory drilling revealed core recovery & RQD of 80% to 90% indicating good to very good bedrock as tunnelling medium. However highly adverse geological conditions like abnormal depth of weathering, caving, sheared, fractured / closely jointed rock mass, squeezing and flowing types of failure encountered during the execution (Fig. 2). These conditions generated cost overruns and delays in completion of the project. Initial proposal of exploring the damaged/collapse area was proposed to be done through drilling few exploratory drill holes along the tunnel alignment. However these may not have resulted in deciphering the subsurface geological conditions all along the remaining tunnel sections due to its point depth information. Moreover it is time-cost consuming and costly.

KSEB entrusted NHPC to provide technical support to resolve the hindrances being faced by them in construction of diversion tunnel due to encountered adverse geological conditions. Accordingly, a cost & time effective innovative approach of 2D resistivity imaging was planned for assessment of geological conditions along tunnel alignment and Adit-I.

High Resolution 2D Resistivity Imaging technique along 4Km stretches of diversion tunnel & Adit-I area were taken up during Feb-March 2017.

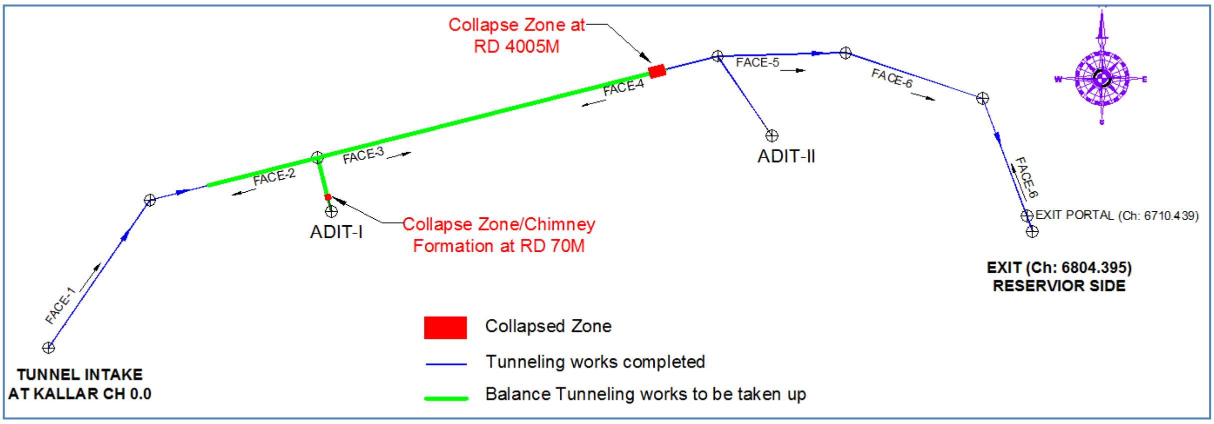


Fig. 2: Areas showing geological difficult problems

METHODOLGY/TECHNOLOGY ADOPTED:

Resistivity Imaging: Resistance is a basic physical property of any earth material and resistivity methods utilizes this fundamental property to scan the subsurface in terms of resistivity of the medium. Resistivity technique measures variations in the electrical resistivity of the ground, by applying electric currents across arrays of ground electrodes. Initially, this method was able to provide point information below the surface in one-dimension only and had very limited application in field investigations. With the advancement of technology, development of resistivity surveying techniques has been very rapid in the last few decades and has tremendously increased the practical applicability to utilize this technique for producing the image of the subsurface in terms of resistivity values of the material under investigation in two-dimensional/three-dimension space. Data is processed using advanced software based on finite element or finite difference methods. This technique is very helpful in detecting shear zones/cavities where the conventional seismic refraction technique fails.

2D Resistivity imaging Survey for a length of about 4Km was carried out for Diversion Tunnel and Adit-I through Dipole-Dipole, Schlumberger and Gradient protocols were utilized, data processing was carried out with software based on finite-difference & finite element modelling for development of 2D dimensional resistivity structure of subsurface below the profiles.

In view of difficult terrain conditions and for deep current penetration, in place of standard current electrodes (0.8m), the electrode length was increased to 1.5m. Moreover, data was collected on a continuous basis to achieve higher resolution and deeper penetration. Tunnel alignment at surface is crossing NH 49 at several locations and heavy traffic caused serious difficulties in data collection.

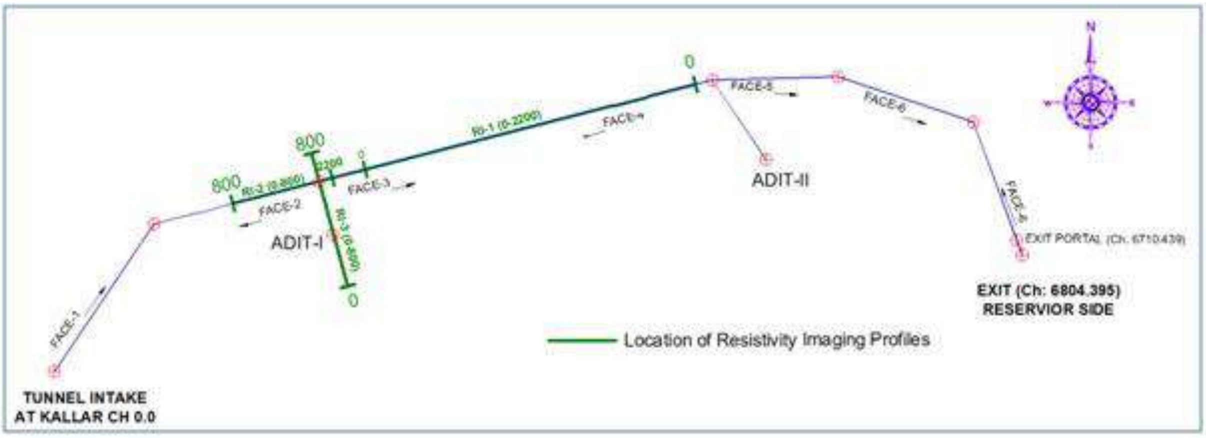


Fig. 3: Plan showing resistivity imaging and TSP layout

Fig. 4: Laying of imaging cables and aarrangement for safe passage of imaging cable across NH-49

ASSESSMENT OF SUBSURFACE GEOLOGY:

The tunnel is driven through migmatite group of rocks essentially made up of hornblende biotite gneiss and granitic gneisses and intrusive pegmatite. The tunnelling hazard in the diversion tunnel occurred due to geological adversities present in the rockmass and this caused multi types failures like caving, development of cracks, squeezing ground condition, stressed saturated rockmass, wedge failures etc during excavation of the tunnel forcing the project authority to halt the construction activities.

Fig. 5: Over break due to failure of wedges **Fig. 6: Flowing condition**

Fig. 7: Completely collapsed Face-IV of DT **Fig. 8: Completely collapsed face of Adit-I**

Based on results of the resistivity imaging survey along the tunnel grade and Adit-I, anticipated lithological conditions have been divided in five zones viz., Zone A, Zone B, Zone C, Zone D and Zone E for better understanding. Accurate geometry of anticipated shear zones depicting adverse geological conditions were identified along the diversion tunnel and Adit-I. Anticipated geological conditions and predicted tunnelling conditions are tabulated as below:

ZONE	Anticipated Lithological Condition	Predicted Tunnelling Condition
Zone A	Zone consisting of top soil. Overburden, boulder zone, weathered rockmass	Will not be encountered in Tunnel grade. Already encountered in Adit-I grade at adit portal.
Zone B	Completely weathered rockmass with saturated/dry conditions. Weathered rockmass expected to behave like soil with very loose surrounding rock.	Highly difficult tunnelling condition expected. Closely spaced ribs support will be required concurrently with excavation.
Zone C	• Migmatite group of rock consisting of hornblend, biotite gneiss and granite gneiss with intrusive pegmatites. • Moderately jointed rockmass. • Overall fair quality of rockmass.	• Overall good tunnelling condition expected, except for few isolated stretches where tunnel will negotiate moderately jointed/saturated zones. • May require provision for minor support system.
Zone D	• Migmatite group of rock consisting of hornblend, biotite gneiss and granite gneiss with intrusive pegmatites. • Slightly jointed rockmass. • Overall good quality of rockmass.	• Good tunnelling medium for excavation is expected. • Self supporting rock. • However, minor support measures may be required at chainage where intrusive bodies /veins within the country rock are actually encountered.

ZONE	Anticipated Lithological Condition	Predicted Tunnelling Condition
Zone E	• Migmatite group of rock consisting of hornblend, biotite gneiss and granite gneiss with intrusive pegmatites. • Strong, massive & fresh bedrock. • Overall very good Quality of Rockmass.	• Very good and stable tunnelling medium is expected. • Self supporting rock (As already negotiated during excavation from intake to RD 1385 m).

SUBSURFACE GEOLOGICAL ASSESSMENT OF DIVERSION TUNNEL:

2D Resistivity imaging section developed on the basis of results is shown in Fig. 9. The location and geometry of shear zone at tunnel collapse location is clearly visible in the section. This zone expected to have about 210m length. Geological section developed by GSI on the basis of drilling is also shown in Fig. 10. As per this section good rockmass was expected at tunnel collapse location. These findings are critical for realistic cost estimate and implementation of appropriate construction methodology which is not in general possible with conventional practice of drilling.

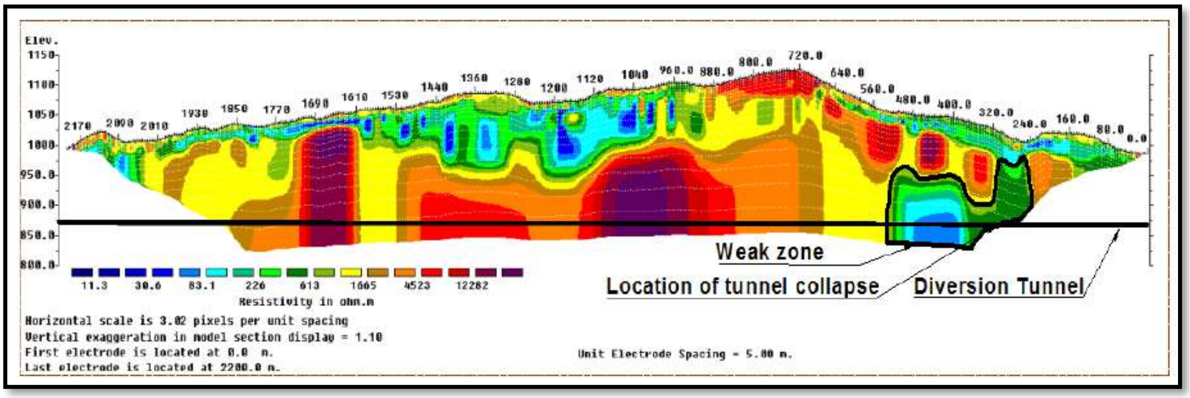


Fig. 9: Resistivity Imaging Section along Diversion Tunnel showing location of Shear Zone

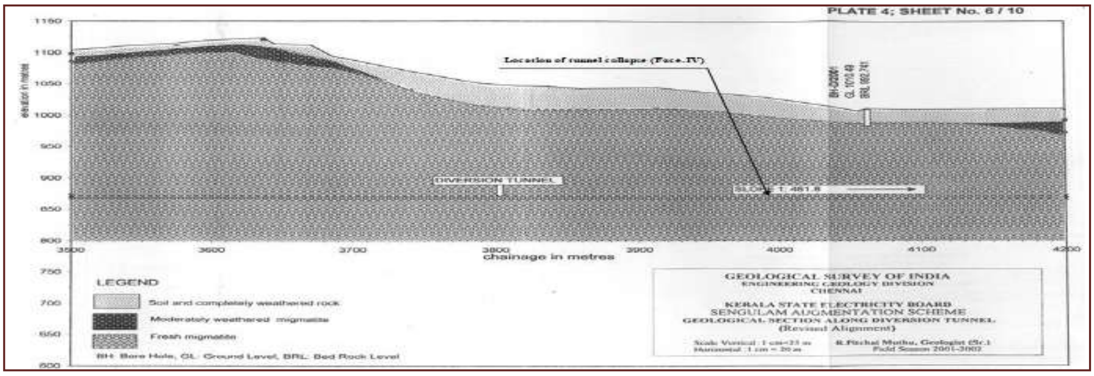


Fig. 10: Geological Section as per GSI at Diversion Tunnel collapse location

Inferred lithological sections showing different zones have been developed along 2620m diversion tunnel on the basis of resistivity imaging is given in Fig. 11. Along the tunnel length of about 12% highly difficult tunnelling conditions are expected and good rockmass conditions are expected along the balance tunnel length.

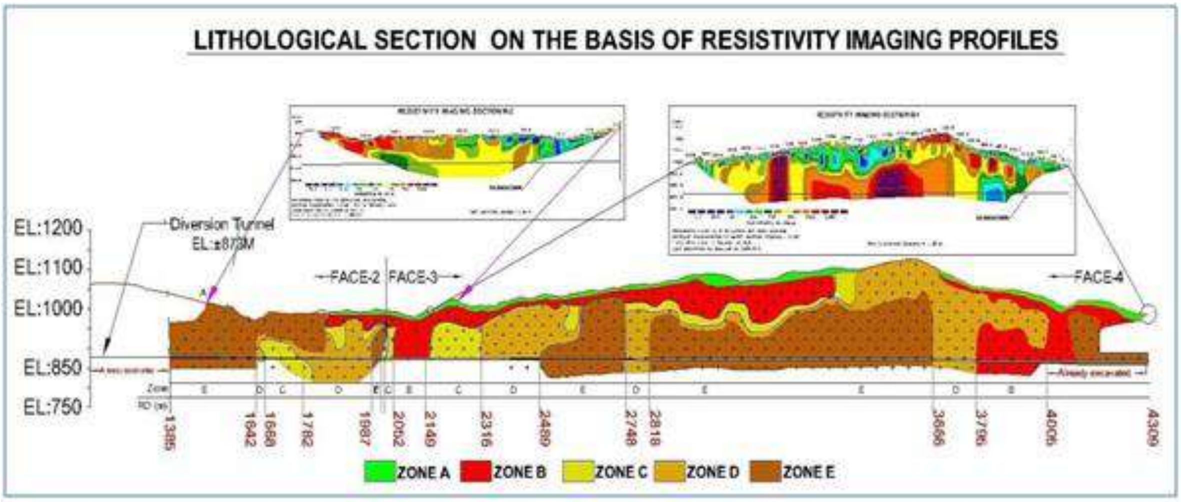


Fig. 11: Geological section along Tunnel Alignment based on Resistivity Imaging

SUBSURFACE GEOLOGICAL ASSESSMENT OF ADIT-I:

2D Resistivity imaging section developed along Adit-I is shown in Fig. 12. The location and geometry of expected shear zone at adit collapse location is clearly visible in the section. Another shear zone expected further is clearly visible in the section. Geological section developed by GSI on the basis of drilling is also shown in Fig.13. As per this section good rockmass was expected after 70m.

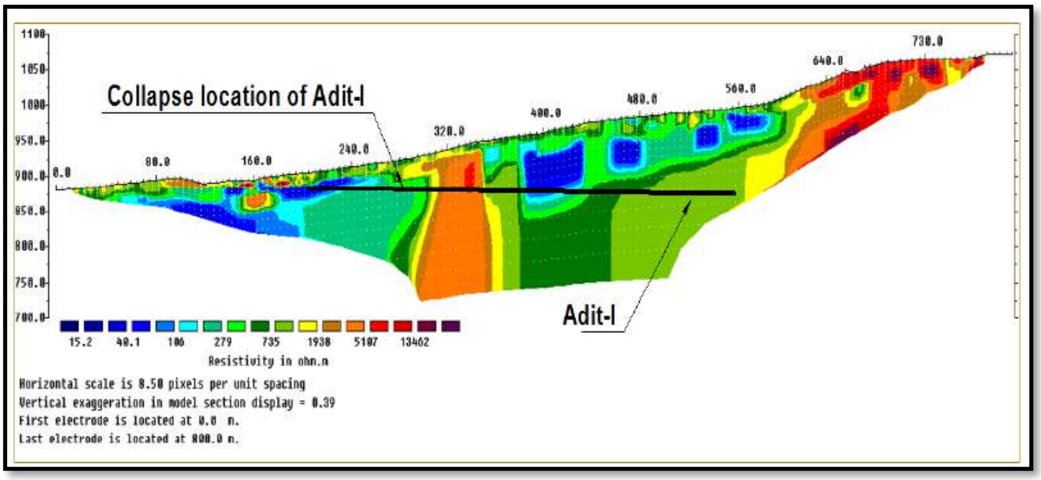


Fig. 12: Resistivity Imaging Section along Adit -I showing location of Shear Zone

Resistivity imaging results suggested the non- feasibility of adit-I along the present alignment as almost 31% rock is very poor and about 39% is highly weathered.

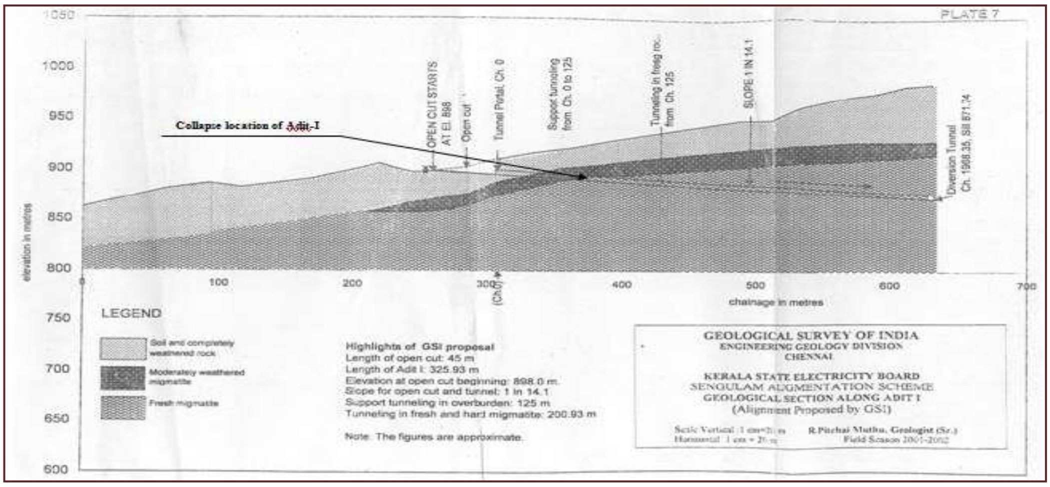


Fig. 13: Geological Section along Adit-I as per GSI

Inferred lithological sections showing different zones have been developed along 260m length of Adit I on the basis of resistivity imaging is given in Fig. 14.

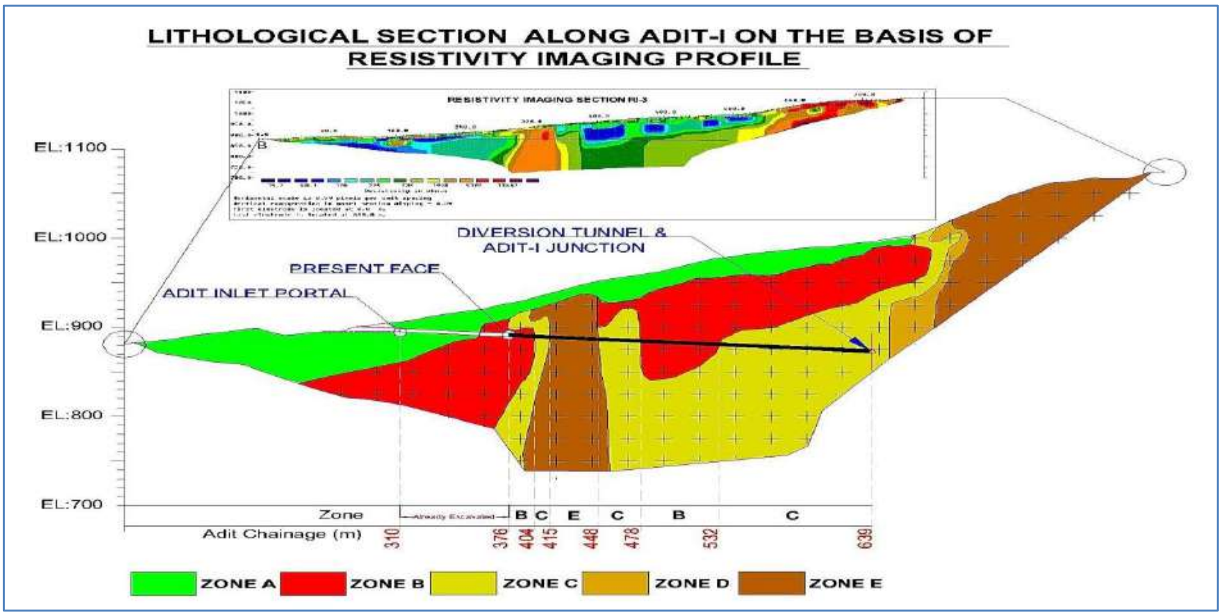


Fig. 14: Geological section along ADIT-I based on Resistivity Imaging results

CONCLUSIONS:

Strategic planning and implementation in carrying 2D resistivity imaging led to assessment of geological conditions along balance tunnel and Adit-I. Despite topographical inaccessibility due to human settlement, concentrated cardamom-tea gardens, heavy traffic on NH 49, geophysical survey for the deep seated balance 4Km long tunnel and Adit stretch with maximum vertical cover of about 260m was managed. Available current electrodes were modified for deep penetration of current up to tunnel grade. The use of advanced high resolution 2D Resistivity Imaging results generated confidence in resolving the critical geological issue being faced during construction. The technique has been successfully conducted within one month duration and the enormous subsurface geological information has been achieved in cost and time effective manner without drilling.

Geometry of the shear zones at tunnel and Adit-I collapse locations were defined accurately without any drilling. Based on these findings detailed methodology for execution of the balance tunnelling works has been proposed. These findings are critical for realistic cost estimate and implementation of appropriate construction methodology. Most important finding of the study was identification of adverse geological conditions along 70% length of Adit-I which is highly critical for execution of the project. This study helped in assessing the geological uncertainties for balance tunnelling works of the project.

Future prospects**:** It is to submit that investigation of HRT area in general for hydropower projects is carried out through geological mapping based on the available outcrops and sometimes limited drilling along the tunnel stretch. 2D/3D Resistivity Imaging and GPR can be effectively utilized in tandem to scan the entire length of HRT and other underground works for better understanding of rockmass characterization. Even if the penetration through these techniques up to the requisite structure level is not achieved in some of the cases, still they can provide insight of the probable weak zones which may have extension up to the structures. Such details are not possible through conventional mapping and even through drilling and may pose problem during construction. Further, as a general practice during investigation stage, dam area is explored with 2 to 3 drill holes, surface and drift logging. In this mode of investigation, zone in between the drillholes remain unexplored and sometimes causes problem during construction. Such lacuna in investigation can be handled with effective utilization of Seismic Tomography to scan the complete dam seat area and other structures with optimized drilling of holes.

Based on the highly encouraging results of resistivity technique, it is proposed to extend its usage in hydro power investigation for generating 3-Dimensional subsurface information of subsurface. It is also proposed that seismic tomography and GPR will also be integrated with resistivity imaging for achieving desired resolution and targeted solution for investigation of HRT, dam, powerhouse area and other appurtenant structures to optimize geological uncertainties in hydropower schemes.

Paper at International R&D conclave on
"Emerging Opportunities and Challenges of R&D in Indian Power Sector"
at CEA on 20th & 21st February 2018

Title of Paper

GEOLOGICAL SURPRISES IN HYDRO POWER PLANTS / PROJECTS:

"Surprises are Inevitable – There will always be unexpected ground conditions and neither the owner nor the design team can completely eliminate surprises from complex underground projects" – **Gould 1995**

Authors:
Anjali Kulkarni
Chief- Corporate Engineering
ajkulkarni@tatapower.com
&
Surendra Chandolkar
Specialist (Geology),
FTM (Corporate Engineering)
Tata Power Company Limited
Contact Details: schandolkar@tatapower.com **- 9223356502**

Contents

1. Abstract:

The total installed power capacity in India is 3,30,860 MW out of which Hydropower accounts for merely 14% i.e. ~45000 MW as on 30th November 2017. The percentage has come down from 45% in 1970 to 14% in 2017. Hydropower potential of the country assessed by CEA of about 1,50,000 MW, of which we have harnessed only ~29% hydro potential. The long-term goal is to increase the share of hydropower capacity from the present level of 14% to 40% of total Installed Capacity.

Construction of hydro power project in the Himalayan states is always a challenging job due to extremely poor strata while excavating dam abutments, underground works (tunneling & powerhouse) and back slope excavation of surface power houses. Himalayan geology makes the job of construction engineers as most difficult and many a times over runs are observed both in respect of time and cost aspects. With the development of new techniques and availability of modern & efficient equipment and chemicals, it has become possible to work through the **Adverse Geological Conditions** successfully and with speed without involving life of workers and engineers with all safety aspects. This paper particularly deals with past experiences of geological surprises encountered during construction of major structures in Himalayas & Tata Powers other project sites.

2. Introduction:

Hydropower projects are subjected to various types of risks viz. Geological surprises, construction risk, connectivity issues due to remote locations poor accessibility, difficult terrain, poor communication facility etc. However, the questions are being asked by hydropower developers ***"how much should be spend on geological investigations and how many drill holes normally need for investigation***"?

As you know, large number of hydro projects have been delayed due to Geological surprises viz. Nathpa Jhakri (1500 MW), Parvati-II(800 MW) in Himachal Pradesh, GVKs Alaknanda project in Uttarakhand, Baglihar, Dulhasti (390 MW), Sewa-II (120 MW) in J&K, Subansiri Lower (2000 MW) in Arunachal Pradesh, and Rangit-III (60 MW) in Sikkim are some examples which are facing sharp cost escalation due to subsequent changes in equipment design necessitated due to geological surprises. In the past almost all the projects faced the geological problem encountered due to weak zones, shear zones, thrust zones, accumulated tectonic stresses, flowing & squeezing ground conditions, swelling ground, heavily water bearing strata & flowing ground conditions, slope failures, seismic safety aspects etc. Some of the case histories reveal necessitated treatment resulting in stoppage of work for many months, reduction in diameter or change in alignment in many cases.

Then, how we define the geological surprises in the hydropower project development. ***"Those which cannot be handled by the defined methodologies and requires special engineering efforts to handle***

the unexpected situation by adopting different construction methodology and equipment's". In these circumstances, the geologist should adopt "VIP Concept (**V**isualize, **I**nvestigate & **P**redict problems) for geological challenges.

Despite detailed investigations, still there is a possibility of facing some uncertainties while implementing the project. Geological surprises may result in taking mitigation measures which could, inter-alia, increase the project cost. Then, the answer of the above question depends on what is already known and what risks have been identified from the available geological information about the site. Geological investigations aim to understand the risks at the site by progressively developing a geological model. According to international experts, ***on such investigation practices 2 to 3% of project construction cost can be incurred.*** Downsizing of geological investigations have resulted in consequential time & cost overruns during construction stage.

The objective of the present study is to develop:

1. An understanding among the HEP developer about the unforeseeable geological surprises and potential risks associated with the project not in the control of the developer.
2. Geological surprises could be minimized by adopting suitable means during planning & investigation stage and during construction stage.
3. Not fully understanding the geological conditions is one of the biggest risks in a hydropower project, and can lead to large cost blow-outs, major repairs and even public safety issues and financial risks.

3. Limitations:

Geology, hydrology and topography issues are leading reasons for slippage of hydro projects delay in commissioning. The basic objective of Geological investigation for any project is a very important activity to decipher the surface & subsurface geological information. This study is to deal with uncertainties & associated geological risks & its mitigation measures before tender preparation & to resolve the dispute, if any arise during construction. There are certain limitations for, quantify types of expected problems, reliable baselines investigation data & its interpretation, geological model, ground behavior & mode of failure, ground water conditions, construction considerations, etc. Right choice of construction technology and contractor, selection of construction technology and methodology, experienced and well-equipped contractors. Better understanding the geological conditions enables engineers to design safe and stable structures, and to minimize project and financial risk. Five steps to achieving a good geological model are proposed (Ref.-2):

1. ***Develop preliminary geological model:***
   Based on available geological information, aerial photos, topographic data and geological surface mapping and collating all available information helps to determine any potential failure mechanisms within the underlying project structures.

2. ***Develop scope of phase-1 investigation campaign:***
   Based on step 1 determine what needs to be confirmed. The investigation planned depend on many factors including known geological conditions, information gaps, constraints, site access, available skills and equipment, time and cost. There should be a clear objective for every activity (test pit, bore hole drilled, geophysical survey & laboratory test) to be performed. The outcome of Step-2 is the scope of works for the phase-1 investigation campaign to ensure improving the understanding of the identified geological risks.

3. ***Undertake phase-1 investigation campaign:***
   The 3rd step is to undertake the phase-1 investigation campaign. The investigation should be supervised by qualified engineering geologist who will closely monitor drilling rates, water loss, colour of drill cuttings, hole collapse and groundwater levels etc. Laboratory testing should only be performed at reputed laboratories, otherwise there is a risk of destroying samples and wasting time and money for little benefit. The outcome of Step-3 is significantly more factual geological and geotechnical information.

4. ***Update geological model:***
   This step is to interpret additional information to update preliminary model to improve understanding of the geological risks at the site.

5. ***Undertake phase-2 investigation campaign***
   This is the final step in the process of investigation campaign. It is very common for hydropower projects to undertake more than one geological investigation campaign. This is because the geological model may change due to the information discovered in the first campaign, which may raise further questions or unknowns. The second campaign, if required, is likely to be very focused, as it will be addressing a specific question, and will help to finalize the geological model.

It is important to have a clear, systematic process to achieve a good geological model and, therefore, ensure that the subsurface geological risks are well defined. Geological investigations do not reduce geological risks; they merely improve the understanding of the risks. Thus, a good understanding of the geological conditions reduces the uncertainty of capital cost, and therefore enables developers to make well-informed and less risky investment decisions. CEA has proposed an ideal approach in phasing out the total scope of survey and investigation of HEP constitute a four-stage program:

1. Pre-feasibility State investigation,
2. Feasibility Stage investigation

3. Detailed Investigation (DPR) Stage
4. Construction Stage investigation

In addition to conventional geological investigation, modern investigation technology for understanding better engineering geological information viz. Remote sensing & GIS applications for mapping & surveying, various geophysical exploration methods and engineering geological software's can improve quality and efficiency of geological data acquired. During construction especially in underground structures, there is a likelihood of coming across geological surprises which are not anticipated at the time of Detailed Project Report. Experience says about the post construction monitoring is also necessary to assess how the project components are behaving during operation from the forecast made. Some instruments can be installed during construction to monitor rock pressures and deformations due to tectonic movements.

4. Tata Power's experience:

4.1 Maharashtra Projects:

Tata Power has wide experience of HEP since last more than 100 years. Tata Power owns three hydro projects of cumulative capacity of 447MW are under operation in Maharashtra. These are Khopoli, Bhivpuri & Bhira listed in chronological order of commissioning. All the three projects are supplying power to the Mumbai.

4.2 Dagachhu HEP:

Dagachu HEP is 126MW (2x63) located at Bhutan is the Public-Private Partnership venture. Druk Green (59%), Tata Power (26%) as a strategic partner while the Royal government of Bhutan has 15% stake in the project commissioned in March 2015. The pressure shaft was planned by raise boring drilling machine through a pilot hole of 380mm diameter and reaming of 4.10m. It was predicted that there is a collapsible mica schist band between 42m to 56m. By pressure grouting with cement slurry stabilization work was carried out. During excavation water flow and continuous collapsing due to cavity formation was observed from sides of shaft and about 700cum of muck was removed from bottom. This cavity formation was advancing upward posed a serious threat of pressure & surge shaft. To restrict further collapse, a temporary plug was constructed at bottom, and pressure shaft & cavity was filled with sandy

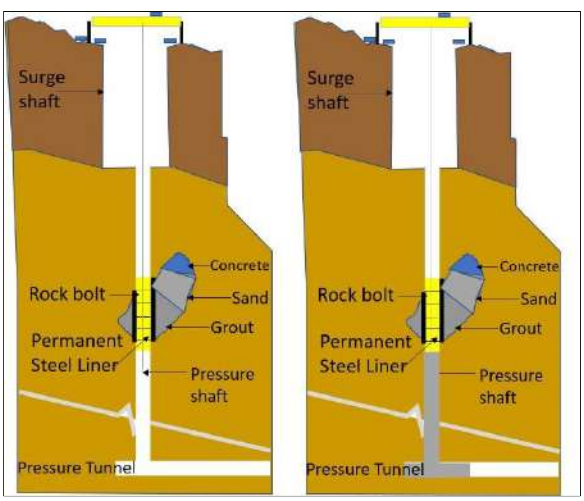


Figure 1 Schematic section of Pressure shaft

material. Subsequently 23 holes drilled around pressure shaft from bottom punctured the cavity. Through these holes sand filling was carried out followed by concrete filling and grouting for stabilization. Then the liner sinking was done to stabilize the collapsible zone.

4.3 Dugar Hydropower Ltd. (DHPL)

DHPL has been awarded to the consortium of "Tata Power Company Ltd. & SN Power Holding Singapore Pte. Ltd." (Owners) in May 2011, by Directorate of Energy, Government of Himachal Pradesh on Build-Own-Operate-Transfer(BOOT) basis for a period of 40 Years from Commercial Operation. The pre-feasibility study was carried out by DHPL for 380MW. Subsequently the capacity has been increased from 380 to 449MW. In view of economic viability due to remote location, accessibility & anticipated geological hurdles the project is kept on hold.

4.4 Itezhi Tezhi Hydro Power Project, Zambia

The Company has commissioned two units of 60 MW each of its 120 MW Itezhi Tezhi hydro Power Project in Zambia, in which Tata Power has a 50% stake. The synchronization of both the units was completed in January, 2016. It is currently owned by Tata Power and ZESCO, a Zambian power utility, on a 50:50 basis on a 25year BOOT (Build-Own-Operate-Transfer) concession term.

4.5 Adjaristsquali Georgia LLC (AGL)

AGL is a SPV of Tata Power, Clean Energy Invest LLC & IFC developing Adjaristsquali three stage cascade hydropower project on upstream of Batumi in Georgia. In the first scheme Shuakhevi HPP, two transfer tunnels & one HRT comprising a total length of ~32km transfers water from Chirukhistsqali and Skhalta to the Didachara dam from where it is transferred through the headrace tunnel to the Shuakhevi power house. Soon after water filling reduced amount of water came through the tunnel and concluded the tunnel was blocked in between due to massive rock fall & collapse at various locations. Which was a major geological surprise for the project. The tunnel excavation was completed in 2016

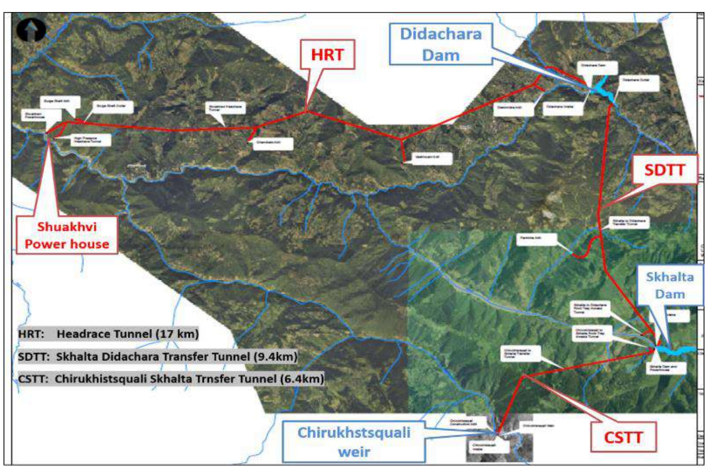


Figure 2 Shuakhevi hydro power project layout

with rock support classes of I to IV in major sections. All tunnels are mostly unlined, with exceptional support of fiber reinforced shotcrete with wire mesh, rock bolts of designed length for different rock class, grouting and installed Lattice Girders for support where necessary during excavation. After dewatering and inspection tunnel failure was confirmed at various locations. The fallen rock material tested have been reported potential swelling characteristics and shows free swelling behavior when saturated.

Figure-3 Cavity formation, damaged shotcrete & wedge failure due to presence of swelling clay

The inspection & review of data indicates that the sections where rock fall has occurred are either due to under supporting or improper rock mass classification. Evaluation of rock support in swelling clay zones needs a knowledge & experience. Geological mapping has not identified this as potentially hazardous for the tunnel stability. As the clayey material has swelling property which varies from time with different magnitudes & weathering property once exposed to the water after saturation needs suitable rock support.

4.6 Koromkheti Georgia LLC HPP (KGL):

KGL located downstream of Shuakhevi project was earlier planned for 150MW capacity at the time of feasibility study stage. During detailed investigation most of the project area found affected due to hydrothermal alteration resulting in to reduction in installed capacity to 112MW due to change of powerhouse location further upstream. The existence of critical hydrothermal alteration has a potential to make a project unfeasible. About 10 alternate options for tunnel alignment were studied during feasibility.

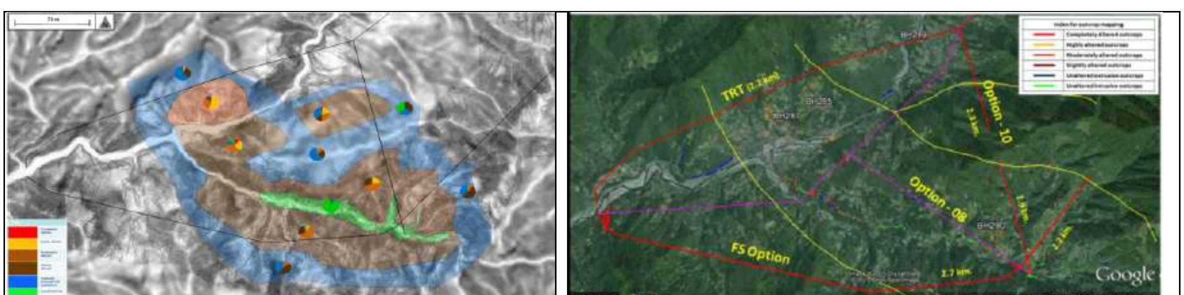


Figure 4: Findings of alteration mapping

The geological investigation was more focused on mapping for determining the rock mass at tunnel grade to avoid uncertainties. Efforts was made on predicting tunneling conditions to get better estimates of potentially altered rock mass the tunnel will driving through and required support measures. The surface geological mapping indicted that tunnel will encounter altered rock mass having very low compressive strength and lower rock mass rating (Q values), thus will pose difficult tunneling condition with significant cost implications.

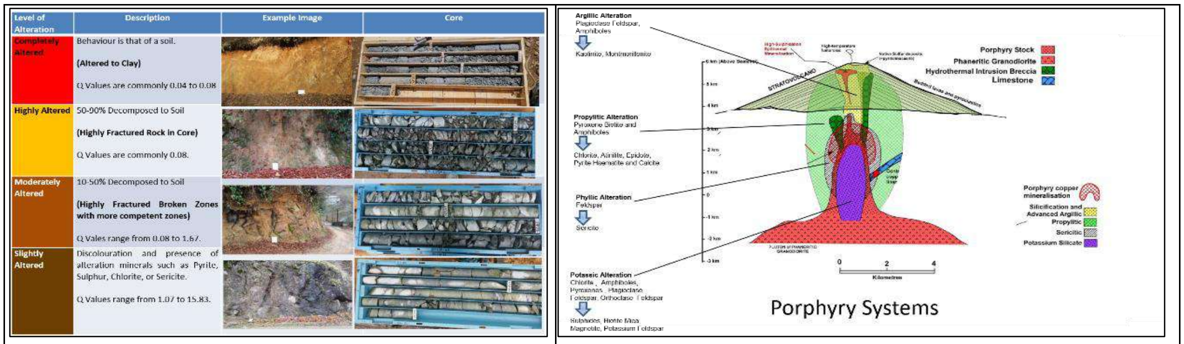


Figure 5: Alteration zones & causes

5. Conclusions:

Even after extensive investigation using advance techniques an element of uncertainty remains in the subsurface geology and geological surprises cannot be ruled out.

- Complex geology plays a dominant role in major decisions in Hydropower development.
- Geo-challenges delay construction schedule and increase cost of the hydropower projects.
- Major challenge is to predict geological condition and confirm rock mass condition.
- Thorough and convincing investigation is very essential to deal risks and dispute.
- More thoroughly investigated project and precise geological information have fewer cost overruns and fewer disputes.

In my view to minimize the dispute & delay during construction (before selection of contractor & finalization of contract) if additional information is felt necessary should be produced for increasing level of confidence of project developer and it brings transparency in the contract agreement while tendering.

6. References:

1. CEA website, Hydro project best practices:
2. Five steps to better understanding geological risks in hydropower projects by Gregg Barker & Richard Herweynem of Entura 24th October 2016.
3. HCC website http://www.hccindia.com/
4. Guidelines for investigations and explorations at DPR stage by Geological Survey of India
5. Geological challenges in development of hydropower by S.C. Sunuwar

Challenges in Hydro Sector in India

Arpita Upadhyay,
Deputy Director
Central Electricity Authority

Sharvan Kumar
Director
Central Electricity Authority

P C Jiloha
Chief Engineer
Central Electricity Authority

Abstract:

India has vast Hydropower Potential of 148701 MW out of which 40177.8MW (excluding pumped storage) is under operation and 94758.7MW is yet to be developed. Hydropower being a clean, green source of energy has capability to cascade multiple benefits while transforming economy of remote areas. Being a renewable source of energy with no consumables involved, hydropower development hardly has any recurring costs and hence calls for no high long term expenditure. Being cheaper as compared to electricity generated from coal and gas fired plants, it also reduces the financial losses due to frequency fluctuations. Hydropower is inflation free due to non-usage of fossil fuel and proves itself to be a highly reliable source of energy. Presently the major hurdles and challenges in low capacity addition and development of hydropower can be attributed to Geological Surprises, delays in clearances, local issues (law and order problems, agitations, etc.), land acquisition, rehabilitation and resettlement and contractual disputes between contractors and companies. Due to these impediments the number of stalled projects are on rise. This has severe cost and time implications on development of this clean energy. Research and analysis of these challenges and comparative statement of deviation from forecasted cost at the time of project inception, and the actual cost incurred by project developer along with the reasons for the cost overrun and subsequent variations, with some suggestions thereof are presented in this paper.

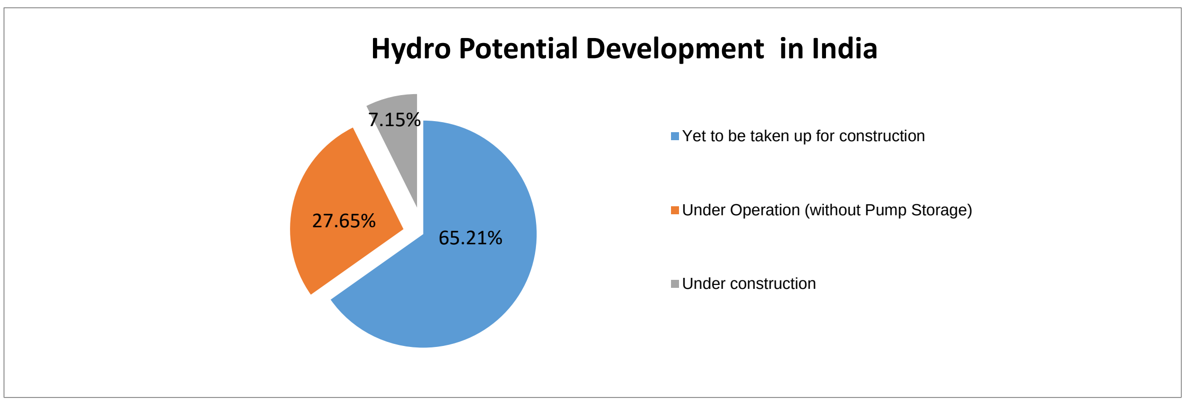
HYDRO POWER: A CLEAN SOURCE OF ENERGY

With the present exponential rise in the world population and the resulting mammoth expansion of human needs for food and energy security, it’s imperative to seek stable energy solutions. With no dearth in new and evolving technologies- the number of industries, automobiles and gadgets are on rise and yet there are several weak points when it comes to energy security - namely, our reliance on dirty fossil fuels, an aging power infrastructure and highly volatile fuel costs. Power is one of the most critical components of infrastructure, extremely crucial for the economic growth and welfare of nations. The existence and development of adequate infrastructure is essential for sustained growth of the economy. Keeping in view the hazardous environmental and climatic impact of conventional sources of energy it’s the need of the hour to increase reach and accessibility of clean energy technologies.

Currently, the power sector is at a crucial juncture of its evolution and Hydropower being a clean, green source of energy, as it burns no fuel and does not produce pollutants, or wastes associated with fossil fuels or nuclear power, and has capability to cascade multiple benefits while **transforming economy of remote areas.** It significantly contributes to development of the adjoining region. Hydroelectric installations bring electricity, highways, industry and commerce to communities, thus developing the economy, expanding access to health and education, and improving the quality of life. It offers a vast energy potential and is available where development is most necessary. Hydropower has one of the highest energy efficiency varying from **85%-95%** and longest life span of all power generation technologies. With an average lifespan of **35 years** and capacity to be renovated, modernized and upgraded with time development of hydropower can help in realizing a sustainable and affordable energy sector.

According to International Energy Agency(IEA), Hydropower generation by countries like China, Unites States, Russia, Brazil, Canada, Norway, India, Venezuela, Japan Sweden accounts for about two-thirds of the world's hydropower generation. Most industrialized nations have developed their hydropower potential, but undeveloped resources still remain in countries such as China, India, Brazil, and regions of Africa and Latin America. As a mature technology, hydropower provides over 16% of global electricity production. India has vast Hydropower Potential of **148701 MW** out of which **94758.7MW** is yet to be taken developed and only **40177.8MW** (excluding pumped storage) is in operation and **10383.5MW** is under construction as on 31.12.2017[1 Data as per CEA reports] .This is illustrated in **FIG-1** below

FIG-1



Due to its unique capabilities of **quick starting and closing**, hydropower stations are found to be economical choice to meet peak load in the grid. Seasonal load curves of regional grids also match with the pattern of hydro power generation. During summer/monsoon season when the generation at hydro power plants is high, the load factor of the system is also high due to heavy agricultural load. During winter, the thermal stations operating at base load and hydro stations work as peak load stations taking care of weather beating loads. Thus the operational needs of hydro & thermal stations are complimentary and a balanced mix helps in optimal utilization of the capacity.

Although hydropower generation is highly capital-intensive mode of electricity generation as the initial expenditure from survey and investigation of remote sites to final commissioning of plant is marred by several impediments. Yet being renewable source of energy with no consumables involved there is very little recurring cost and hence no high long term expenditure, unlike the plants based on conventional energy. It is cheaper as compared to electricity generated from coal and gas fired plants. Hydroelectricity increases the stability and reliability of electricity systems. The operation of reliable electricity systems depends on rapid and flexible generation sources to **meet peak demands**, maintain the system voltage levels, and quickly re-establishment of supply after a blackout. Energy generated by hydroelectric installations can be injected into the electricity system faster than that of any other energy source. The capacity of hydroelectric systems to reach maximum production from zero in a rapid and foreseeable manner makes them exceptionally appropriate for addressing alterations in the consumption and providing **ancillary services** to the electricity system, thus maintaining the balance between the electricity supply and demand. It also reduces the financial losses due to frequency fluctuations and it is more **reliable** as it is **inflation free** due non subject to market fluctuations, contrary to use of fossil fuels. Hydropower is considered as renewable source of energy because it uses and not consumes the water for generation of electricity, leaving this vital resource available for other uses. Hydroelectric power plants with accumulation reservoirs offer incomparable operational flexibility, since they can immediately respond to fluctuations in the demand for electricity. The **flexibility and storage capacity** of hydroelectric power plants make them more efficient and economical. In addition to this, it is the only large renewable source of electricity and its cost-benefit ratio, efficiency, flexibility and reliability assist in optimizing the use of thermal power plants. Further, apart from energy supply hydroelectric power plant reservoirs collect rainwater, which can then be used for consumption or for irrigation and drinking water consumption. In storing water, they protect the water tables against depletion and reduce our vulnerability to floods and droughts. Hydroelectric power plants don't release pollutants into the air. They very frequently substitute the generation from fossil fuels, thus reducing acid rain and smog. In addition to this, hydroelectric developments don't generate toxic by-products.

FIG-2

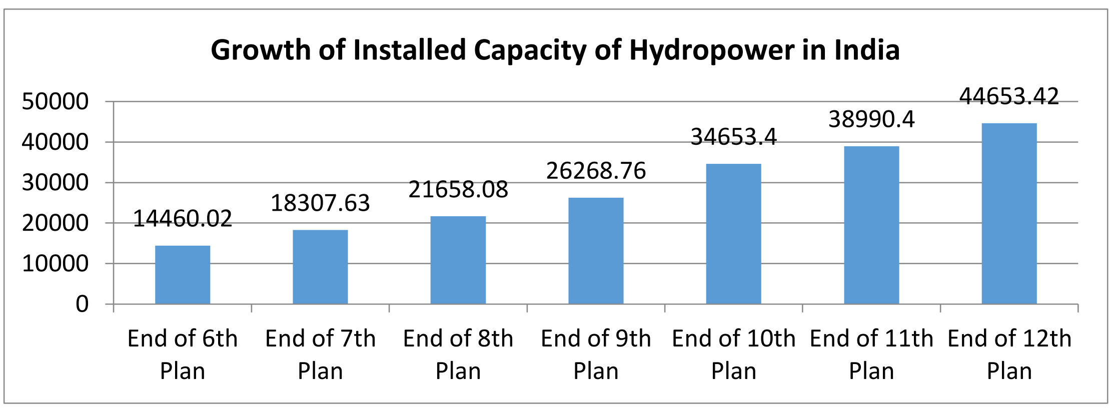


Fig-2 above depicts the capacity addition in Hydropower in India since the 6th Plan to 12th Plan. [2 Data is taken from CEA Reports]. As can be observed from the plot, there has been a significant

increase in the installed capacity of hydropower from 14460.02MW by the end of 6th Plant to 44653.42 by the end of 12th Plan.

However, hydropower is mainly criticized for its negative environmental impacts on local ecosystems and habitats. It is professed that damming a river alters its natural flow regime, which in turn changes the aquatic habitat and disturbs the river's natural flora and fauna. However, its impacts are well understood and manageable through measures for mitigating and compensating the damages. It is a matter of debate that as decomposition of a fraction of the flooded biomass (forests, peatlands, and other soil types) leads to emission of greenhouse gases like methane. However, Hydroelectric plant's Green House Gas (GHG) **emissions factor** (4 to 18 grams CO_2 equivalent per kilowatt-hour) is 36 to 167 times lower than the emissions produced by electricity generation from fossil fuels. Compared to other renewables, on a lifecycle basis hydropower releases fewer Green House Gas emissions than electricity generation from biomass and solar and about the same as emissions from wind, nuclear, and geothermal plants. In **emitting less GHG** than power plants driven by gas, coal or oil, hydroelectricity can help **retard global warming**. Today hydroelectricity prevents the emission of GHG corresponding to the burning of 4.4 million barrels of petroleum per day worldwide. Also, associated submergence of land, thereby loss of flora and fauna and large scale displacement, due to the hydropower projects is also sometimes exaggerated. Study shows that project catering only to hydro power needs, causes little submergence. As quoted by Ministry of Power, sample of 12 projects of NHPC contributing 6231 MW of power required submergence of only 4850 ha of land i.e. the area of submergence per MW is only 0.78 ha. Considering 16 hydropower projects of NHPC covering commissioned Power Stations, under- construction projects and proposed projects it can be seen that number of displaced families per MW is only 0.26, whereas, number of affected families per MW is 0.66 only.

Thus Hydroelectricity means clean and cheap energy for today and for tomorrow. With an average lifetime of 50 to 100 years, hydroelectric developments are **long-term investments** that can benefit various generations. They can be easily upgraded to incorporate more recent technologies and have very low operating and maintenance costs. Hydroelectricity is a fundamental instrument for **sustainable development**. Hydroelectric enterprises that are developed and operated in a manner that is economically viable, environmentally sensible and socially responsible represent the best concept of sustainable development. That means, "development that today addresses people's needs without compromising the capacity of future generations for addressing their own needs"

Indian Scenario: Impediments and Challenges in development of Hydro power

India's generation capacity will have to increase up to seven times the present figure to meet our growth needs. The **demand of electricity has been growing at an average 6.8 percent per year for the last three years [**3 Data is taken from MoP website**]**. The major part of our energy mix consists of fossil fuels. They are finite sources and have serious environmental consequences. In times of depleting resources and climate threats, the best way forward for India is to take the dual path of energy efficiency and renewable power generation like hydroelectricity. It is imperative to tap into this huge power resource and judiciously utilize the non-renewable resources, keeping energy conservation in mind.

As hydropower is one of the least expensive sources of power since the cost of hydropower is dominated by only the initial capital cost of building the facility while the ongoing operating and maintenance (variable) costs are low. Moreover, since hydropower generation does not require burning fuels, operations costs are not vulnerable to fuel price fluctuations. Existing hydropower facilities are very cheap to operate and they can operate for about 50 years or more without major replacement. The cost of hydropower is highly site-specific and depends on different factors, including topology of site, hydrologic characteristics, site accessibility. Total capital expenditure incurred for commissioning of a project is only project cost and it is mainly funded by the Equity and Loan with standard debt equity ratio of 70:30 for financing.

While the world's largest Hydro Electric Power Station, the Three Gorges Dam in China has Installed Capacity of 22500 MW, India is still struggling to target a maximum capacity of 2000MW of Subansari Lower, Parbati-II (800MW), Dibang (2880MW)! As per CEA Reports 16 hydro projects aggregating to 5182MW capacity are stalled due to several challenges encountered at various stages of the project.

Since Hydro projects are located at remote sites and are constructed under adverse conditions there are pertinent challenges which account for **reasons of delay** ranging from **natural, unavoidable and uncontrollable to manmade factors**. Adverse geological conditions, natural calamities like floods, cloud bursts landslides etc. and agitations/strikes/bandhs by local groups, law and order problems civil disturbances are difficult to accurately account for at initial stages of project inception. They can be also be categorized into two broad types- Technical risks including engineering and commercial problems, while non-technical risks including environmental and social factors, community issues, and health and safety challenges. The exact assessment of these delays/challenges is unforeseen and **unpredictable at the planning stage** and these delays in project implementation only leads to undesirable escalation in project costs.

Geological Surprises due to Poor Geology and inadequate Geo-technical investigation:

Geo-technical investigation for a hydro project needs to be undertaken with adequate understanding of local and regional environment as it significantly impacts the design, construction and operation of hydro projects. Thus data collected through geo-technical investigations should have detailed description of geological situation and assessment of the history of the site for appropriate engineering drawing and design. However due to **geological surprises** in the unstable terrain of the young fold Himalayan belt where hydropower potential is maximum, many unpredictable situations arise. As the features of hydroelectric projects being site specific, depend on geology, topography, hydrology of the site it is difficult to consider investigation as complete in true sense keeping in view the heterogeneous rock starta of Himalayan region that varies frequently even in short reaches. The construction time of hydro project is highly influenced by geology of the area and its accessibility. Even when extensive investigations using new techniques of investigations are under taken an **element of uncertainty** remains in the subsurface geology and the geological surprises during actual construction which could cause time and cost overruns and cannot be completely ruled out.

Therefore it is essential that state-of-the-art investigation and construction techniques are adopted to minimize geological risks as well as overall gestation period of hydel projects. Geological impediments were major hurdles in execution of *Naptha Jakhri Hydroelectric project (1500MW) and Rampur HEP(412MW)*. **Poor Geology** is a major hurdle in projects like *Tapovan Vishnughad (520MW), Pare HEP, Parbati-II(800MW).*

In projects like *Kameng(600MW),* Arunachal Pradesh, due to poor geological conditions the initially underground high pressure tunnel was subsequently converted to over ground, also due to need for slope stabilization, heavy seepage conditions boring of HRT was suspended. Further change in design parameters for better silt management the dam layout was changed leading to substantial upward variation in both excavation and concreting causing delay in project. Projects like *Tehri Pumped Storage Project (1000MW)* got carried over to XIIth plan due to poor geology.

Environmental and Forest Clearances:

Owing to factors like **non- issuance of Forest Land clearances, Wild life Clearances, Environmental Clearances** presently **40 no of projects** aggregating to 26570 MW(as on 31.12.17) are held up and are yet to be taken up for construction even after the accord of Concurrence by CEA. Due to the fact that hydropower projects are primarily located in hilly areas, diversion of forest land is sometimes unavoidable. However, efforts can be made to minimize the utilization of forests by hydropower developers. **16 no** of projects are taken up for construction but are stalled due several reasons like slow progress of works, financial constraints with developer, poor geology, contractual problems, Rehabilitation and Resettlement issues.

Design changes, law and order problems:

Design changes, law and order problems -bandhs and strikes, frequent disruptions by local people have affected projects like *Subansiri Lower (2000MW), Vishnughad Pipalkoti(444MW),Vyasi(120MW),Singoli Bhatwari(99MW).* In the last 10 to 15 years, there has been tremendous social resistance to the large hydro projects.

Further, Hydro projects require **consent of State Govt** and clearances from other statutory authorities, being site specific and complex in nature various activities involved in the projects are interlinked requiring clearances from various ministries. Due to this, adhering to a specified and planned time schedule becomes difficult leading to inadvertent delays. **Interlinked activities** like submission of EIA/EMP studies to MOEF&CC after completing the prescribed procedure along with the report of mandatory public hearing conducted by State Pollution Control Board are a time consuming process. Submission of incomplete proposal, forms, raising multiple queries with supplementary information in phases by appraising agency, and their **late compliance leads** to a lengthy, cumbersome process and subsequent delays in obtaining Environmental Clearances.

Incorrect assessment of land requirement is also a reason of delay due to which at later stage there is increased requirement of submergence area, job facilities, dumping area, quarries, realignment of roads and new roads as in the case of *Parbati-II HEP (800 MW).*

Adverse **cascading impact** of one project on other as in the case of *Parbati-III* where water discharged by upstream Parbati-II will not be available for generation of electricity by certain month, and as a result, downstream Parbati-III cannot become fully operational till commissioning of Parbati-II project for want of water discharged by this project.

Delay in award of contracts due to project specific clarifications and delayed bid submissions, requirement of experience certificates by bidders for meeting qualifying criteria is also a major impediment in project execution.

Natural Calamities:
Projects in State of Uttarakhand like *Lata Tapovan(171MW),Singoli Bhatwari(99MW)* have been stalled due to severe **Weather Phenomenon** -flash floods in 2013.Moreover projects like *Alaknanda, Kotlibhel-IA,I-B,St-II*(aggregating to 1345MW) are under review by Hon'ble Supreme Court.

Inter-state issues are also troubling hydro power projects. Development of four hydro projects — *Shivasamudram(345MW), Mekadatu(400MW), Hogenekkal(120MW) and Rasimanal(480MW)* have been affected due to Cauvery water dispute between Tamil Nadu and Karnataka.

Resulting Time and Cost Overrun and Subsequent Variations

Thereby, due to these impediments the cost of projects increases significantly. Sometimes, the **revised cost ranges between 12-148%** of the original approved cost at Detailed Project Report Stage. Frequent delays and the cost overruns generate multiple problems -at times making the project unviable forcing to the total abandonment of the project. Further it's a big loss to nation in terms of capacity addition leading to deviation from the targeted capacity.

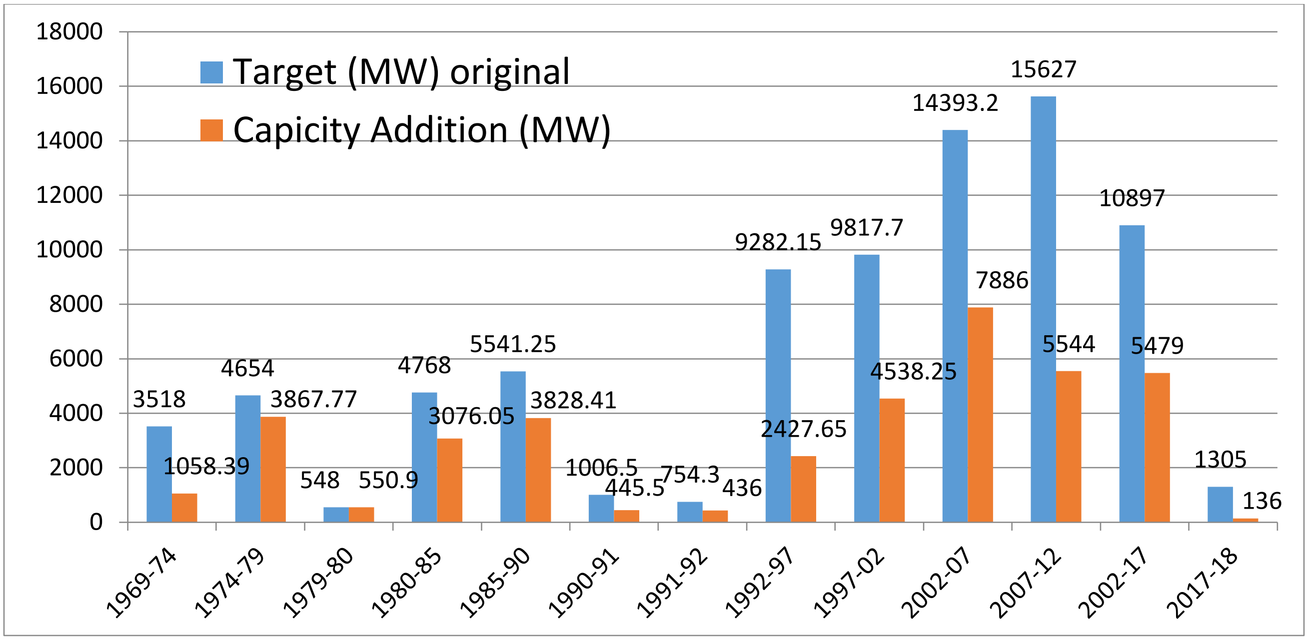


FIG-3

Fig-3 depicts the Plan-wise **Hydro Capacity Target Addition Vs Actual Target Achieved** [Data is taken from CEA Reports]. It can be observed that there is a steep **decline** in the target capacity addition achieved over the years. This may be attributed to the above discussed impediments, causing stalling of projects and resulting in prolonged delay in project construction with time overrun. Thus the project gets **carried over** to the next five-year plan. This deviation undermines the stipulated targets of the planning stage.

Huge time and cost overruns, high upfront cost to establish projects, long-drawn process to get green clearances, additional cess imposed by various state governments on projects, leads to **high tariff** and subsequent **reluctance of states to sign power purchase agreements (PPAs)**. This is hampering the hydroelectric power development in the country. In recent times the steep escalation in capital cost of hydropower subsequently impacts the tariff of hydropower project. Additional cess is also imposed by various state governments on hydro projects and it creates an additional burden. Uttarakhand and Sikkim charges “Green Cess” and “Environment Cess”, respectively. Similarly, Jammu and Kashmir as well as Uttarakhand charge “Water Cess”, which also adds to the project cost. The unit cost of projects is variable depending on manpower needs, remoteness of location, transportation needs, material costs etc.

Therefore, the initial investment needs for particular projects must be studied individually due to the unique nature of each hydropower project and avoiding future cost escalation. **Parameters affecting investment costs** and the return on investment include the project scale, which can range from over 10- 2000 MW, the project location, the presence and size of reservoir, the use of the power supplied for base or peak load or both, and possible other benefits alongside power production, such as flood control, irrigation, fresh water supply, etc. The way in which the project is financed is also a key factor in project's pace.

Though due care and diligence is taken during preparation of DPR to make the cost estimates realistic to the extent possible. However, many times project cost escalates due reasons beyond controls. Since each project has unique features the time for clearances varies from project to project there are **procedural delays** in clearances from appraising groups/ministries.

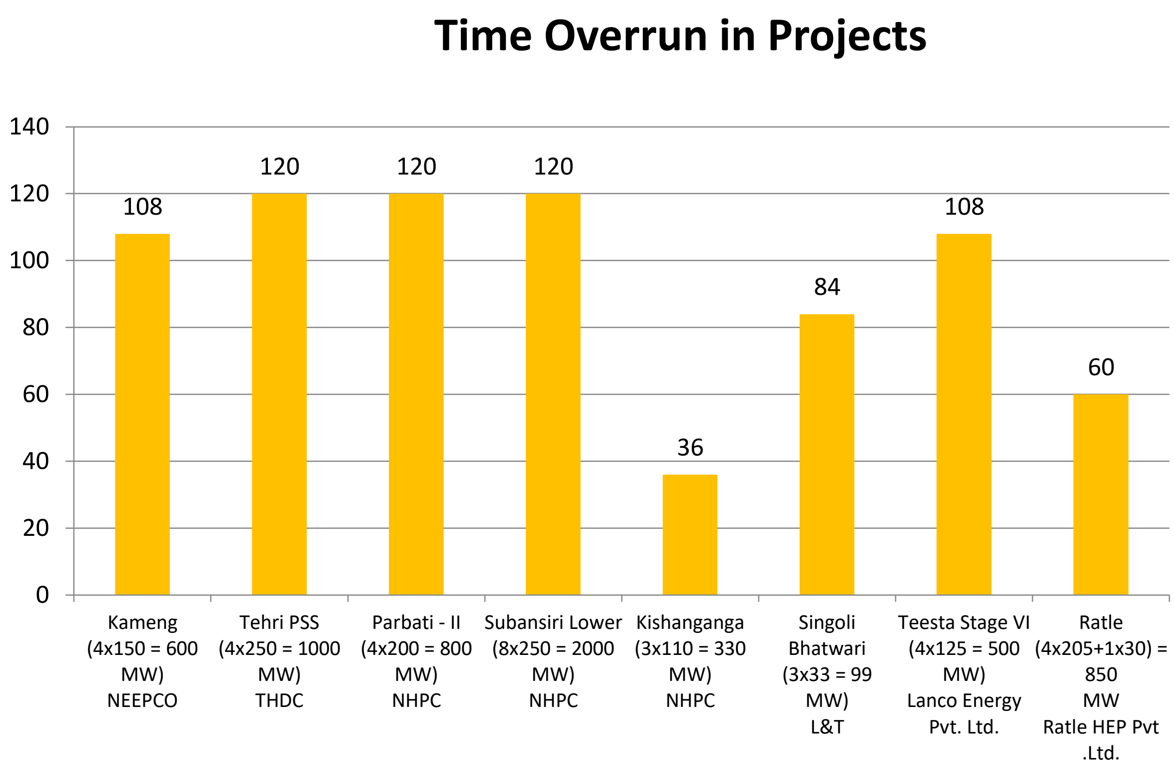


FIG-4

The **Fig-4** [Data is taken from CEA Reports] compares time overrun for few projects with different capacities varying from 330MW to 1000MW like Kameng HEP, Tehri PSS, Parbati-II, Subansiri Lower, Kishanganga, Singoli Bhatwari, Teesta Satge VI, Ratle , the reasons of whose delay are discussed in the **impediments** for hydro projects in this paper. The huge time overrun from the scheduled date of commissioning at the time of project inception to the anticipated/final date of project commissioning shows the period added to the **long gestation** period of hydro plant. Time and cost is essence of any contract to ensure completion as per the stipulated schedule. Development of a plant takes around 10 years from planning to commissioning as construction of hydro plant is virtually a battle against nature. Undertaking huge electromechanical and hydromechanical works inspite of large scale investigations and precautions is fraught with **surprises and unpredictable developments**. Thus treating anticipated dates of completion based on certain assumptions and estimations about local working conditions, structures, machines, performance of contractors is a risk in itself. A small snag or delay due to one factor can trigger series of events with a **domino-effect** and send all estimations of schedules into tailspin. As most of the hydroelectric projects are located in hilly areas with poor accessibility, communication and in general areas experience various natural calamities like unprecedented flash floods, cloud bursts, landslides, earthquakes besides local law and order problems. A hindrance/stoppage of work for even a short duration can affect the pace of works and then lot of time is consumed in reverting back to the desired pace of execution. Sometimes, the effect of hindrance shifts the work completion to non-working period and thus making a major impact on the construction schedule for more than 4-6 months in a single stretch.

CHART-1

Project	**Orgiginal Cost (Rs. in Crores)**	**Anticipated Cost* (Rs. in Crores)**	**Cost overrun (Rs. in Crores)**	**Percentage variation in Cost**	**Time overrun(months)**
Kameng (4x150 = 600 MW) NEEPCO	2496.9	6179.96	3683.06	147.51	108
Tehri PSS (4x250 = 1000 MW) THDC	1657.6	3939.11	2281.51	139.64	120
Parbati - II (4x200 = 800 MW) NHPC	3919.59	8398.75	4479.16	114.28	120
Subansiri Lower (8x250 = 2000 MW) NHPC	6285.33	18559.49	12274.16	195.28	120
Kishanganga (3x110 = 330 MW) NHPC	2238.67	5882.01	3643.34	162.75	36
Singoli Bhatwari (3x33 = 99 MW) L&T	666.47	1577	910.53	136.62	84
Teesta Stage VI (4x125 = 500 MW) Lanco Energy Pvt. Ltd.	3283.08	7542	4258.92	129.72	108
Ratle (4x205+1x30) = 850 MW Ratle HEP Pvt .Ltd.	5517.02	6257	739.98	13.41	60

*As provided by project developer [4]

The **Chart-1** shows a **Comparison of the Original Cost at the time of project inception and the anticipated Final Cost at the project completion**. It can be drawn from above that the **percentage variation in cost** of these projects is as high as **158%**. The unforeseen and unanticipated impediments lead to time overrun and undesirable escalation in project costs. This may be due to **exchange rate variation** affecting components procured from abroad and associated hike in customs duty. There may be changes in **scope of project** due to inevitable design changes occurred due to poor geology or better design discovered at latter stage. There may be changes in **bill of quantities, addition/deletion** of components as per revised needs. In time duration of stalling there can be **variation in statutory levies/taxes and cess** which need to be incorporated at a later stage. This **underestimation/overestimation** leads to cost overrun of the project and the project developer may lose interest and willingness in continuing the project due to staggering finances as seen in the case of *Ratle HEP*. The **financial health of the project** developer during time overrun to meet the cost overrun is a big hurdle in development of hydropower.

The **Fig-5** below shows bar graph comparing the escalation in costs of the discussed projects reaching as high as **11149.82crores** as in case of Subansiri Lower(2000MW) due to unsought local agitation/bandhs.

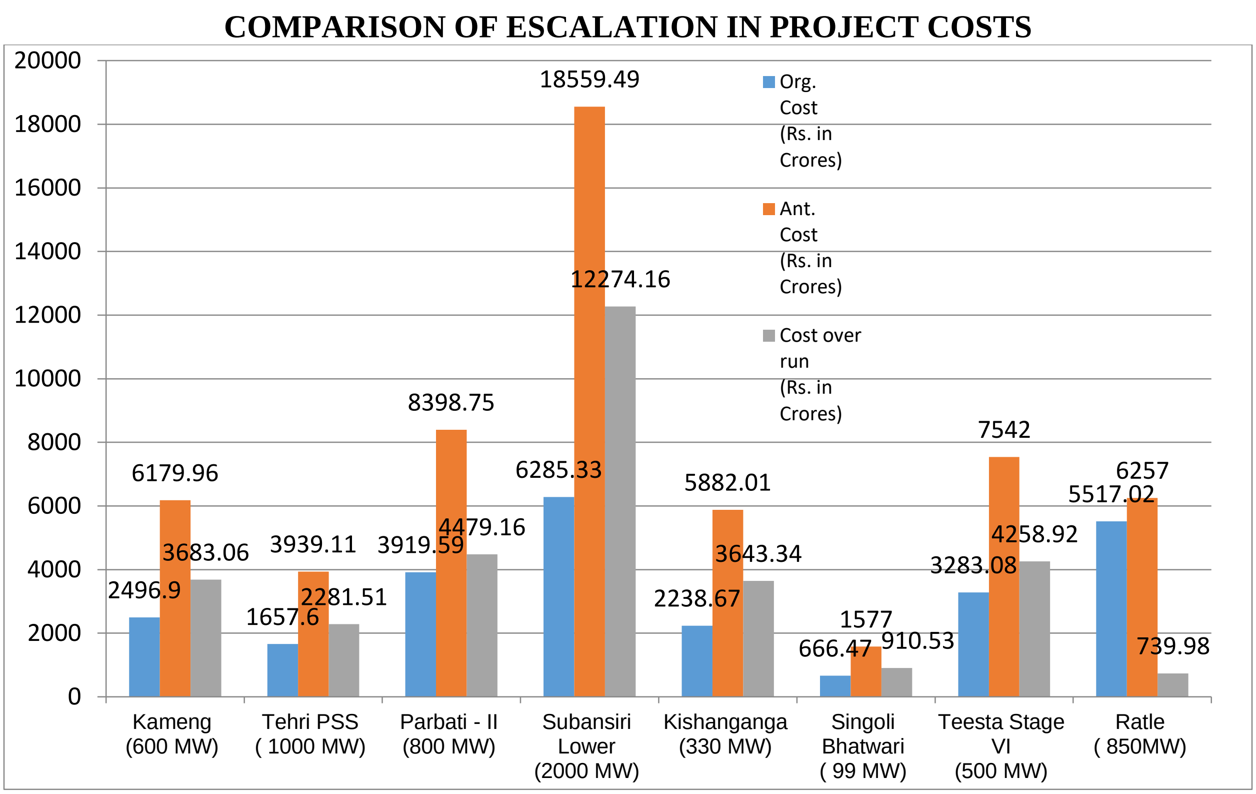


FIG-5

Fig-6 [5 Data is taken from CEA Reports] below represents the case of *Chamera-III Project 231MW* in Himachal Pradesh, which was accorded Techno Economic Concurrence(TEC) on 10.10.2003. Project was commissioned and declared under Commercial Operation on 4.7.2012 with a *lapse of 8 years 9 months* after grant of TEC. There was an **increase of 45.71%** in the submitted completion cost comparing it with CCEA sanctioned cost at Feb 2005 PL with an increase in project cost by Rs 642.48 crores w.r.t to the approved DPR cost at planning stage. This was due to *agitation by locals* which disrupted the work at site and damage to equipments by them in June 2006.Later, washing away of Coffer dam during flash flood in July 2007 and shutting down of main crusher plant by State Govt. Price Escalation, Over/Under estimate contributed to 26% and 18% of the total variation (45.71%) in cost contributed.

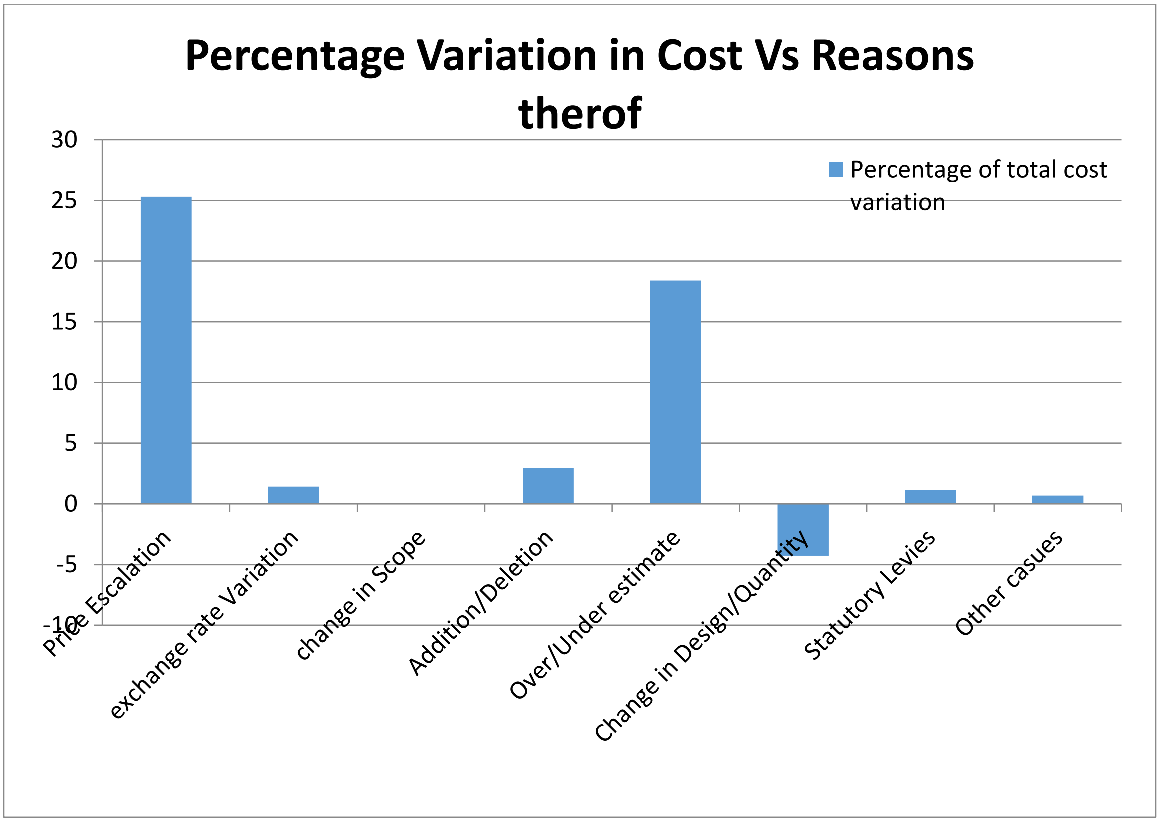


FIG-6

CONCLUSION

The Initial investment approval accorded to a hydro project at the Detailed Project Report stage is at certain **Price Level which does not include price escalation, increase on account of price variation, exchange rate variation and any other change in statutory levies**. Unforeseen Impediments and challenges like poor geology, geological surprises, natural calamities, local agitation/bandhs, Rehabilitation and Resettlement Issues, Environmental and Forest Clearances, Contractual Problems cause huge time and cost overruns resulting in **high tariff** and subsequent reluctance of states to sign power purchase agreements (PPAs). Thus *hampering the development of clean green hydroelectric power in the country*. For instance, the revised costs to establish the projects such as Kishanganga, Teesta VI and Kameng are higher by 62 per cent, 29 per cent and 47.51 per cent, respectively. Though the financing (loan) is for 12 or 15 years, to repay the complete loan within 12 to 15 years the cash flow is derived from tariff only. So, during the initial years, the tariff is fixed more and due to this high (upfront) cost the tariff of hydro power project is coming in the range of **Rs 5-6 per unit** and the states are not ready to purchase at this rate. Moreover, with the tariff of *Solar power falling to Rs 2.44 per unit* for (Bhadla solar power project) and *wind power to a record low of Rs 2.64 per unit* there is stiff **competition for**

hydropower procurement .Thus the inherent challenges and impediments in development of hydropower primarily on account of risk associated with implementation should be mitigated to have compatible risk adjusted returns for the project developers and attracting more investment in the sector. Government must adopt a two pronged approach of removing the impediments and restoring the investor's interest in the sector to create an enabling environment. Different financial incentives (e.g. tax credit bonds, production tax credit, incentive payments) should be provided to encourage the growth of hydropower generation. Further for expediting *hydropower expansion in mission mode* some steps which can be taken are: (i) **Declaring all hydro projects as renewable energy sources as done in the UK and Brazil** and introducing Hydro Power Obligation (HPO) (ii) Reinstating mega power benefit for hydro projects which offered incentives in terms of waiver of customs duties (discontinued after 2012) and (iii) proving better financing options (long-term loans, tax-free bonds, etc.).Also, as the capacity of many existing hydropower plants has potential to be raised by 5 to 20%, as such **refurbishment projects** may be taken up frequently. They are easier from a technical and social point of view, and fast in implementation with relatively more cost effective benefits than new plants.

Thus hydropower-a clean energy technology must be **incentivized** as it helps in **decarbonizing the energy mix** in two ways- the primary benefit is its clean, renewable electricity. The secondary benefit is as an enabler to greater contribution of other renewables on the grid. Hydropower development also has capability of transforming rural economy along with other benefits. The most important being water supply, flood and drought control, and irrigation, navigation and recreational activities also have their place. Such **multiple outcomes** can be achieved only from sustainable hydropower development. This role will become even more important in the coming decades, as the shares of **variable and uncertain renewable electricity sources – primarily Wind Power and Solar Power** will also increase considerably. The possible contribution of hydropower to **help balance fluctuations in electricity supply** from wind and solar power can be immense

Looking into the future, the most important drivers for hydropower development will continue to be: long and productive local generation capability with low life-cycle costs, proven reliability of electricity production, with few service interruptions, safe operation, with minimum risks to hydropower staff and the general public. Environmental and socially sustainable development, providing climate change mitigation, flexible operations, energy services enhancing grid stability and enabling use of variable renewables, large-scale energy storage for seasonal load balancing, provision of many non-energy services such as flood control, water supply and irrigation, especially in the context of growing freshwater needs and adaptation to climate change. Efforts are to be made to understand and mitigate the impediments in development of hydropower as discussed in the paper and thus **curbing the huge time and cost overruns to pave a unpolluted green path towards development of this clean source of energy-Hydropower.**

References:

[1], [2], [5] Data is taken from CEA Reports

[3] Data is taken from MoP website

[4] Data is as provided by project developer

Disclaimer

All views expressed in the paper are of the authors and not necessarily of the organization they represent.

Design Challenges on Redundancy in Power and Control Circuit of Large Variable Speed Hydro Generating Unit

Research findings from a THDC Funded Project Conducted at IIT Roorkee

Lead Researcher:
Dr. Thanga Raj Chelliah
Assistant Professor of Hydro-Electric Systems
Hydropower Simulation Lab.
IIT ROORKEE
Mobile: 9456593798
Email: thangfwt@iitr.ac.in

Research Fellows (Co-Researchers):
Mr. Raghu Selvaraj
Junior Research Fellow
Hydropower Simulation Lab.
IIT ROORKEE
Email: raghu.dwt2016@iitr.ac.in
Phone: 9043463240

Mr. Karthik Desingu
Junior Research Fellow
Hydropower Simulation Lab.
IIT ROORKEE
Email: karth.dwt2015@iitr.ac.in
Phone: 7060864358

Mr. Anto Joseph
Senior Research Fellow
Hydropower Simulation Lab.
IIT ROORKEE
Email: antoj.dwt2014@iitr.ac.in
Phone: 9557506886

Design Challenges on Redundancy in Power and Control Circuit of Large Variable Speed Hydro Generating Unit

Raghu Selvaraj, Karthik Desingu, Anto Joseph and Thanga Raj Chelliah
Hydropower Simulation Laboratory,
Department of Water Resources Development and Management,
Indian Institute of Technology, Roorkee, India-247 667.
raghu.dwt2016@iitr.ac.in, karth.dwt2015@iitr.ac.in, antoj.dwt2014@iitr.ac.in, thangfwt@iitr.ac.in.

Abstract

Due to the shortcomings and the threats posed by the conventional fossil fuel and nuclear power sources, the power engineering community is now focusing on renewable energy sources such as solar, wind, fuel cell, and biomass. In India, as part of this vision, ambitious target of 175GW renewable energy generation is planned with 100 GW of solar energy, 60 GW of wind and 15 GW of bio mass power by 2022. The stochastic nature of renewables impacts the quality and security of the supply within the hosting networks, the technical issues related to this integration represent a challenge for regulating authorities, network operators, and manufacturers. To overcome these ramping requirements an additional bulk energy storage system must be adopted to operate with high power discharge, quick response, voltage and frequency supports for transmission line. Among the various bulk energy storage systems Pump Storage Power Plants (PSPP) offer an attractive solution with good dynamic stability. Variable speed PSPP is emerging now for the sites with wide variation in water head. This article discusses the practical challenges associated with the excitation system (power converter and control system redundancy) of a large rated variable speed DFIM based hydro generation unit. In addition to that it suggests a possible solution to provide redundancy in excitation circuit to increase the continuity of operation of generating units.

I. Introduction

Pumped Storage Power Plant (PSPP), Compressed Air Energy Storage System (CAESS), Battery Energy Storage System (BESS), Flywheel Energy Storage, Superconducting Magnetic Energy Storage System (SMES) and Supercapacitors are the major sources considered as grid level energy storage systems [1]. Among them, PSPP facilitates bulk storage with high ramp. In India, 4804 MW fixed speed PSPPs were installed which suffer a major drawback of reduction in energy efficiency at partial generation/pumping mode. The aforementioned drawback can be overcome by the variable speed PSPP. In order to enable variable speed operation of synchronous machines based PSPP, power electronic converters, equivalent to machine rating, must be employed in stator circuit to match the grid requirements. Such employment of large rated power electronic converter is not economical [2]. Therefore, DFIM based variable speed PSPPs are gaining preference all over the world (e.g. 400 MW PSPP, Ohkawachi, Japan; 250MW PSPP, Linthal, Switzerland, 2X390 MW PSPP, Frades-II, Portugal) since they provide variable speed operation with reduced power converter rating and high dynamic stability [3], [4]. In India, the first variable speed PSPP having 4 nos. of 250MW DFIM totaling to a capacity of 1000MW is under construction at the Tehri Dam of Uttarakhand state.

As per the regulation of National Load Despatch Centre (NLDC) in India, the generating plants should meet grid demand as per the schedule given in every 15 minutes. To effective implementation of this regulation Central Electricity Authority (CEA) (India) had mandated the power plants above 100 MW capacity should have power and control redundancies [5]. In case of synchronous machine based fixed speed hydro, redundancy is ensured by means of two fully automatic power converter units with independent control and automatic change over. But it noted that redundancy in DFIM based variable speed hydro is not yet adopted in any of the commissioned hydro generating units because of few operational challenges discussed in section III [6].

This article is organized as follows, section II describes a 250MW DFIM based variable speed hydro and it is followed by the technical challenges associated with power redundancy of large rated variable speed PSPP in section III. Section IV suggests a possible solution for power redundancy. Concluding remarks are summarized in section VIII.

II. System Description of 250MW DFIM Variable Speed PSP

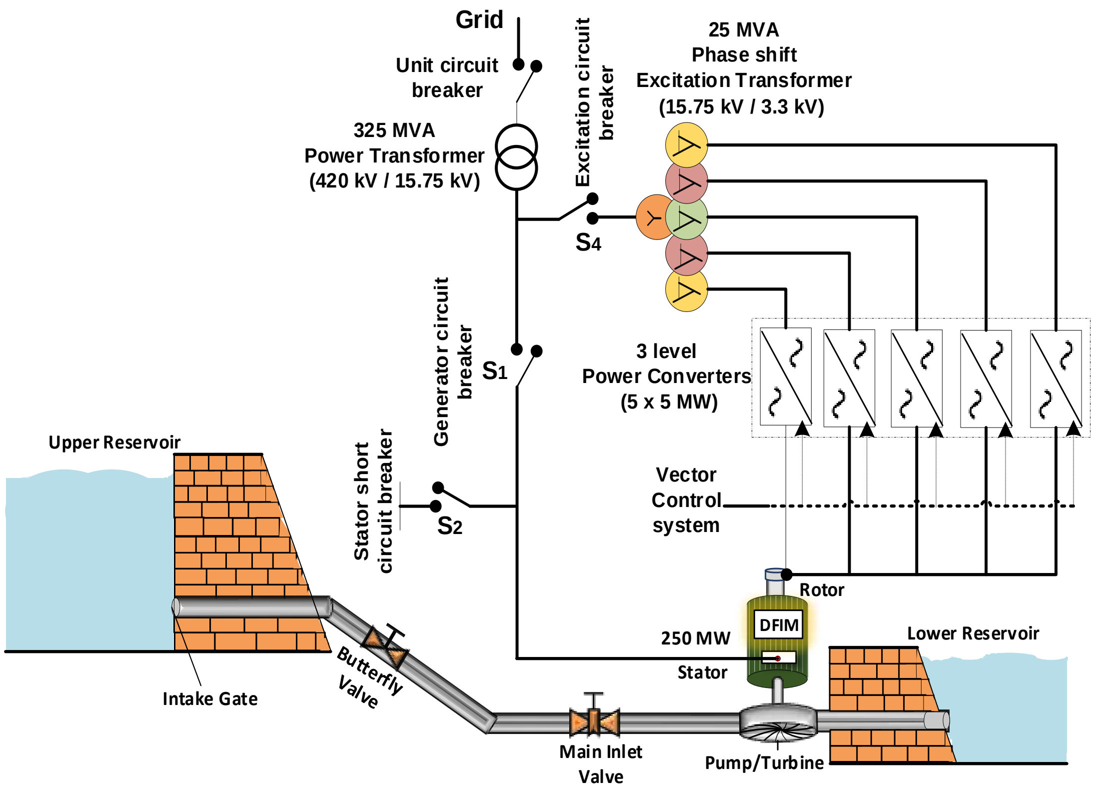


Fig.1 Hydrological and electrical depiction of a 250 MW variable speed PSPP unit

Stator circuit of DFIM is directly connected to 400 kV grid with the help of power transformer and rotor circuit is also connected to the power converters through phase shifting excitation transformer. Due to limitation in semiconductor devices ratings, voltage source converters are employed in parallel to share the rotor currents. Grid voltage oriented vector control is employed to ensure dc link voltage control with unity power factor. Detailed hydrological and electrical depiction is shown in Fig.1. The machine is able to operate in three modes namely: synchronous, super-synchronous and subsynchronous modes to transfer/absorb electrical power.

III. Operational Issues of Power Converters in Variable Speed PSPP

A 250 MW machine employed with five parallel connected converters in rotor side to handle the rotor current of 11,600 A is considered in this article. The identified operational issues associated with DFIM the serving to variable speed PSPP's are:

a. Power Redundancy during the Converter Fault.

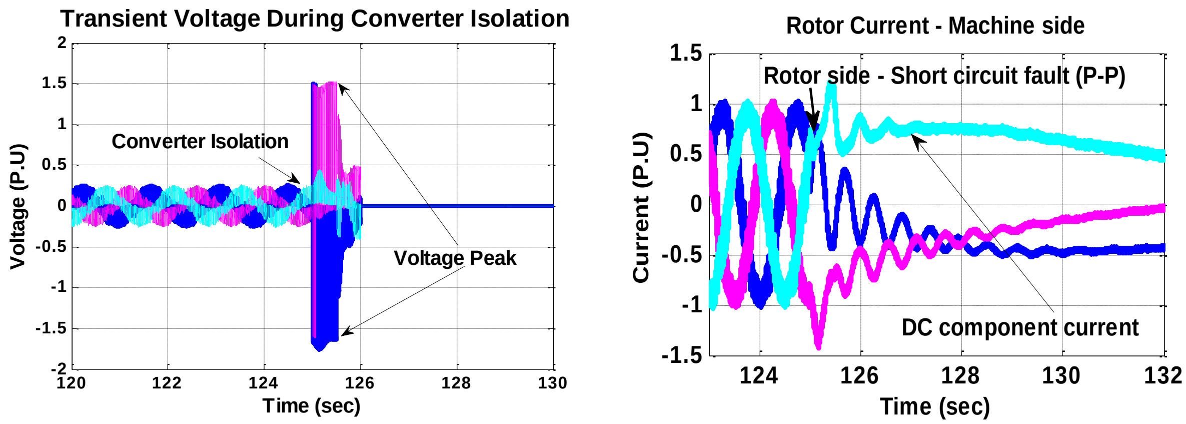
Electric drives suffer with 38% failure due to the faults such as power semiconductor devices failure, dc link capacitor, and gate driver failure [7][8]. Faults associated with these power converters may result in stoppage of unit for more than 8 hours. To overcome the financial implication due to unscheduled stoppage redundancy in power and control circuit needs to be implemented. The following issues are identified while employing contactors for the isolation of faulty converters.

i. Contactor used in series with each power converters in parallel converter system

The contactors employed in series with power converter generates high transient voltage in the parallel connected systems [9]. Due to the sudden transient voltage in rotor winding causes insulation failure. In addition, it may cause deleterious effects on the power devices are in operation. To investigate the effect of interruption through a breaker/contractor in rotor excitation circuit, the drive is modeled and isolation operation is performed in Matlab Simulink environment. From the test results, it is observed that rotor voltage reaches upto 1.75 p.u, shown in Fig. 2(a) during isolation of single converter. As per the standard ANSI/IEEE C37.013-1993, the transient recovery voltages (TRV) is limited to 1.34 times rms value of the rotor voltage and the TRV rate is limited to 0.6kV/µs in DFIM unit [10]. But it is observed that rotor excitation voltage is increased beyond its limit which may cause damage in rotor windings and maintenance related issues [11], [12].

ii. Detection of dc component during a fault

In short switch circuit fault, high current amplitude with very low frequency is produced in rotor side (typically absence of zero crossing). The short switch fault poses problems/challenges in detection of fault component due to the dynamic slip frequency variation. According to the standards IEC 62271-100 and IEEE C37.013-1997, the isolation process should be completed within 40ms [13]. To analyze the dc component magnitude a short circuit fault is created in single power converter at rotor circuit. From the test results, it is observed that short circuit fault in rotor possess high current magnitude (about 1.85 p.u) and very low-frequency (< 0.5 Hz) is shown in Fig.2 (b). The detection of dc component and



(a) Response of contactor used to isolate faulty converter from a rotor excitation circuit of 250MW DFIM

(b) Response of Rotor side –short circuit fault (IGBT –single leg)

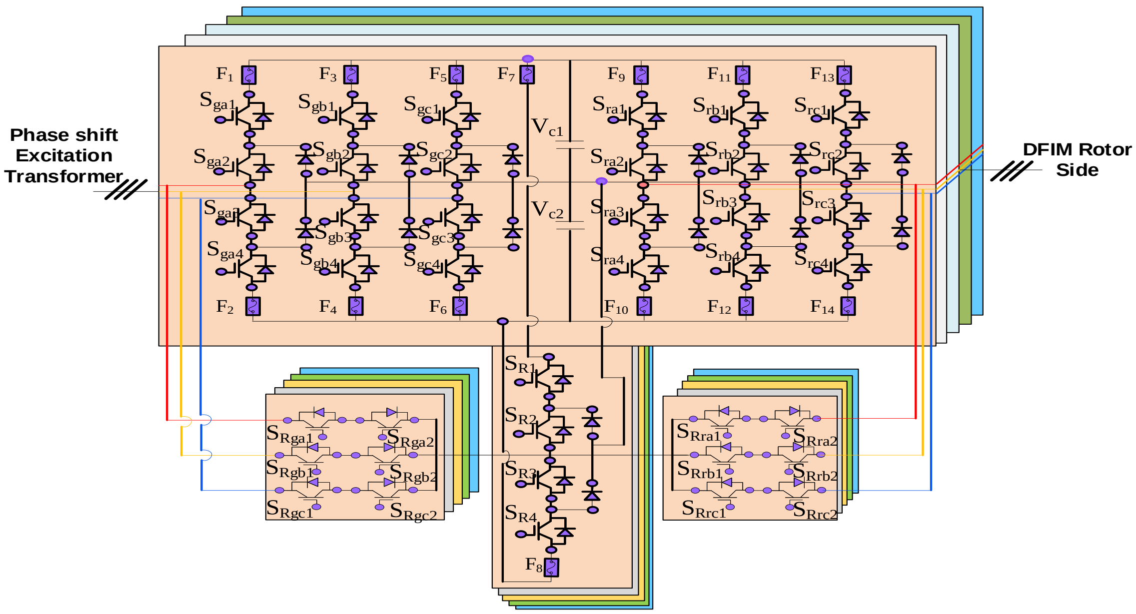
Fig. 2. Operational challenges in power redundancy of typical 250MW hydro generating unit

to break such a high amplitude current during fault by contactors is very difficult, prolonging the fault isolation process resulting the possibility of damage of other converter modules.

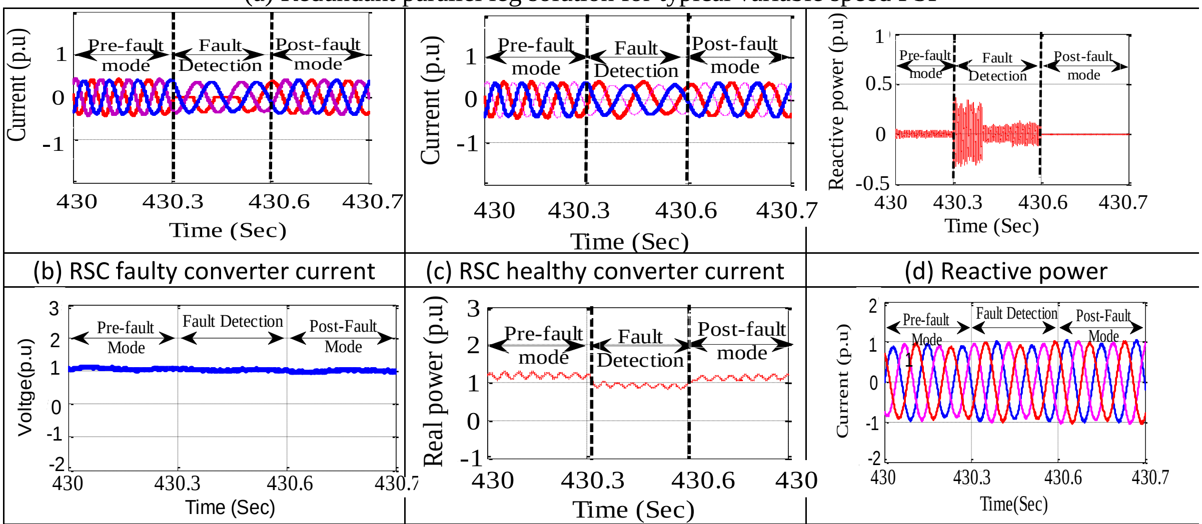
IV. Research Solutions for Power Converter Redundancy

In industrial applications, N+1 flying spare parallel redundancy converters are adopted to obtain high reliability [14][15]. While opting N+1 redundancy scheme for variable speed PSPP, isolation of faulty converter from the rotor excitation circuit may generate overvoltage across rotor windings, which causes motor insulation failure as discussed in the previous section. In addition to that faulty converter generates higher amount of dc component which will pose difficulty in fault identification. To overcome these operational issues, an efficient redundant operation or circuit to be designed with low cost to meet the requirements of redundancy.

Compared to N+1 redundancy, various redundant options were tried out in the Hydropower Simulation Laboratory of Indian Institute of Technology Roorkee. From the test results, it is observed that switching state redundancy, DC bus midpoint configuration, redundant parallel leg configuration are suitable for large rated PSPP. Among them switching state redundancy and DC bus midpoint configuration operate with reduced power delivery and suffer from mechanical vibration. Therefore, parallel leg redundancy topology is



(a) Redundant parallel leg solution for typical variable speed PSP



(b) RSC faulty converter current | (c) RSC healthy converter current | (d) Reactive power

(e) DC link voltage | (f) Real power delivery | (g) stator current

Fig. 3. Performance of redundant parallel leg in typical 250 MW DFIM

identified as a suitable method for rotor excitation circuit. The research team has developed redundant parallel leg circuit for large rated variable speed PSPP with park current vector approach for fault identification without degradation in output voltage as shown in Fig.3.

The redundant parallel leg circuit shall be helpful to the generating units with higher reliability. It may be noted that this method (redundant parallel leg topology) is under testing phase in the laboratory and its performance shall be comprehensively discussed in the future article. In addition, the research team is working towards the fault reconfiguration in parallel connected converter fed rotor excitation with less number of devices. To investigate the operation of proposed parallel redundant leg circuit a 250 MW DFIM is simulated in Matlab Simulink environment and the results are shown in Fig.3. In order to observe the performance, fault is created in the A-phase of RSC at 430.3 sec. At fault instant, there is an oscillation in the real power delivery, shown in Fig.3 (e), and the machine absorbs the reactive power from the grid, shown in Fig.3 (d). After the fault identification and reconfiguration of redundant parallel leg the system is restored with the desired power delivery, which can be seen at Fig.3(b-e).

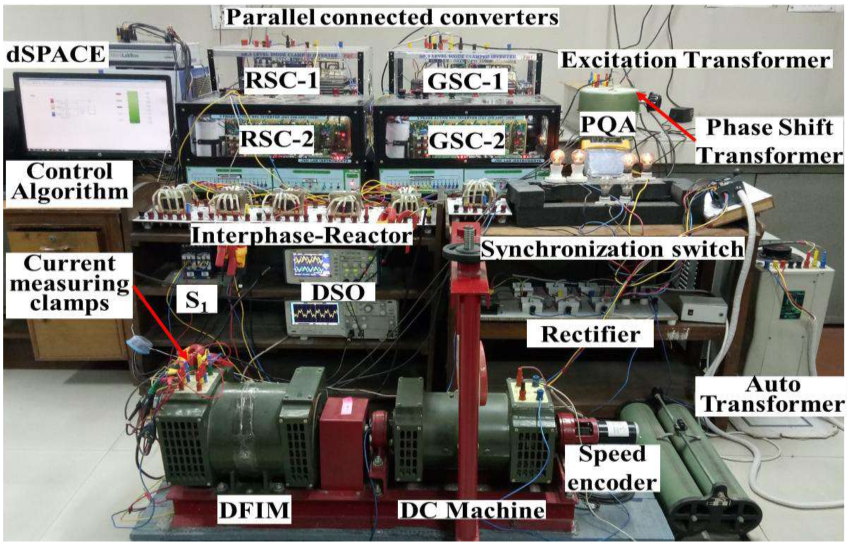


Fig. 4. Experimental set-up

Experimental set-up of 2.2kW DFIM with available equipments in the laboratory, shown in Fig. 4, is developed to validate the results obtained from simulation tests. To supress the circulating current interphase reactors are used. GSC and RSC are controlled by a dSPACE 1202 real time controller (TMS320F240 DSP). In-built hall effect current sensors in converter module is used for measuring rotor and stator currents and Quadrature Encoder Pulse (QEP) type encoder (1024 pulses per revolution) is used for speed and position measurement.

V. Conclusion

Power converter plays a vital role in integration of RES to the utility grid. The identified fault tolerant operation finds wide range of applications including hydro, wind, solar and flywheel energy systems. The proposed redundant parallel leg ovecomes the practical challeges associated with the implementation of redundancy in large rated asynchronous hydro generating systems. The simulation results were validated in an experimental set-up rated at 2.2kW capacity. However, the experimental setup available in the laboratory has its own limitation (e.g. two channels of power converters were used instead of five channels, etc.). To realize its suitability to the projects, a real-time power hardware in-loop (PHiL) simulation is highly recommended. The laboratory presently seeks funding opportunity to develop this set-up which shall be helpful to policy makers and project authorities during design stage of their future projects.

Acknowledgement

Authors thank THDC India Limited for the financial support provided this work, along with research fellowships.

References

1. J.P. Deane, B.P. Gallachóir, and E.J. McKeogh, "Techno-economic review of existing and new pumped hydro energy storage plant," J. Renew. Sustain. Energy Rev, vol.14, no.4, pp. 1293-1302, May 2010.
2. M. Swain, "Pumped storage hydropower plant," Electrical India, pp. 127-136, November 2013.
3. T. S. Kuwabara, A. Furuta, H. Kita, and E. Mitsuhashi, "Design and dynamic response characteristics of 400MW adjustable speed pumped storage unit for Ohkawachi power station," *IEEE Trans. Energy Convers*, vol. 11, no.2, pp. 376-384, June 1996.
4. M. Harris, "Switzerland's 1000-MW Linthal pumped-storage plant connected to grid", *Hydro Review*, Zurich, January 2016.
5. Central Electricity Authority of India, "Technical standards for connectivity to the grid – Hydropower plant," 2007.
6. A. Joseph and T. R. Chelliah, "A Review of Power Electronic Converters for Variable Speed Pumped Storage Plants: Configurations, Operational Challenges and Future Scopes," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. PP, no. 99, pp. 1-1.doi: 10.1109/JESTPE.2017.2707397
7. J. K. Lung, Y. Lu, W.L. Hung, and W.S. Kao, "Modeling and dynamic simulations of doubly fed adjustable-speed pumped storage units," *IEEE Trans. Energy Convers*, vol. 22, no.2, pp. 250-258, June 2007
8. A. Erlich, and U. Bachmann, "Dynamic behavior of variable speed pump storage units in the German electric power system," in *Proc. 15th Triennial World Congress Conf.*, pp. 1-6, Spain, July 2002.
9. R.R. Errabelli, and P. Mutschler, "Fault-tolerant voltage source inverter for permanent magnet drives," *IEEE Trans. Power Electron*., vol. 27, no. 2, pp. 500-508, February 2012.
10. D.L. Swindler, P. Schwartz, P.S. Hamer, and S.R. Lambert, "Transient recovery voltage considerations in the application of medium-voltage circuit breakers," *IEEE Trans. Ind. Appl*., vol.33, no.2, pp.383-388, March 1997.
11. IEEE application guide for transient recovery voltage for AC highvoltage circuit breakers, *IEEE Std* C37.011-2005, vol.1, no.1, pp. 01-62, 2006.
12. D. Braun, and G. Koeppl, "Transient recovery voltages during the switching under out-of-phase conditions," in *Proc. IEEE Intl. Conf. Power Sys. Transients*, pp.1-5, USA, September 2003
13. IEEE standard for ac high-voltage generator circuit - breaker rated on a symmetrical current basis, revision of *IEEE Std*. C37.013-1993
14. Y. Song, and B. Wang, "Survey on reliability of power electronic systems," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp.591-604, January 2013.
15. R.-D. Klug and A. Mertens, "Reliability of megawatt drive concepts," in *Proc. IEEE Int. Conf. Ind. Technol.*, Maribor, Slovenia, Dec. 2003, pp. 636–641.

DAY 1: 20TH FEB 2018

SESSION 3:

RENEWABLE ENERGY

A snapshot of Research and Development projects undertaken by CPRI during the 12th Five Year Plan

A. Chakraborty
Engg. Officer,
Central Power Research Institute
Email:arka@cpri.in

R.A.Deshpande
Additional Director,
Central Power Research Institute
Email:rad@cpri.in

Abstract: A safe, reliable and environmentally sustainable Power Sector forms the key to continual economic development of the nation. Thus providing access to reliable and quality power supply to all citizens/ establishments forms the central focus of the Ministry of Power for the nation and the "24x7 Power For All" program is aimed at delivering on it. The country, also, has set an ambitious target of adding 175 GW of renewable generation capacity by 2022 to demonstrate its commitment to a better future for the next generation and to fight the adverse effects of climate change. In order to realize an uninterrupted and reliable power supply and also integrate high penetration of renewables into the grid effectively, several R&D projects have been undertaken through the various research schemes of Ministry of Power which are co-ordinated by Central Power Research Institute (CPRI) under the guidance of Central Electricity Authority (CEA).

Introduction

One of the core visions of the Government of India is to provide each household access to electricity round the clock through its '24x7 Power for All' program. The Government of India has also stressed on incorporating clean energy into the Indian Power System and has set an ambitious target of adding 175 GW of renewable generation capacity by 2022. Research and Development is a priority focus area in the power sector. With a vision for providing affordable quality power to each strata of the Society , it is not only necessary to ensure that, state-of-the-art technology is utilized but also appropriate technology is developed addressing the societal needs and achieving national prosperity.

In order to enhance the supply of energy at affordable price and deliver it efficiently and sustainably, a focussed approach for carrying out applied research has been undertaken by the Ministry of Power. In accordance to Section 3(4) of Electricity Act, 2003, the Central Electricity Authority (CEA) has prepared a National Electricity Plan, in agreement with the National Electricity Policy. The first National Electricity Plan covering the review of 10th plan, detailed plan for 11th plan and perspective plan for 12th Plan was notified in the Gazette in August, 2007.The Second National Electricity Plan covering the review of 11th plan, detailed plan for 12th plan and perspective Plan for 13th plan was notified in the Gazette in December, 2013 in two volumes (Volume-I, Generation and Volume-II, Transmission). The major thrust areas of research for the Power Sector has been identified in the National Electricity Plan document. [1]

Research and Development on the priority areas identified in the National Electricity Plan for the Indian power sector is promoted through Central Power Research Institute (CPRI), which encourages applied research leading to technology development in the power sector through the following three schemes:

- In-House R&D (IHRD)
- Research Scheme on Power (RSoP)
- R&D under National Perspective Plan (NPP)

CPRI has played crucial role in creation of a conducive environment for R&D to flourish in the country by carrying out/co-ordinating various research projects on identified thrust areas leading to new technology development, evaluation studies for bringing out new standards and process improvement, in a collaborative nature involving Utility, Industry, Academia and Research Organizations.

Research Areas

The operation of Indian Power Sector is based on three activities namely Generation, Transmission and Distribution. During the 12th Five year plan research projects were undertaken on various identified areas related to the above three areas with special emphasis on improvement in efficiency and development of technologies customized as per Indian Requirements. A total of 80 projects were recommended for execution after comprehensive evaluation done by Technical Committees with members from Academia and Industry and approved by the Standing Committee on R&D(SCRD) chaired by Chairperson CEA and having representation from IITs, MNRE, DST, POWERGRID, NTPC etc.

The following figure shows the number of projects undertaken in each area:

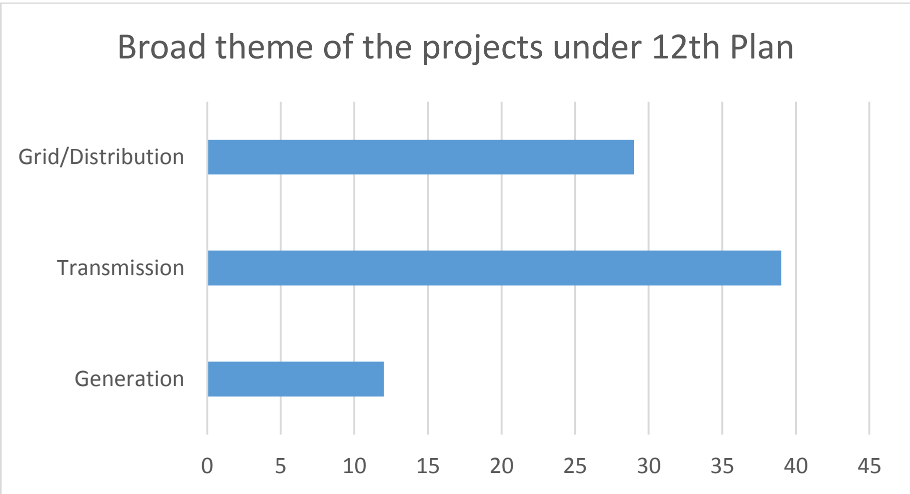


Fig 1: Theme of projects undertaken during 12th Plan

The projects under Generation mainly addresses the challenges in Thermal and Hydro Generation. The projects under Transmission explored new technologies for improving the transmission scenario of India. Majority of the projects undertaken under Grid/Distribution were not only related to improving the operating capabilities of micro-grid and smart grids but also development of energy efficient technologies for the Indian Power Sector.

Research undertaken in the area of Power Generation

The total installed capacity of the Indian Power sector as on December 2017 stands at 330.861 GW. The generation capacity mix is illustrated in the figure below (source: Central Electricity Authority (CEA)) [2]

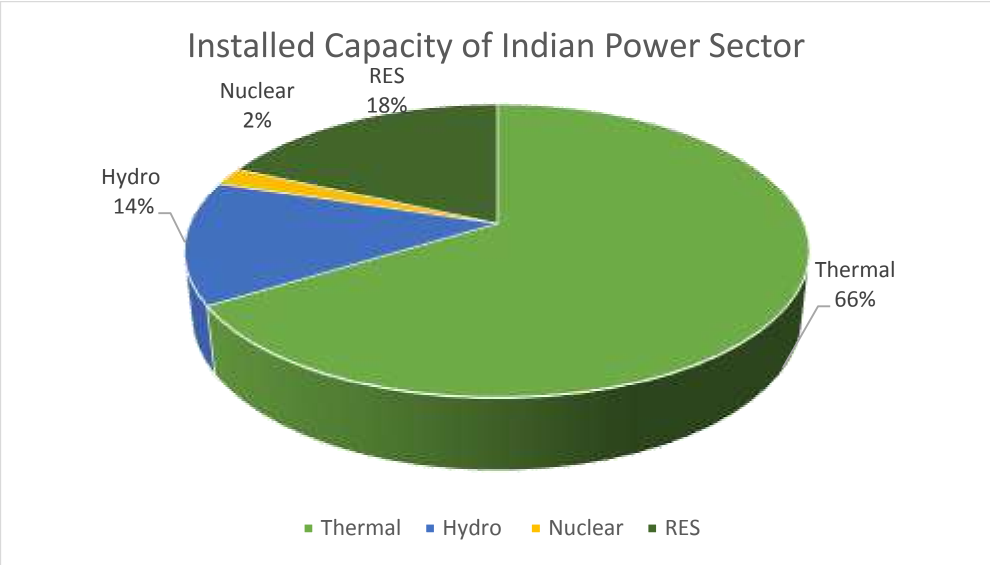


Fig 2: Installed capacity mix of the Indian Power Sector

As the generation sector is mostly dominated by the Thermal and Hydro based plants much research on identified topics were carried out during the 12th Five year plan for the improvement in efficiency of the plants and devising the state of the art capabilities for the power plants.

Research projects on Thermal Generation

The most important component in Thermal Generation is coal. However, the air pollution emissions accompanying the coal combustion are significant; among these pollutants are oxides of sulphur (SOx) and nitrogen (NOx), which lead to acid rain and ozone depletion. In addition, greenhouse gas emissions (CO2, CH4, etc.) have become a global concern. In order to reduce the harmful gasses new methods like co-firing of coal i.e firing of coal with renewable fuel (i.e. Biomass) is envisaged. A project undertaken evaluated the combustion characteristics of the alternative fuels (biomass & RDF (Refuse derived fuel from municipal solid waste) etc.) mixed with high ash coals through advanced combustion experiments like TGA, Drop Tube Reactor. The study will help in finding the right mix for the co-firing technology so that the utilities can use it at an optimal cost. The second important component is water which is increasingly becoming a premium resource in terms of both cost and availability. There is need for reducing water consumption in power plants especially in water stressed areas. Thus a study has been undertaken to formulate guidelines for best practices in water & waste usage in coal based thermal power plants. The other studies relate to remaining life assessment studies on steam generator, studying erosion characteristics of boiler tube and development of gasification reactor for conversion of multi fuel to syngas for power generation.

Research projects on Hydro Generation

India is a land of rivers. The potential of Hydro-generation is immense. However, some of the present challenges in the Hydro power plants needs to be addressed like measures to tackle erosion/corrosion of underwater parts, simulation and development of Test Facility to Study the performance of Coating Material Characteristics, measures to increase service life of components. Research projects have been undertaken during the 12th Five year Plan to investigate on the above issues. In addition CPRI has also undertaken research for development of Run-of-the-River low head micro hydroelectric system for off-grid microgrid operation. Such hydro power generation scheme will be appropiate for communities residing in remote forest locations as recurrent power failure of grid connectivity due to thick forest cover can be prevented by setting up microgrid generation. Also, implementation of low head micro hydroelectric schemes will help in water conservation & drought prevention.

It has been observed that acute problems are faced during execution of underground works as well as surface structures, including dam foundation & allied components of hydroelectric projects, especially in the Himalayan region. Generally, the problems encountered are due to adverse geological set up and complex issues related to geothermal condition, release of toxic/inflammable gas etc. Accordingly, for successful completion of the project, awareness and due preparedness is necessary. Thus two projects were undertaken one for compilation of of data on latest technologies in geological & geotechnical investigations and problems faced & mitigation measures adopted during execution of hydroelectric projects and development of a selection methodology for road header and tunnel boring machine in different geological conditions for rapid tunnelling. These projects will help in minimizing geological surprises and in enhancing the efficiency of project construction under challenging situations with due knowledge about the advancements & best practices in project investigation and execution.

Research projects on Transmission

The Indian Power Sector at present faces various challenges in the area of Transmission. On one side there is a need to develop technologies for reducing transmission loss and also focus on some of the latest technologies indigenously. A High Temperature Superconducting cable was indigenously developed in one of the projects undertaken.

The other projects undertaken were aimed at improvement of performance of transformers, partial discharge, High Voltage and Ultra High Voltage Transmission lines and experiments to enhance performance of insulating fluids. A study was also undertaken to device a Comprehensive Test to distinguish between the Qualities of Primary and Secondary Grade Electrical (CRGO) Steels. Keeping up with the global trends in application of nano materials in power sector, projects relating to development of nano-materials for enhancing electrical insulation were undertaken.

Riding on the latest trend of incorporating smartness into devices projects were undertaken to come up with technologies for smart transmission network like Fault Signature Analysis for fault detection and location assessment using measurements from Phasor Measurement Units (PMUs) and Smart Transmission through Wide Area Measurement System to control and co-ordinate HVDC/FACTS devices.

Research projects on Grid, Distribution and Energy Conservation

Generation from Renewable Energy Sources (RES) is continuously increasing due to its low carbon emission. The major avenues for energy generation from RES in India are roof-top solar plants, wind mills, biogas plants, solar lighting, standalone solar and biomass- based power generators and micro-hydro plants.

As per data from MNRE, at the end of October 2017 India's installed grid-interactive solar power capacity was 15574.71 MW, compared to 32715.37 MW of wind power capacity, 4399.35 MW of small hydro capacity and 8181.70 MW of biomass capacity. In off-grid captive power, solar photovoltaic (PV) had an installed capacity of 539.13 MW, biomass cogeneration 661.41 MW, biomass gasifier 163.37 MW and waste-to-energy 175.45 MW. [3]

Projects undertaken mainly aims at simulation, development of micro grids and study on suitable control mechanism, stability and providing an intelligent and efficient solution for smooth operation of standalone and grid connected solar PV micro-grid and smart grids. Some of the projects undertaken also intends to study PV degradation and identification of best-suited technology for maximum solar PV generation along with development of Solar PV and Wind forecasting technologies.

One of the prime challenges for generation from RES has been storage of energy for use at a later time period. Thus projects related to new technologies like redox-flow battery and ultra-capacitors were undertaken to find an optimal solution for energy storage.

Research on Light Emitting Diode Technology

Energy efficient lighting technologies had always been an area for research in the Power Sector. With the massive push for LED lights by the Government in 2016-17, projects aiding to indigenous development of LED lamps and luminaires were taken up. These projects were suitably identified and designed to answer some of the challenges faced by the LED industry of India like indigenous and cost effective development of blue light emitting packages, capacitor less power electronics for LED lights and novel technology for thermal management of LEDs. A study was also initiated to evaluate the photo biological effects of LED.

Research on Electricity based Cooking Technologies

With a push to facilitate smooth adoption of electric cook stoves for the Indian household, CPRI in collaboration with Bureau of Energy Efficiency has initiated research on “Electricity based Cooking Technologies”. The outcome of the projects are expected to enhance the efficiency of electricity based cooking appliances , enable adaptability of these appliances for different kinds of vessels and cuisines common to Indian households.

Benefits from the Research projects

The R&D projects approved under the research scheme cover all facets of the power sector from generation, transmission, distribution/renewable integration and energy efficiency. These projects not only addresses some of the key challenges in the Indian Power Sector but also has laid the ground work for development of future technologies for the Indian Power Sector.

Under the 12th Five year Plan, there are five proposals under the NPP scheme on development of new technologies in the areas of transmission, generation and renewable energy. These projects aim at design and development of indigenous technologies with the objective of cost reduction, import substitution and employment generation. The projects when successfully completed will aid to Government of India’s vision of “Make in India”, “Skill India” and “Start-up India”.

Conclusion

With greater emphasis on manufacturing and indigenization, the need for R&D in Power has become all more essential and mandatory. R&D co-ordinated by CPRI has been highly successful in the past in developing innovative technology like fault current limiters based on high temperature superconductivity. Similarly STATCOM for steel industry and IT Park, Dynamic Voltage restorers for process industry have been developed. It is expected that the outcome of the research projects under the 12th Five year Plan will also benefit the power fraternity of India at large.

Acknowledgement

The authors are thankful to Ministry of Power, Central Electricity Authority (CEA) and members of Technical Committees and Standing Committee on R&D(SCRD) for helping CPRI in co-ordinating the research projects. The authors also thank CPRI management for their continual support, encouragement and direction provided to the R&D Management division of CPRI.

References

1. National Electricity Plan for a Period of 2017- 2022
2. "Power Sector at a Glance ALL INDIA" on Ministry of Power website.Link: http://powermin.nic.in/en/content/power-sector-glance-all-india
3. Programme/ Scheme wise Physical Progress in 2017-18 & cumulative upto the month of October, 2017 on MNRE website. Link: http://mnre.gov.in/mission-and-vision-2/achievements/

Energy generation and water savings from Floating Solar PV (FSPV) power plants

Abstract

The dependence of world's energy system on the use of fossil fuels raises serious environmental concerns, the foremost being an irreversible change in the planet's climate. Anthropogenic activities, with emissions from fossil fuels at the core, contribute to a variety of climate change impacts. These impacts range from diminished food security, increased frequency of natural disasters, extinction of species, escalated spread of vector borne diseases, rise in sea-level and accelerated erosion of coastal zones (Barros et al., 2015; Harley et al., 2006; Pearson & Dawson, 2003). The Intergovernmental Panel on Climate Change (IPCC) indicates that the net damage costs of climate change are likely to be significant and to increase over time (ESCT, 2016).

Globally, India is the fourth largest emitter in the world [annual emission of 2341 million tonnes, as of 2014 (JRC, 2015)], with the power sector contributing towards half of the country's carbon emissions. Further, as discussed in the previous section, India's economic growth is exerting pressure on existing energy infrastructure necessitating an expansion in the energy generation capacity. Any expansion plans, however, based on the current energy mix would result in an increase in not only carbon emissions, but also fuel imports. For example, despite high coal reserves, the share of imported coal in the country has grown rapidly and is expected to rise beyond 30% in the next few years because of challenges in domestic production and the quality of coal (Gupta. V, 2014). Similarly, the import of natural gas is also likely to increase from about 25% to over 60% by 2035 (CSO, 2015). Resultantly, these imports, apart from exacerbating the environment would also impede our energy security. A shift in India's energy mix for electricity generation, thereby increasing the share of renewable energy, is imperative.

Most of the renewable energy technologies such as biomass, solar and hydel, however, have a large spatial footprint. Large tracts of land are required to undertake any multi-megawatt scale energy generation. This puts a restriction on (required) land, which usually has multiple uses ranging from agriculture

and ancillary functions to supporting habitats and industries. These multiple uses also put an economic premium on land and provide the central motivation behind the development of land-neutral solar PV power plants. The development and deployment of land-neutral projects are particularly beneficial in regions where either land is in short supply, or where development of land (in case of wasteland) is expensive.

Detailed analyses of the water bodies (across 12 states of India[1]) reveal a cumulative potential of 750 Giga-watt peak (GWp). Further, if these 12 states are filtered based suitability of renewable energy policy and regulation, then the top five states have a combined potential of 190 GWp, a significant portion of which could be tapped in the coming five years.

The existing land-neutral projects include conventional PV arrays, as well as concentrated PV arrays that benefit from the surrounding water body, thereby preventing the overheating of solar cells. Common benefits, as reported, from these installations were a reduction in water evaporation from the reservoir/pond (Ferrer-Gisbert et al., 2013) and decreased algal growth (due to the reduction in sunlight penetration within the water body) (Alam & Ohgaki, 2001). Also, electrical yields were improved (Choi, Lee, & Kim, 2013), in most reported cases due to the cooling benefit offered by the underlying water surface.

The motivation behind these land-neutral solar PV power plants is threefold, namely [a] avoiding the displacement of land that could be used for agricultural expansion; [b] reduction in evaporation losses from reservoir, a definite positive for farming; and [c] accumulation of benefits from additional energy yield, largely due to the result of cooling (of solar PV modules) from water, consistent with the negative temperature coefficient performance for PV modules.

---

[1] The 12 states considered were Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Uttar Pradesh, Odisha, Gujarat, Maharashtra, Madhya Pradesh, West Bengal, Chandigarh and Rajasthan

Emerging Issues in Large-scale Wind Integrated Power Systems and their Potential Solutions

Zakir H. Rather* and Hazem Karbouj

Department of Energy Science and Engineering, IIT Bombay, Powai, Mumbai, India-400076

*zakir.rather@iitb.ac.in

Abstract: *Wind energy integration introduces various technical challenges in secure and stable operation of power system, ranging from short term frequency and voltage stability, to long term balancing and scheduling issues. However, at higher wind penetration level, in addition to known concerns, wind integration at higher penetration level introduces new and emerging operational issues. This paper, identifies such emerging issues, analyses them in detail, and subsequently suggests various potential solutions to countermeasure these challenges in large-scale wind integrated power system.*

I. Introduction

The steadily rising demand for electricity due to the rapid global economic growth, the likely fossil fuel depletion, climatic concerns associated with burning fossil fuel, and other factors make the dependence on renewable energy resources an inevitable choice. Among all renewable resources, global wind power installed capacity is the second largest after hydropower, and it is expected to be the largest ever among all the renewables due to rapidly growing wind power installation [1]. Fig. 1 shows the growth of global and Indian cumulative installed wind power generation capacity. Further, India has an ambitious target to install 60 GW of wind power and 100 GW of solar Photo Voltaic (PV) generation by the year 2022.

While, renewable energy integration has multifold advantages and environmental benefits, it introduces various technical issues in grid operation, hence warrant to address such issues for secure and stable renewable energy integration. High penetration of wind energy affects power system dynamics due to various factors, such as, intermittent and variable nature of wind, different characteristics of Wind Power Plants (WPPs) compared to conventional power plants (synchronous), capacity of WPPs, interconnection to the power grid, etc.

Wind energy conversion technology is broadly classified into four types, Squirrel Cage Induction Generator (SCIG) based wind turbine (Type 1), wound rotor induction generator based wind turbine (Type 2), Doubly-Fed Induction Generator (DFIG) wind turbine (Type 3), and full-converter wind turbine (Type 4) [2], with their respective diagrams shown in Fig. 2.

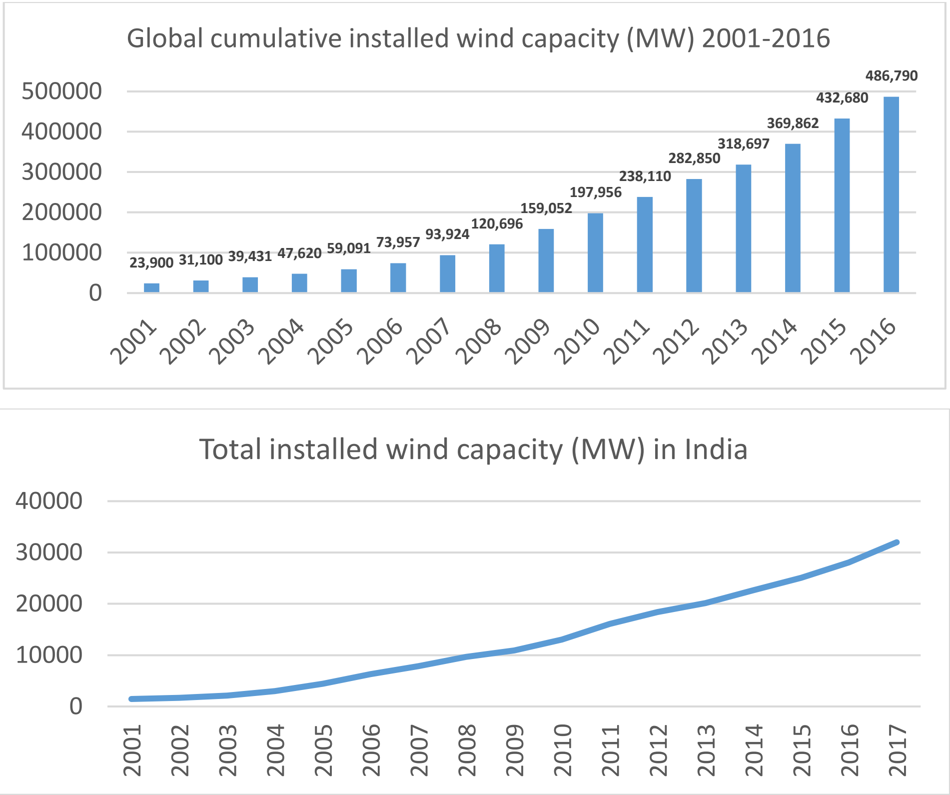


Fig. 1 Global and Indian wind power installed capacity [1]

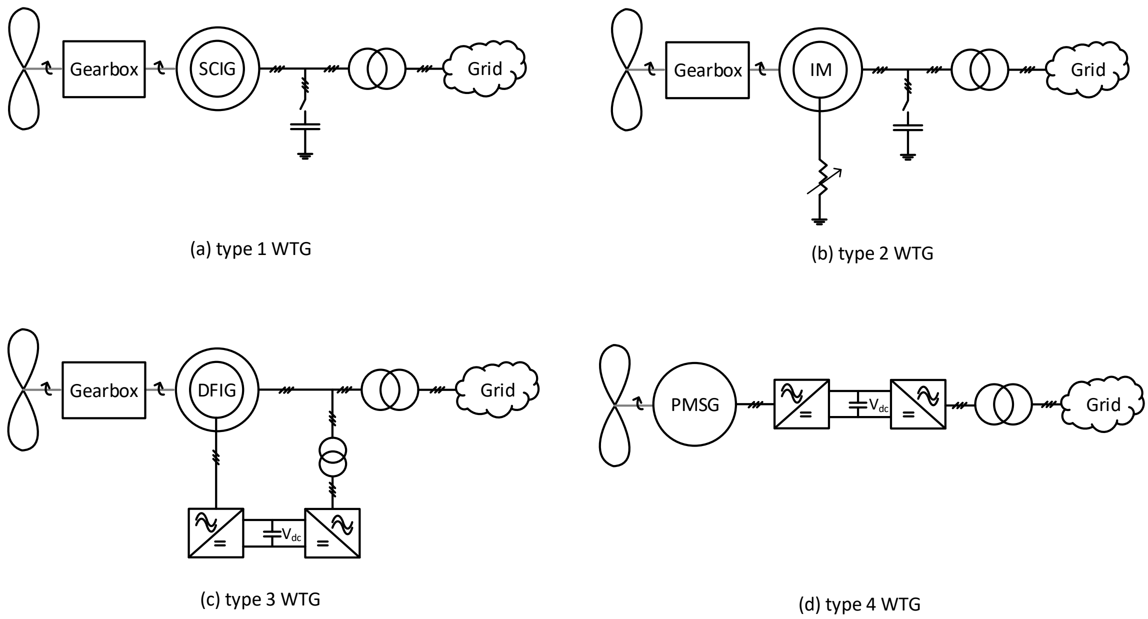


Fig. 2. Wind turbine generator types

Lack of the controllability of Type 1 and Type 2 Wind Turbine Generators (WTGs), coupled with poor grid support performance, have been the main reasons for WTG technology evolution into power electronic interfaced Type 3 and Type 4 WTGs, also known as Variable Speed WTGs (VSWTG). Type 3 WTG has highest market penetration currently, primarily due to its economic high hand compared to Type 4 WTGs. However, due to various advantages of

Type 4 WTG, such as, low maintenance and more control flexibility, offshore WPPs are generally based on Type 4 WTG technology, and are foreseen to dominate the WTG market in future.

Various countries such as Denmark, Ireland, Germany, UK are already experiencing significant wind power penetration, and are expected to see further increase in wind penetration level. Similarly, in the context of 2022 renewable energy targets of India, some of the Southern and Western states, such as, Tamil Nadu, Andhra Pradesh, and Maharashtra are also expected to experience high volume of wind power penetration.

While there are various challenges associated with wind integration, ranging from short term frequency, small signal, transient, and voltage stability, to long term issues, such as unit commitment and scheduling concerns, there are various emerging, yet critical issues associated with large scale wind integration, that warrant attention and potential countermeasures for secure and stable operation of power system at high penetration of wind power. In this backdrop, the main focus of this paper is to identify such emerging issues, their potential impact on system operation during high wind spells, such as, during monsoon months in India, and suggest potential solutions to address such emerging issues.

The potential list of emerging issues, concerning dynamic operation under large scale wind penetration are as below.

- Reduced system inertia
- Delayed active power recovery from wind turbine generator
- Diminished dynamic reactive power and short circuit power resources

II. Lack of adequate system inertia

Initial Rate of Change of Frequency (RoCoF) $\frac{df}{dt}$, due to a power disturbance of ΔP can be expressed as given in (1)

$$\frac{df}{dt} = \frac{-\Delta P}{2\,E_{sys}} \times f_o \qquad (1)$$

It can be observed from (1) that the kinetic energy E_{sys} stored in the rotating mass of generator play an important role in limiting the RoCoF, and eventually frequency nadir, see Fig. 3. When a system is exposed to a sudden generation-load imbalance, E_{sys} is released inherently to maintain the balance initially. Kinetic Energy (KE) is characterized by inertia constant H which refers to the time duration for which the generator is able to supply its rated power solely from its stored KE [6].

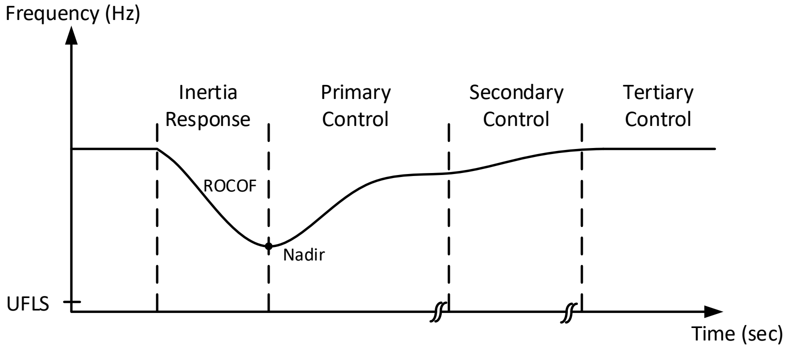


Fig. 3 Typical system frequency response

In high wind penetrated systems, conventional synchronous plants are displaced by WPPs. Such wind driven displacement of conventional power plants can be either permanent due to phasing out of conventional plant, or temporary due to non-commitment of conventional plant in a given unit commitment interval with high wind penetration. Therefore, due to less conventional plants synchronized to the grid, the net system inertia from connected rotating mass is diminished. On the other hand, power electronic interfaced variable speed WTGs lack inherent inertia contribution, required for frequency stability during any dynamic event. It is important to mention that because of VSWTG ability to extract more energy from wind, generate/consume reactive power and improve power quality, make VSWTGs more suitable in comparison to fixed speed WTGs (which are direct coupled to the grid) [3].

The main reason for VSWTG inability to contribute to the system inertia is DC bus in back-back converter which provides an electrical decouple between the network frequency and the WTG speed [4-5].

To illustrate the impact of wind penetration on system inertia, IEEE 9 bus benchmark system was developed in DIgSILENT PowerFactory platform, and was studied for various wind penetration levels. Fig. 4 shows system frequency response for three different values of wind penetration and thus net system inertia. It can be observed that even though the system is subjected to the same disturbance, the system inertia has a significant impact on system RoCoF and nadir value. Therefore, under high penetration of wind/solar PV power, power system is prone to violate set limits of RoCoF and frequency protection, for a dynamic event, and in worst cases may lead to cascaded events resulting in outage of large section of the generation, or system blackout. To avoid, such, scenarios, it is imperative to have adequate countermeasures in place, if the system is expected to experience higher levels of wind power penetration.

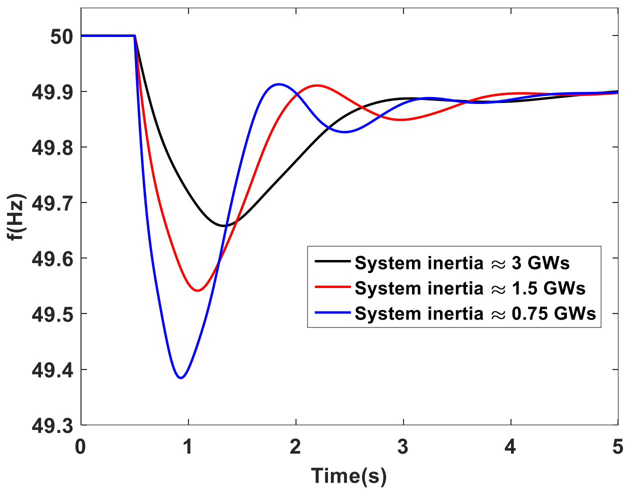


Fig. 4 IEEE 9 bus system frequency subjected to the same disturbance for different total system inertia

III. Delayed active power recovery of wind power generators

An emerging, yet potentially more critical issue in large scale wind integrated system, is slow recovery of WTG active power output from following a fault induced voltage dip [7], [10]. Relatively slow recovery of WTG output following a voltage dip can be due to either one or combination of different factors, such as, to avoid unacceptable mechanical stress on the wind turbine due to high ramp rate, grid stability active power injection driven ramp limit, and delayed voltage recovery. While, at low penetration of wind power, slow WTG output recovery is unlikely to result in any noticeable effect, at higher wind penetration level, a severe voltage dip affecting large network with significant portion of wind generation may result in significant temporary shortfall in net generation, as described in Fig. 5. Such type of shortfall in generation is likely to result in frequency excursion of varying severity, which may in the worst possible case, even lead to system collapse. Therefore, slow active power recovery from WTG introduces a complex coupling between voltage and frequency dynamics in large scale wind integrated system [7].

A study carried out on wind integrated IEEE 39 bus system under varying wind penetration level has shown that, the system may experience severe frequency excursion following a fault induced voltage dip, as shown in Fig. 6. It can be observed that, the frequency nadir varies from 49.8 Hz to 48.55 Hz as the wind penetration increases from 20% to 60% [7].

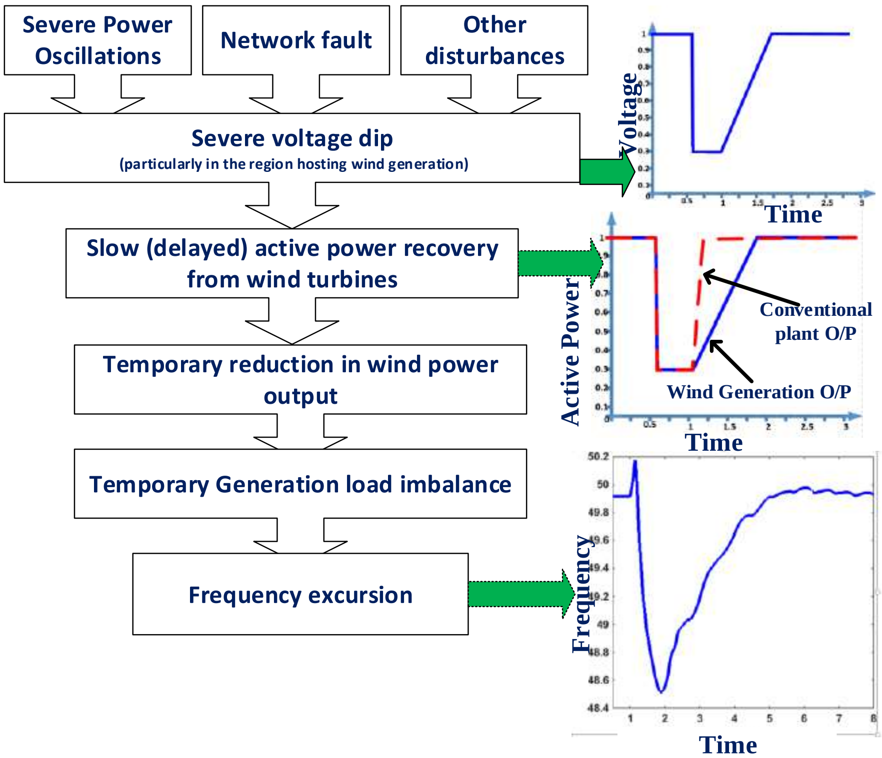


Fig. 5 Voltage dip induced frequency excursion

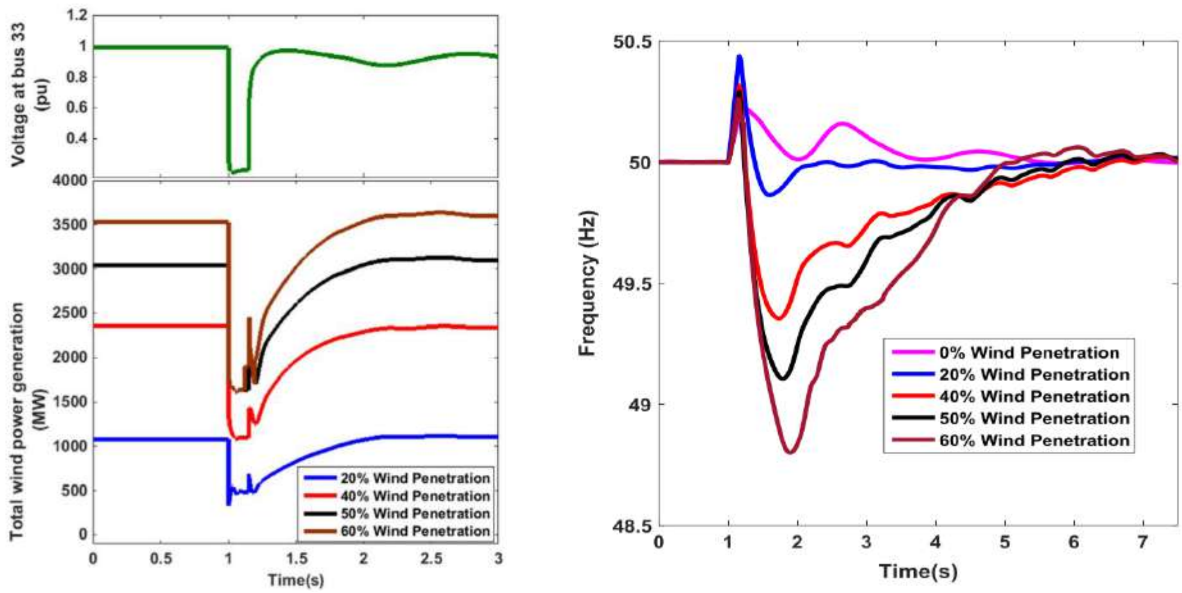


Fig. 6 Impact of delayed active power recovery on system frequency

IV. Dynamic reactive power control and short circuit power:

In conventional power systems, synchronous generators have been the main source of dynamic reactive power. However, displacement of conventional power plant by nonsynchronous generation resources such as WPPs and other renewable energy sources result in diminished dynamic reactive power reserve [8].

Lack of adequate dynamic reactive power, in wind integrated power system, is likely to impact voltage stability of such systems. An investigation on the Danish power system has suggested that, wind driven diminishing dynamic reactive power in the system, can lead to the system voltage collapse during sever faults, as shown in Fig. 7 [8]. Wind integration, particularly at higher penetration level may also reduce power system security level to unacceptable range. One such study, that has investigated how increase in wind penetration level can reduce voltage and transient stability based security of the Danish power system, has shown the system security level reaching to extremely low level at high wind penetration, as shown in Fig. 8 [11].

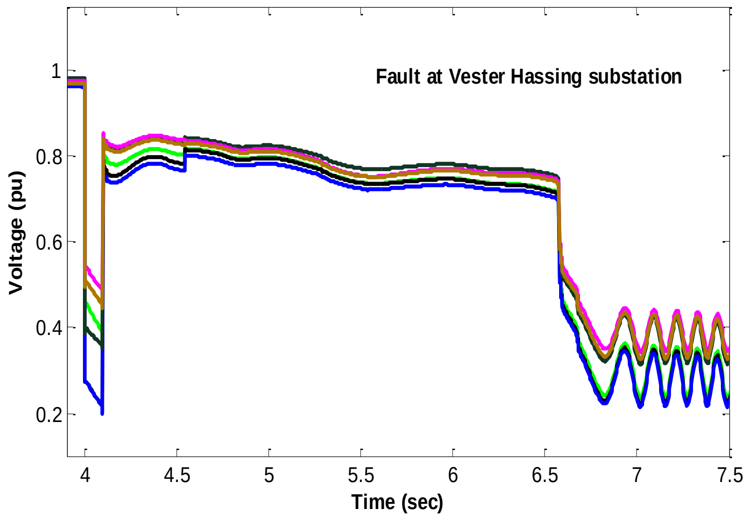


Fig. 7 Fault response of 2030 Danish power system

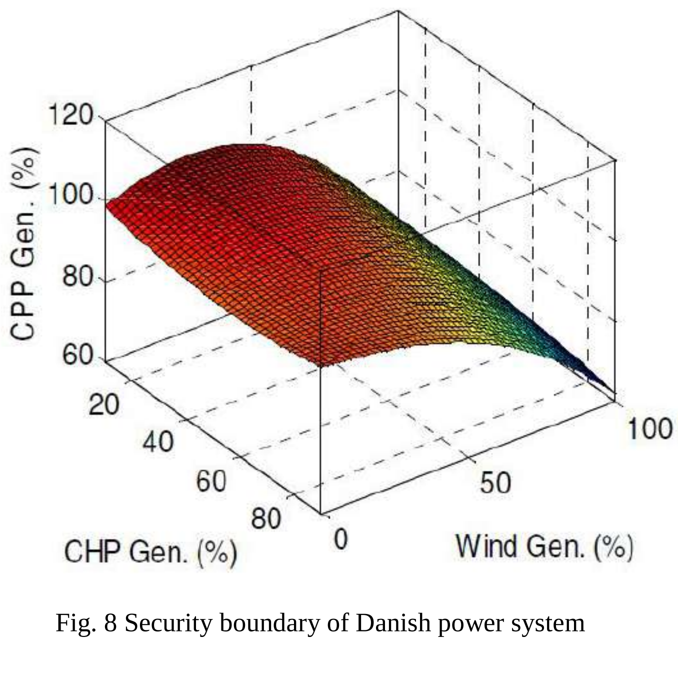


Fig. 8 Security boundary of Danish power system

Conventional synchronous generator has capability of injecting short circuit current as high as 7-8 per unit, however, the corresponding value in power electronic converter interfaced wind turbines can be as high as 2 per unit. Therefore, wind power integration, particularly at higher level, result in reduced system short circuit power availability, and as such, the protection schemes designed for synchronous generator dominated system, may not be able to sense a fault due to low short circuit current in the system.

V. Potential Solutions

Wind power penetration, at higher level, as described above, may introduce new and emerging issues that warrant countermeasures to ensure secure and stable operation of large scale wind integrated system. It is important to ensure that a system should have adequate inertia to ensure secure and stable system operation. Therefore, alternative sources of inertia to compensate diminishing synchronous inertia, should be in place. Various alternative sources of non-synchronous inertia include emulated inertia from variable speed WTG [12], battery storage [13], power electronic interfaced controllable loads, while as, synchronous condensers, pumped hydro storage power plants, are potential sources of synchronous inertia. For example, frequency excursion induced emulated inertial response of a 50 MW WTG connected to IEEE 14 bus system, developed in DIgSILENT PowerFactory, is shown in Fig. 9. However, it is important to note that such emulated inertial response from WTG results in reduction of wind turbine speed, and as such, along with the the system frequency recovery, wind turbine speed also recovers, thus the net active power output of WTG decreases as can be observed from Fig. 9. At higher wind penetration level, aggregate emulated inertial response from WTGs followed by WTG speed recovery may result in delayed frequency recovery, and in the worst case, may result in second frequency dip [14].

Renewable energy integration, particularly wind and solar PV power, has generated significant interest in estimation and monitoring of system inertia, besides being taken care by inertia constrained dispatch.

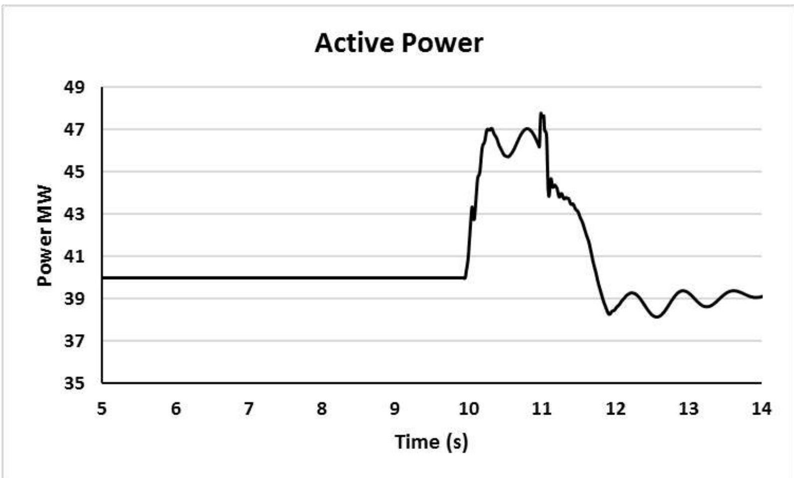


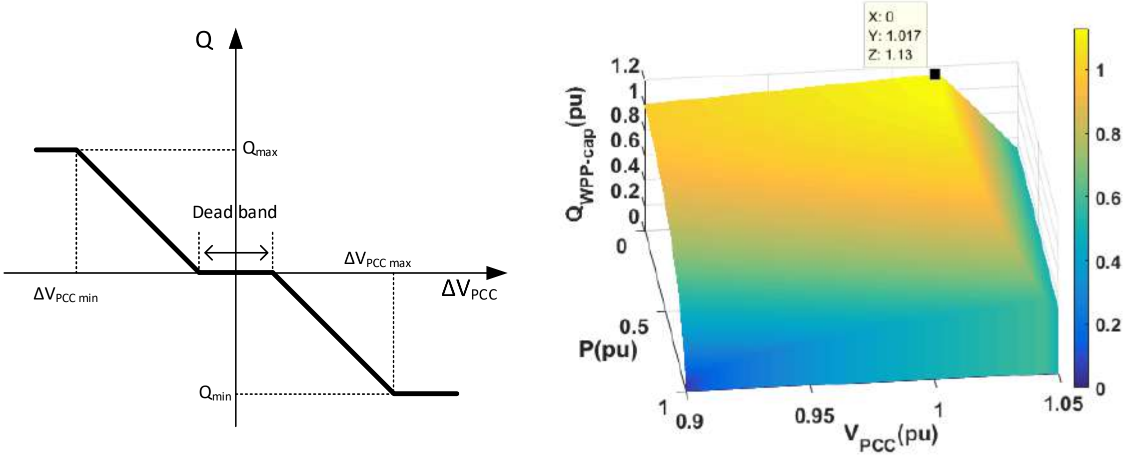
Fig. 9 Emulated inertial response from a 50 MW WTG

On the other hand, voltage dip induced slow active power recovery from WTGs, need to be considered while planning large scale penetration of wind power. A detailed system analysis, considering various potential scenarios can be conducted for a given system, and the trend of delayed active power impact can be estimated. Various measures, such as, strengthening of grid with adequate dynamic reactive power, support from emulated inertial response of WTGs and battery storage devices, that are not affected by the voltage dip, revisiting the system stability enforced ramp limits on WTG output, and better understanding of potential mechanical stress in wind turbine due to fast recovery, may help to address the slow recovery issue to a reasonable extent,

Further, generally synchronous generators have been the main source of dynamic reactive power in conventional systems, and as such, has not been of a significant concern. However, in renewable energy integrated system, maintaining adequate dynamic reactive power and short circuit power is increasingly becoming a hard operational constraint for system operator. Various potential measures to address this issue include, i) infrastructure reinforcement through synchronous condensers, FACTS devices such as SVC, STATCOM, TSSC, and ii) procurement of dynamic reactive power through ancillary service market. For example, Denmark is addressing lack of sufficient dynamic reactive power and short circuit power by installing synchronous condensers at critical locations, both in the Southern and the Eastern Danish grid. India, on the other hand, is exploring option of installing FACTS devices at some critical locations to maintain voltage stability in the grid. Ireland is planning to introduce dynamic reactive power as an ancillary service product, and therefore, procure it from ancillary service market. While, different options are being undertaken by different countries, to address such issue, it is also important to consider local potential solutions in planning potential countermeasures. The optimal solution may, however, lie in combination of these potential sources. For example, a study on Danish power system has concluded that combination of synchronous condenser (new and refurbished), SVC, and overloaded grid side converter of WTGs can be an optimal way to go forward.

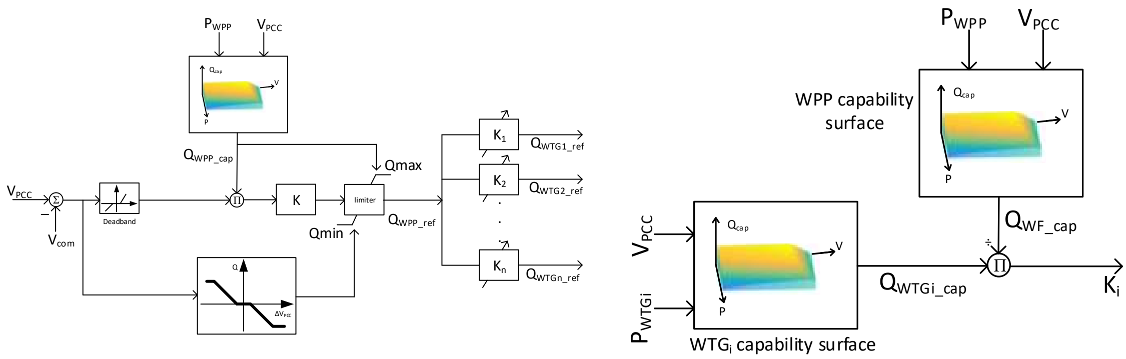
WTGs which are considered as one of the main source of the problem (lack of adequate dynamic reactive power), may become a potential solution to address the issue. Variable speed WTGs, if controlled optimally, can provide dynamic reactive beyond Low Voltage Ride Through (LVRT) requirement. The conventional voltage control strategy (Q-V droop) which is typically employed to comply with mandatory grid code requirement is shown in Fig. 10 (a). However, WPP may have higher capability to generate/consume reactive power depending on various factors such as Point of Common Coupling (PCC) voltage, wind direction and speed, WPP cables specifications, etc. Fig. 10(b) shows proposed accurate WPP reactive power capability as a function of PCC voltage and WPP active power generation [9]. Factors like WPP collector impedance and voltage limited reactive power capability of WTG converters are taken into account. Wake effect is included inherently in the capability formulation.

Based on the aforementioned reactive power capability formulation WPP centrlised reactive power control, Fig. 11(a) is proposed to contribute to voltage disturbance events based on the available reactive power reserve, while complying with grid code requirement. Fig. 11(b) shows the proposed reactive power dispatch among WTGs in WPP [9].



(a) (b)

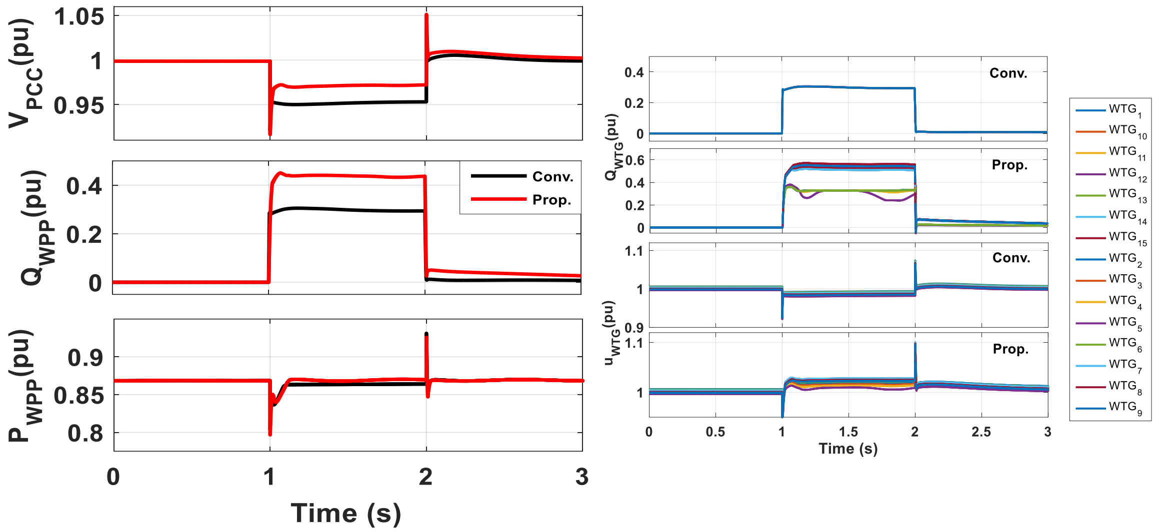
Fig. 10 (a) Conventional fixed Q-V droop , (b) Accurate WPP reactive power supply capability



(a) (b)

Fig. 11 (a) Proposed WPP centralised control , (b) WTG participation factor calculation

To verify the effectiveness of proposed control strategy, a voltage disturbance event is created at t=1 sec, and cleared at t=2 sec. Results shown in Fig. 12, shows that the reactive power contribution of WPP to the system is higher compared to conventional fixed (Q-V) droop which reflected as PCC voltage magnitude improvement. The reactive power dispatch among WTGs is shown in Fig. 12(b), WTGs with higher reactive power reserve are generated higher reactive power than others on contrary to conventional reactive power control strategy which dispatch the same reactive power to WTGs regardless their respective reserve.



(a) (b)

Fig. 12 (a) WPP reactive power response, (b) WTGs reactive power response (conventional and proposed)

VI. Conclusion

Various emerging, yet critical issues with large scale wind penetration, have been described in detail. It has been shown that, such emerging issues, may result in system instability and insecurity, if adequate countermeasures are not put in place. Lack of sufficient system inertia, voltage dip induced slow recovery of WTG output, lack of adequate dynamic reactive power and short circuit power have been identified as concerns of critical importance in system dynamics under high penetration of wind energy. Further, to address these emerging issues, various potential countermeasures have been discussed. Besides, various potential solutions to address the issue of voltage dip induced slow recovery in WTG output, have been suggested. It has also been shown that, WTGs that introduce such challenges, if controlled effectively, are likely to alleviate and in some cases address such issues. It has also been concluded that while planning for higher wind penetration, it is imperative to consider these emerging issues and their potential countermeasures.

References

[1] International Renewable Energy Agency, “Roadmap for a Renewable Energy Future,” IRENA, 2016.

[2] M. Singh and S. Santoso, “Dynamic models for wind turbines and wind power plants,” National Renewable Energy Laboratory, 2011.

[3] G. Lalor, A. Mullane and M. O'Malley, “Frequency Control and Wind Turbine Technologies,” IEEE Trans. on Power Syst., vol. 20, no. 4, pp. 1905-1914, 2005.

[4] N. Miller, C. Loutan, M. Shao and K. Clark, “Emergency response: US system frequency with high wind penetration,” IEEE Power and Energy Mag., vol. 11, no. 6, pp. 63-71, 2013.

[5] X. Yingcheng and T. Nengling, “Review of contribution to frequency control through variable speed wind turbine," Renewable Energy, vol. 36, no. 6, pp. 1671-1677, 2011.

[6] A. Ulbig, T. S. Borsche and G. Andersson, “Impact of low rotational inertia on power system stability and operation,” in IFAC Proceedings, 47(3), 7290-7297, 2014.

[7] Z. H. Rather and D. Flynn, “Impact of voltage dip induced delayed active power recovery on wind integrated power systems,” Control Eng. Practice, vol. 61, pp. 124–133, 2017.

[8] Z. H. Rather, Z. Chen, P. Thøgersen and P. Lund, “Dynamic reactive power compensation of large-scale wind integrated power system,” IEEE Trans. Power Syst., vol. 30, no. 5, pp. 2516-2526, 2015.

[9] H. Karbouj and Z. H. Rather, “Dynamic reactive power from wind power plant: Voltage control ancillary service support,” in 1st Int. Conf. on Large-Scale Grid Integration of Ren. Energy in India, New Delhi, India, 2017.[10] M. Tsili and Papathanassiou, S. , “A review of grid code technical requirements for wind farms,” IET Renew. Power Generation, 3 (3), 308–332, 2009.[11] Liu, Chengxi; Sun Kai; Rather, Zakir Hussain; Chen, Zhe; Bak, Claus Lath; Thogersen, Paul; Lund, Per,"A Systematic Approach for Dynamic Security Assessment and the Corresponding Preventive Control Scheme Based on Decision Trees ," IEEE Trans. Power Systems, vol. 29, no. 2, 03.2014, p. 717-730.

[12] J. Morren, S. W. De Haan, W. L. Kling, and J. Ferreira, “Wind turbines emulating inertia and supporting primary frequency control,” IEEE Trans. Power Syst., vol. 21, no. 1, pp. 433–434, 2006.

[13] G. Delille, B. Francois, and G. Malarange, “Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system’s inertia,” IEEE Trans. Sustain. Energy, vol. 3, no. 4, pp. 931–939, 2012.

[14] Ruttledge, L., Miller, N., O’Sullivan, J., and Flynn, D., “Frequency response of power systems with variable-speed wind t turbines,” IEEE Trans. Sustain. Energy, 3 (4), 683–691, 2012

भाखड़ा ब्यास प्रबन्ध बोर्ड
मध्य मार्ग, सैक्टर 19-बी, चंडीगढ़-160019
0172-5011773, फैक्स 0172-2549857

कार्यालय आदेश

क्रमांक 01 /एचआरडी - 1044 (CEA) दिनांक 01.01.2018

Central Electricity Authority, Ministry of Power, Govt. of India, New Delhi द्वारा आयोजित करवाये जा रहे Conclave में भाग लेने व उसमें **"Perovskite-based low-cost and high efficiency solar cells"** विषय पर तकनीकी पेपर प्रस्तुत करने के लिए भाखड़ा ब्यास प्रबन्ध बोर्ड से निम्नलिखित अधिकारी को मनोनीत करने हेतु स्वीकृति प्रदान की जाती है:-

Sr. No	Name of the officer	Name of the programme	Date & Venue
1.	Er.Tajinder Kaur, Jt.Secy. (Power), BBMB Sectt., Chandigarh	Conclave on Emerging opportunities and challenges of R&D in Indian Power Sector	Conference to be held on 15-16 Feb. 2018 At Vigyan Bhawan in New Delhi.

कार्यक्रम में भाग लेने हेतु कोई शुल्क देय नहीं है।

अधिकारी नियमों के अन्तर्गत स्वीकार्य यात्रा/ दैनिक भत्ते के हकदार होंगें।

व्यय बोर्ड सचिवालय के ट्रेनिंग लेखा को प्रभार्य होगा।

इस कार्यालय के पत्र क्रमांक 2779-99 /एच.आर.डी.- 1007 दिनांक 19.10.2012 की शर्तों के अनुसार अधिकारी उपरोक्त प्रोग्राम में शामिल होने के उपरान्त एक महीने के अन्दर-अन्दर तकनीकी पेपर / रिपोर्ट प्रस्तुत करेंगे तथा कार्यक्रम/ वर्कशाप में प्राप्त सामग्री बीबीएमबी के **नज़दीकी लायब्रेरी** में जमा करवायेगें।

यह आदेश अध्यक्ष, बीबीएमबी की स्वीकृति उपरान्त जारी किया जाता है।

निदेशक / एच.आर.डी.

पृ: क्रमांक 01-11 /एचआरडी -1044 (CEA) दिनांक 01 .01.2018

उपरोक्त की प्रति निम्नलिखित को सूचना एवं आवश्यक कार्रवाई हेतु प्रेषित है :

1. Er.Seema Saxena , Chief Engineer(Research & Development), Central Electricity Authority, Ministry of Power, Govt. of India, Sewa Bhawan, R.K.Puram,New Delhi- 110066 w.r.t. D.O.No. CEA/ PLG/ R&D/ Conclave/ 2017/392-96 dt. 7.12.2017 (E-mail: ce-rndcea@nic.in) Mob. 9810531680
2. वित्तीय सलाहकार एवं मुख्य लेखा अधिकारी बीबीएमबी, चण्डीगढ़।
3. विशेष सचिव , बीबीएमबी, चण्डीगढ़।
4. सचिव (कार्मिक अनुभाग), बीबीएमबी, चण्डीगढ़।
5. उप सचिव/ एचआरडी, बीबीएमबी सचिवालय, चण्डीगढ़।
6. संबंधित अधिकारी।
7. वरि.लेखा अधिकारी, बीबीएमबी, चण्डीगढ़।
8. वरि. निजी सचिव टू अध्यक्ष, सदस्य (सिंचाई एवं विद्युत), बीबीएमबी, चण्डीगढ़।
9. निजी सचिव टू निदेशक/एचआरडी, बीबीएमबी, चण्डीगढ़।

संलग्न/ तकनीकी पेपर क्रम संख्या1के लिए

निदेशक / एच.आर.डी.

Perovskite-based low-cost and high-efficiency solar cells

Keywords – ***Perovskite Solar Cell, Hole Transport Material (HTM),Electro transport material (ETM), Fill factor(FF), Copper indium gallium selenide** (CIGS) cells, **open circuit voltage Voc ,short circuit current Isc, Dyesensitized solar cells (DSSC),***

I. **Overview** :Global energy consumption has been continually increasing with population growth and fast-paced industrial development in recent decades, which demands renewable energy sources in view of long-term sustainable development. Generating cost-effective and environmentally benign renewable energy remains a major challenge for both technological and scientific development. Solar cells based on the photovoltaic effect with the advantages of decentralization and sustainability have attracted great attention in the past 50 years. Currently, the photovoltaics market is dominated by crystalline silicon-based solar cells with a share of 89% . This dominance is now being challenged by the emergence of a new generation of photovoltaic cells, based on nanocrystalline materials and conducting polymer films, making solar power much more expensive in comparison with fossil fuels. A new type of solar cell made from a material called 'perovskite' is significantly cheaper to obtain and use than silicon. It could generate as much power as today's commodity solar cells. Highly efficient solar cells using perovskite can be made using a simple and inexpensive technology.

II. PEROVSKITE- MATERIAL

Perovskites are a family of materials with the crystal structure of calcium titanate, that is, ABX_3. There are numerous materials which adopt this structure with exciting applications based on thermoelectric, insulating, semiconducting, piezoelectric, conducting, antiferromagnetic, and superconducting properties . ABX_3 describes the crystal structure of perovskite class of materials, where A and B are cations and X is an anion of different dimensions. The standard compound is methylammonium lead triiodide ($CH_3NH_3PbI_3$), with mixed halides.

Perovskites possess intrinsic properties like broad absorption spectrum, fast charge separation, long transport distance of electrons and holes, long carrier separation lifetime, and more, that make them very promising materials for solid-state solar cells. A perovskite based solar cell is a type of solar cell, which includes a perovskite structured compound, most commonly a hybrid

 Author : Er. Tajinder Kaur, Joint Secretary/Power, BBMB, Chandigarh.

organic-inorganic lead or tin halide-based material, as the light-harvesting active layer. Perovskite materials are usually cheap to produce and relatively simple to manufacture.

III. PEROVSKITE-BASED SOLAR CELLS

Solar cells made up of perovskites material, have a simple architecture and can easily be produced in large quantities because the vapour deposition process used to make them is compatible with conventional processing methods for fabricating such solar cells. Prototype solar panels incorporating nanotechnology are more efficient than standard designs in converting sunlight to electricity, promising inexpensive solar power in the future. Organo-metal-trihalide perovskite semiconductors, with the formula (CH3NH3)PbX3 — where Pb is lead and X can be iodine, bromine, or chlorine — were first employed in 2009 as the light-absorbing component. In these devices, the perovskite materials were coated onto the surface of a film made of titanium dioxide (TiO2) nanoparticles.

When the perovskite layer absorbs light, electrons, and holes are generated. These charge carriers are subsequently transferred to different transport materials — TiO_2 for the electrons and to another material for the holes. The transport materials then carry the charges to separate electrodes, and a voltage is produced.

Perovskite solar cells are causing excitement within the solar power industry with their ability to absorb light across almost all visible wavelengths, exceptional power conversion efficiencies as tested in lab and relative ease of fabrication. Perovskite solar cells still face several challenges but much work is put into facing them and some companies are already talking about commercializing them in the near future.

IV. CHALLENGES AHEAD

Like any other new entrant into the highly competitive solar-panel market, perovskites will have initial difficulties in taking over silicon solar cells. Also, since cost of silicon solar cells are falling, the financial aspect of both silicon and perovskites would have to be taken in to consideration. A major challenge in the perovskite solar cells (PSCs) is in the field is stability; Unlike silicon cells, perovskites are soft crystalline materials and prone to problems due to decomposition of maerial over time. In a commercial context, this tends to inflate the costs of perovskite-based solar cells compared with conventional silicon cells. There, have therefore been many efforts in synthesizing perovskite materials that can maintain high efficiency over long time period. This is done by introducing different cations (positively charged ions) into the crystal structure of the perovskite.

Although success has been reported in several studies, these solutions can often be difficult and expensive to implement.Thus, it is better to augment perovskites initillay rather than replace silicon solar cells to improve their efficiency. This might be an easier way to break into the solar market than trying to introduce an entirely new kind of solar cells. Quantum Dot based (QD) solar cells have shown great potential as next generation, high performance low cost photovoltaics due to the outstanding optoelectronic properties of quantum dot and their multiple excitation generation (MEG) capabilities. The recent development of organic–inorganic perovskite hetro junction solar cells has shown great future as light harvesters.

There is however one small challenge associated with the use of perovskite materials. The material contains small amount of lead, which is toxic. Tests will be needed to show how toxic it is. Steps can also be taken to ensure that the solar cells are collected and recycled to prevent the materials from getting into the environment .Further degradation in perovskite solar cells is a synergetic effect of exposure to humidity, oxygen, ultraviolet radiations, and temperatures.

COMPREHENSIVE OUTLOOK

In a span of a couple of years, perovskites have demonstrated that they possess the right mix of properties to offer a solution to our energy requirements. Though they evolved out of liquid electrolyte DSSCs, they are now established as a class of their own with extensive research focus pushing the efficiency limit by 20%. Low temperature solution processing assures low per watt cost and quick energy payback times. Device architectures ranging from pin to mesoporous to meso superstructure configuration throw wide open the possibilities for incorporation of novel materials and synthesis approaches. Use of materials with high mobility as HTM will further improve the FF while optimization of the interfaces and selection of HTM and ETM may push forward the efficiencies to higher values. Incorporation of narrow band gap perovskites and plasmonic light harvester may broaden the spectral response with better light harvesting. Interface engineering and introduction of self-assembled layers will reduce losses and improve efficiency. Understanding of the underlying photophysical phenomenon will further help improving device structures and better selection of materials. Exploration of tandem cell configuration with perovskite based cell as the top cell will push forward the achievable efficacy limit further. With the amount of research effort under way, guided by the adherence to the issue of best practices , this technology holds great promise to addressing our energy concerns. Addressing the issues of stability and use of lead can go a long way in maturing this technology for commercial application, though in the present legal framework use of lead is not a problem as CdTe based solar cell has received wide acceptance despite Cd content. Use of lead extensively in lead acid batteries and its content at comparable levels in CIGS and silicon modules to perovskites suggest that in the short term the concern may not be pressing, but these technologies are increasingly being phased out and alternatives are explored to minimize the environmental impacts of these heavy metals. Replacement of lead with tin in perovskite solar cell is already under investigation and may offer an environment friendly alternative.

V. CONCLUSIONS AND FUTURE OUTLOOK

In summary, perovskite solar cells exhibit impressive competitiveness with other photovoltaic techniques due to their unique advantages:

(i) Low-cost, earth abundance, and easy preparation.

(ii) Near-perfect crystalline structure at low temperature

(iii) Large charge-carrier diffusion length for mixed-halide perovskite ($CH_3NH_3PbI_{3-x}Cl_x$) thin films, which is nearly 100 times higher that the other low-temperature solution-processed thin films

(iv) lower value of "loss-in-potential" in a solar cell, which allows the Voc of the best perovskite cells much higher than the traditional DSSCs, organic solar cells and It can even compete with crystal silicon solar cells .

(v) Perovskite materials are better than silicon at absorbing higher-energy w.r.t. blue and green photons.

Meanwhile, perovskite materials also have some ineluctable disadvantages:

(i) Perovskite materials are extremely sensitive to oxygen and water vapor, which reacts to break down the crystal structure and dissolves the perovskite material . Therefore preparation of perovskite thin films requires manufacturing in inert atmosphere.

(ii) It is challenging to prepare large continuous films, which limits it for large scale production.

(iii) The lead is the most-used in perovskite solar cells which is toxic and could leach out of the solar panel onto rooftops or the soil below offering potential hazard to environment and living beings..

(iv) Since there is a phase transition from tetragonal to cubic at 55°C, the longer-term stability of perovskite solar cells has not been verified. There are a few studies on storage lifetime but only limited on an operating cell (under illumination at the maximum power) for a sealed cell at 45°C The studies have showed a decrease in efficiency after certain time period.

In view of the advantages and disadvantages addressed above, some new strategies can be forwarded to further improve the efficiency of perovskite solar cells. Research results in this field has offered many promising results towards remarkable efficiency improvement in solar cells.

Needless to say, the development of higher-efficiency solar cells will not only have a profound economic impact, but it will also represent significant social and environmental benefits. The perovskite technology would allow the mass production of solar cells with high efficiency and at relatively low temperatures, which would account for a substantial reduction of cost. In the meantime, the technology can lead to high-throughput device fabrication due to the simple deposition process required. Furthermore, flexible substrates could be used, which would allow an easier handling, transportation, installation, and building integration of these new photovoltaic devices. We believe that this new class of perovskite solar cells will find widespread applications and will eventually lead to devices that rival conventional silicon-based photovoltaics.

References:

1. Wikipedia **Perovskite solar cell, solar cells.**
2. Roni Peleg, senior editor of Perovskite-info
3. Jiandong Fan, Baohua Jia, and Min Gu ,Centre for Micro-Photonics, Faculty of Science, Engineering and Technology, Swinburne University of Technology,Hawthorn, Victoria 3122, Australia Jiandong Fan, Baohua Jia, and Min Gu,Centre for Micro-Photonics, Faculty of Science, Engineering and Technology, Swinburne University of Technology,
Hawthorn, Victoria 3122, Australia.
4. https://www.nanowerk.com/spotlight/spotid=45249.phpPerovskite solar cells - a true alternative to silicon.
5. https://www.perovskite-info.com/perovskite-solar

Title of the Project:

MUNICIPAL SOLID WASTE TO ENERGY POWER PLANT BY FEASIBILITY STUDY OF WASTE TO ENERGY POSSIBILITY IN INDIA.

Written by:

1) Ravindra Deshpande — Executive Engineer (Project & Planning), MSPGCL, Mumbai
Contact No. 8879770725 / 9822280829
Email – eegpp14 @ mahagenco.in
eegpp14@gmail.com

2) Ajay Bamne — Dy. Chief Engineer (Project & Planning)
Contact No. 8879770710
ajayabamne1@rediffmail.com

Under the Guidance of:

1) Shri. V,M. Jaidev — Director (Projects), MSPGCL
2) Shri. V.Y. Mahulkar — Chief Engineer (P&P), MSPGCL

The paper is submitted in response to call for Papers for **International R&D Conclave on Emerging opportunities and challenges in Indian Power Sector** during 15-16 February, 2018 organized by **Central Electricity Authority**.

1.0 PREFACE:

Waste is an inevitable product of society, and India is facing one of the greatest challenges for how to manage large quantities of waste in a sustainable way. Future generations in India, have a big task ahead to understand the technology of waste recycling, which will effectively recycle larger fractions of waste materials. Further they should know –"How to minimize the amount of waste produced, and largely recycle the complete waste materials?"

However, there still is a considerable part of undesired end-products that must be taken care of, and a more suitable solution than simple land-filling needs to be found.

Increasingly, untreated municipal waste is being viewed as too valuable a commodity to relegate to disposal methods that meet objectives solely focused on environmental and public health protection and aesthetics. In the case of municipal solid waste (MSW), waste to energy applications are being implemented world-wide for the purpose of thermally treating waste and recovering energy in the process.

The waste management sector faces a problem that it cannot solve on its own. The energy sector in India, however, is considered to be a perfect match, because of its need to continuously meet a growing energy demand. Waste is now not only an undesired product of society, but a valuable energy resource as well.

Energy recovery from waste can solve two problems at once:

1) Treating non-recyclable and non-reusable amounts of waste;
2) Generating a significant amount of energy which can be included in the energy production mix in order to satisfy the consumers' needs.

The interaction between waste management solutions and energy production technologies can vary significantly, depending on multiple factors. Different countries across the world choose to adopt different strategies, depending on social, economic and environmental criteria and constraints. These decisions can have an impact on energy security, energy equity and environmental sustainability when looking at the future of the energy sector. If in India, waste-to-energy (WTE) technologies are developed and implemented, while following sustainability principles, then a correct waste treatment strategy and an environment-friendly energy production can be achieved at the same time, solving challenges in both the waste management and energy sectors.

2.0 PREAMBLE

In India, Waste is collected by or on behalf of local authorities and is disposed of through the Waste Disposal System in dump yard. When considering waste as an energy resource, it is important to take into account the composition of the different types of available waste. Municipal Solid Waste (MSW) is broadly classified in various ways as under –

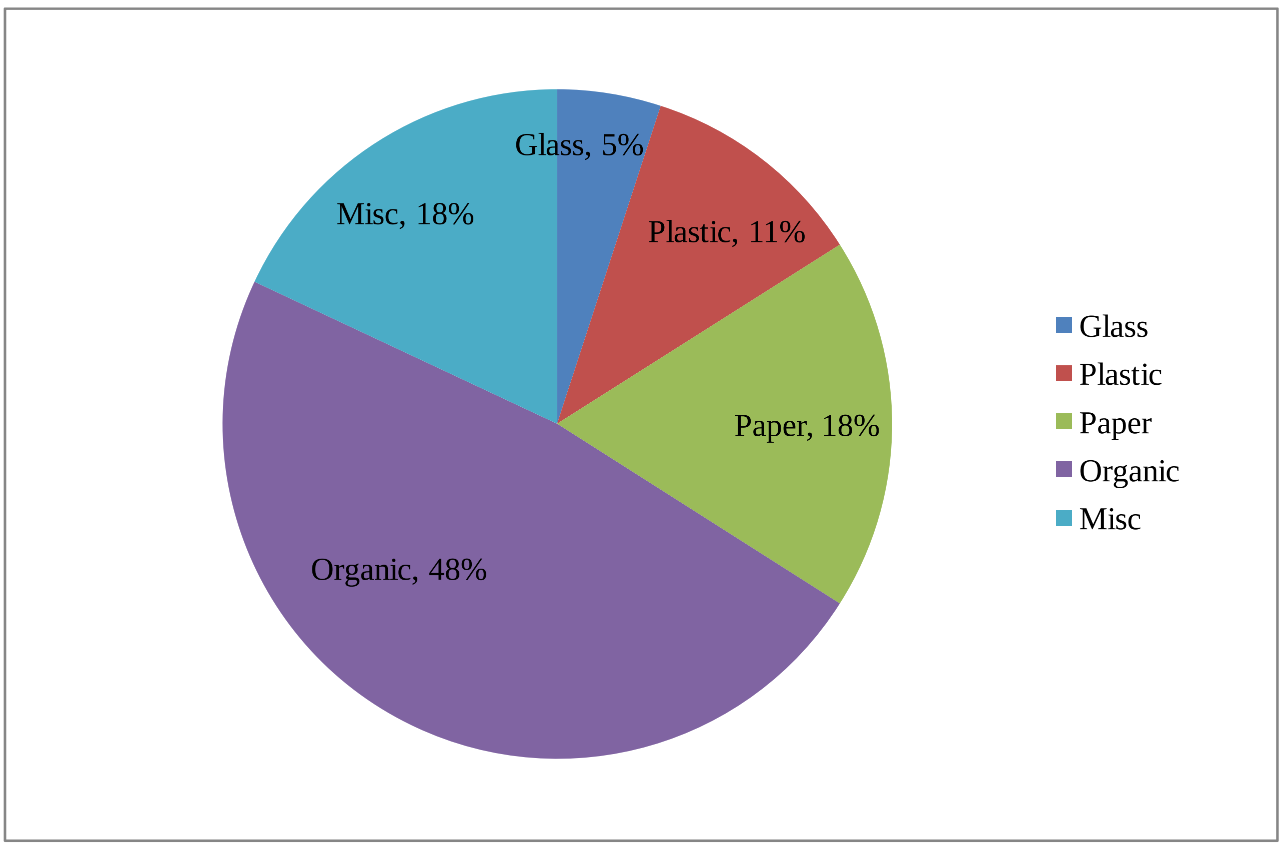
Table-1: Types and Sources of Waste in India.

Type of Waste	Generation Source	Major Composition
Municipal Waste	Residential Waste	Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (e.g. bulky items, consumer electronics, white goods, batteries, oil, tyres), household hazardous wastes, e-wastes.
	Industrial Waste	Housekeeping wastes, packaging, food wastes, wood, steel, concrete, bricks, ashes, hazardous wastes.
	Commercial, institutional & Office Generated Waste	Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes, e-wastes.
	Construction & demolition	Wood, steel, concrete, soil, bricks, tiles, glass, plastics, insulation, hazardous waste.
	Municipal services	Street sweepings, landscape & tree trimmings, sludge, wastes from recreational areas.
Process Waste		Scrap materials, off-specification products, slag, tailings, top soil, waste rock, process water & chemicals.
Medical Waste		Infectious wastes (bandages, gloves, cultures, swabs, blood & bodily fluids), hazardous wastes (sharps, instruments, chemicals), radioactive wastes, pharmaceutical wastes.
Agricultural waste		Spoiled food wastes, rice husks, cotton stalks, coconut shells, pesticides, animal excreta, soiled water, silage effluent, plastic, scrap machinery, veterinary medicines.

Municipal Solid Waste (MSW) from residential, industrial and commercial sources is the most common waste stream used for energy recovery. However, construction waste, bio-waste from agriculture and forestry activities, hazardous waste and many others also can be considered feasible for energy recovery, depending on their specific composition, their energy content and the specific needs of society in terms of waste disposal.

In Indian scenario, the major fractions of solid waste include paper, organic material, plastics, glass, metal and textiles. As can be seen, nearly half of the produced waste from society is organic. Specific waste products deriving from construction, industrial and commercial waste are not specified in this figure, but in some cases can represent the majority of a region's waste production.

Figure 1: Composition of solid waste in India.



3.0 ELECTRICITY PRODUCTION POTENTIAL

3.1 Waste as a Fuel:

The choice of WTE technology will be largely dependent on the nature and volume of the incoming waste stream. A key factor is the energy content (calorific value) of the waste, which determines how much energy, can be extracted from it. Table 2 shows approximate net calorific values for common fractions of MSW.

TABLE 2: APPROXIMATE NET CALORIFIC VALUES FOR COMMON MSW FRACTIONS

Waste Material	Net Calorific Value (MJ/kg)
Paper	**15**
Organic material	**5**
Plastics	**36**
Glass	**0**
Metals	**0**
Textiles	**20**
Other materials	**12**

The potential electricity production for export from Waste to Energy facilities is dependent on a range of factors including feedstock heating value and efficiencies within the combustion and energy recovery processes. It can be expected that lower energy recovery efficiencies may be observed in smaller facilities (< 50,000 tonnes per year).

A WTE facility proposed in Mumbai will be a relatively small plant in comparison to the majority of WTE applications constructed world-wide. As a result, it can be expected that lower energy conversion efficiencies will be obtained. Based on these considerations, a range of 300 – 600 kWhr / tonne can be used to predict electricity production from a Mumbai WTE facility. Assuming waste volumes of 1,00,000 tonnes per year, ***annual electricity exports would range between 30 and 50 GWh, where humidity level is high.***

Electricity generated from WTE facilities is generally a firm and consistent supply of power because of the consistent supply of the waste feedstock. However, as previously discussed, average daily waste volumes generated in the winter in the Mumbai can be less than half the volumes generated during the Monsoon and summer periods. This seasonal variability is detrimental to the potential viability of a WTE plant because the facility would be operating at its lowest throughput (and lowest efficiency) during periods when the local demand for renewable electricity is at its highest. The impact of this could be partially or totally offset if a complementary biomass feedstock (such as wood waste) could be sourced during the winter period (hence calorific value is low).

Energy conversion from waste can be obtained by utilizing different technologies. Each one of these WTE solutions has specific characteristics, and can be more or less feasible depending on many parameters. The major factors include the type and composition of waste, its energy content, the desired final energy form, the thermodynamic and chemical conditions in which a WTE plant can operate, and the overall energy efficiency.

The following list of WTE technologies gives an overall picture of the available options on the market.

A) Thermo chemical Conversion

1) Combustion
2) Gasification
3) Pyrolysis

B) Bio-Chemical Process

1) Fermentation
2) Anaerobic Digestion
3) Landfill with gas capture
4) Microbial Fuel Cell

C) Chemical Process

1) Esterification

There are also new developments and research projects aimed at promoting alternatives to the most mature and established technologies. The brief description of these available technologies is as under--

A) THERMOCHEMICAL CONVERSION

Thermo-chemical conversion technologies are used to recover energy from MSW by using or involving high temperatures. They include combustion or incineration, gasification and pyrolysis. The main difference among these technologies is the amount of excess air and temperature within the process that leads to the conversion of final product CO2 and water, or to intermediate useful products keeping aside other technological differences. The dry matter from MSW is most suitable feedstock for thermo-chemical conversion technologies.

1) COMBUSTION

Combustion of MSW is the complete oxidation of the combustible materials contained in the solid waste fuel, and the process is highly exothermic. During combustion of solid waste, several complex processes happen simultaneously. Initially, the heat in the combustion chamber evaporates the moisture contained in the solid waste and volatilizes the solid waste components. The resulting gases are then ignited in the presence of combustion air to begin the actual combustion process. The process leads to the conversion of waste fuel into flue gas, ash and heat. The heat released is used to produce a high-pressure superheated steam from water, which is sent either to the steam turbine that is coupled with generator to produce electricity, or used to provide process steam. It is important to note that the bottom and fly ashes that are formed by the inorganic constitutes of the waste affects the energy balance through its mean heat capacity, even though it is not particularly participated in the combustion process. Depending on the bottom ash treatment options, ferrous and non-ferrous metals can also be recovered and the remaining ash can be further enhanced to be used for road construction and buildings.

2) GASIFICATION

Solid waste gasification is the partial oxidation of waste fuel in the presence of an oxidant of lower amount than that required for the stoichiometric combustion. The gasification process breaks down the solid waste or any carbon based waste feedstock into useful by-products that contain a significant amount of partially oxidized compounds, primarily a mixture of carbon monoxide, hydrogen and carbon dioxide. Furthermore, the heat required for the gasification process is provided either by partial combustion to gasify the rest or heat energy is provided by using an external heat supply. The produced gas, which is called syngas, can be used for various applications after syngas cleaning process, which is the greatest challenge to commercialise this plant in large scale. Once the syngas gas is cleaned, it can be used to generate high quality fuels, chemicals or synthetic natural gas (SNG); it can be used in a more efficient gas turbines and/or internal combustion engines or it can be burned in a conventional burner that is connected to a boiler and steam turbine15. However, the heterogeneous nature of the solid waste fuel makes the gasification process very difficult together with the challenges of syngas cleaning, and there are not many large-scale stand-alone waste gasification plants.

3) PYROLYSIS

Pyrolysis of solid waste fuel is defined as a thermo-chemical decomposition of waste fuel at elevated temperatures, approximately between 500°C and 800°C, in the absence of air and it converts MSW into gas (syngas), liquid (tar) and solid products (char). The main goal of pyrolysis is to increase thermal decomposition of solid waste to gases and condensed phases. The amount of useful products from pyrolysis process (CO, H2, CH4 and other hydrocarbons) and their proportion depends entirely on the pyrolysis temperature and the rate of heating. It is important to note that the mechanical treatment ahead of gasification, sensitivity to feedstock properties, low heating value of waste fuel, costly flue gas clean-up systems, difficulty of syngas clean-up and poor performance at small scale have been a great challenge during gasification of MSW. The main goal of pyrolysis is to increase thermal decomposition of solid waste to gases and condensed phases.

It is important to note that the mechanical treatment ahead of gasification, sensitivity to feedstock properties, low heating value of waste fuel, costly flue gas clean-up systems, difficulty of syngas clean-up and poor performance at small scale have been a great challenge during gasification of MSW.

TABLE 4: COMPARISON OF PYROLYSIS, GASIFICATION AND COMBUSTION

COMPUSTION	GASIFICATION	PYROLYSIS
Excess air Very exothermic	Sub stoichiometric air Exothermic/Endothermic	Normally no air
Higher volumetric flow rate	Lower total volumetric flow	Only heat (external or internal)
Fly ash carry over	Lower fly ash carry over	Want liquid, gases not desired
Pollutants in oxidized form (SOx, NOx etc)	Pollutants in reduced form (H2S, COS)	Pollutants in reduced form (H2S, COS)
Bottom ash	Char at low temperatures Vitrified slag at high	Higher char

4.0 CONVENTIONAL WTE PROCESS

- A waste-to-energy (WTE) plant is a waste management facility that uses MSW as fuel to produce electricity.
- Waste-to-energy plants are similar in design and equipment with normal Thermal power plants, particularly biomass power plants. The MSW is transported by the municipal authority to the WTE plant.
- Then, the waste is put on the receiving hopper having eight hours holding capacity as per the design. With natural settling effect the SW is transferred on vibrator conveyor having provision of hot air encapsulation to remove the moisture, there in increasing the Kcal.
- The dried SW is conveyed on magnetic separator to the boiler feeder hopper, on this conveyor long / big material is manually removed and shredded in batch for smooth operation. The SW is feed to the boiler continuously. The SW is feed on the travel grate in pulsating mode, which ensures the uniformly spreading of SW in the furnace for complete burning. The burnt out ash passes through the ash discharger onto an ash handling system. The Ash can be used in the construction industry for making bricks and cement.
- Heat generated in the furnace using SW is used to produce steam in the boiler drum.
- A turbo-generator uses the steam to produce electricity for export to the local power grid. The heat can also be used for industrial processes or residential district heating near the WTE plant.
- Hot Flue gases produced in the furnace pass through super heater, economizer, air pre heater to use the energy.
- The Flue gas is passed through a bag filer or cyclone dust separator to remove the fine particles. Further the flue gas is passed through our patented technology to deliver a clean gas. The ID Fan is designed to overcome the drop and releasing to the atmosphere through the chimney.

The conventional WTE combustion process is similar to the stoker burners in many coal- Fired boilers. Waste is continuously fed onto a moving grate in a furnace where high temperatures are maintained. Air is added to the combustion chamber to ensure turbulence and the complete combustion of the components to their stable and natural molecular forms of carbon dioxide and water vapor. The hot combustion gases released during the WTE process are directed through boilers to generate superheated steam that can drive turbine generators that produce electricity. Exhausted steam can also be used efficiently for district heating and for industrial processing if those choices are available. It is interesting to note that, according to the EPA protocols, combusting the biogenic fraction of MSW (about 56 percent of the carbon in MSW) results in a GHG reduction because these waste materials decompose into nearly equal portions of carbon dioxide and methane gas if they are land filled. Methane is 21 times more potent as a GHG than carbon dioxide. Energy Benefits of WTE MSW, depending upon the moisture and energy content of the waste materials is a good fuel source. The thermal treatment of MSW results in the generation of 500-600 kWh of electricity per ton of MSW combusted. In European countries, WTE facilities often recover another 600 kWh in the form of steam or hot water that is used for district heating. The corresponding savings in fossil fuel use range from one to two barrels of oil per ton of MSW.

5.0 RENEWABLE ENERGY SOURCE:

WTE shall be designated as renewable by India in Energy Policy. In addition to its energy benefits, WTE avoids the conversion of green fields to landfills. Although. India is not blessed with abundant land, the continuous use of land for land filling is not sustainable, especially in the coastal areas like Mumbai that are experiencing the highest population growth. Since WTE facilities are a point source of emissions, they have been subjected to very stringent environmental regulations.

WTE processing of MSW has the additional benefit of reducing the transport of MSW to distant landfills and the attendant emissions and fuel consumption. It also reduces interstate truck traffic.

1) **Fuel Consumption (Diesel):** Diesel fuel consumption of trucking to and from landfills and by equipment used in the burial of MSW in landfills generates air emissions and has other negative environmental impacts. All this energy consumption and diesel exhaust can be avoided by WTE facilities that use MSW as the fuel for generating electricity and steam energy at plants located near urban centers.

2) **Material Recovery**: Another beneficial effect of modern MSW combustion with energy recovery is material recovery. Using magnetic separators, WTE industry can recover and recycle ferrous scrap metal annually from the combustion ash residue. At some facilities, non-ferrous metals are also removed through the use of "eddy current separators" that cause these materials to literally jump out of the remaining ash and into a recovery area. Metal processors sort this mixed metal into brass, aluminum, copper and other base metals. The remaining ash can be used in the construction and maintenance of landfills and as an aggregate in construction.

Waste to energy technology is also well suited to various forms of combined heat and power applications. Many facilities i.e. WTE plant sell a portion of the steam produced to nearby industries while utilizing the remaining steam for electrical power generation. In some of facilities all the produced steam is sold to industry and no electricity is produced. There are no known industrial applications for process steam currently in Major Parts in India.

6.0 OBSTACLES FOR WTE TECHNOLOGY

The progress of WTE has mainly stifled by three factors

1) Inconsistent environmental regulations for various energy sources. –
2) Uneven support by local officials and agencies.
3) Flow Control

Flow control is the authority needed by a municipality to direct the "flow" of its generated solid wastes into a disposal process chosen by the community, e.g., the local WTE facility.

7.0 ENVIRONMENTAL ISSUES:

Waste to energy facilities encompass a number of environmental considerations that range from emission controls to the potential generation of greenhouse gas offset credits. Potential air emission issues from waste to energy plants include the discharge of a range of contaminants including dioxins and furans, heavy metals, particulates, Sulphur-di-Oxide (SOx) and Nitrogen Oxides (NOx). The adoption of standard operating procedures and modern air pollution control equipment effectively controls each of the contaminants listed above, ensuring that the most stringent emissions standards can also be achieved.

Operation of a WTE facility can result in reduced greenhouse gas emissions. One significant area of potential reductions is in avoided emissions associated with land filling of waste. Land filling of MSW results in the creation and emission of methane as the waste gradually decomposes. WTE facility could result in the reduction of over 30,000 tonnes of GHG emissions per year through avoided methane emissions at the landfill. The actual emission reductions would be somewhat less as a result of the combustion of non-biodegradable material (ie. plastics). Additional greenhouse gas emission reductions may result from the displacement of fossil-fuel generated electricity emissions, depending on the nature of the displaced power (e.g. diesel-generated vs. hydro-generated)

8.0 REGULATORY ISSUES

It is expected that a waste to energy project located in India would require a screening level (Designated Office like MoEF & CC) assessment under the Environmental Act and Socio-Economic Assessment Act. After obtaining an approval a number of operating permits and authorizations may be required including authorizations issued under the following Acts and Regulations:

- ***Environment Act,***
- Air Emissions Regulations
- Solid Waste Regulations
- Special Waste Regulations
- ***Lands Act***
- Land Use Regulations
- ***Water Pollution Act***

9.0 SAMPLE COMPUTATION OF ENERGY POTENTIAL IN MUMBAI

Heat Energy (Dulong's Formula) to calculated heat energy

HV (KJ/Kg) = 338.2*C + 1442.8*(HO/8) + 94.2*S

Where C, H, O and S are the % of these elements on dry ash free basis.

Considering Literature Review taking percentage by Mass theoretical calculations are as follows:

C= 31.22, H= 8.17, O= 55.68, Sulphur very small so neglected

Applying to formulae we get Heat Energy Generated = 12260.69 kJ/kg

First, heat energy generated is used to calculate steam energy which is 70% of heat energy.

Finally after steam energy calculation, net electric power generated by solid waste is calculated after accounting station service allowance and heat losses.

Steam energy available = 70% of heat energy

Steam energy available = (0.70 ×12,260.69) kJ/kg

Steam energy available = 8,582.483 kJ/kg.

Above calculated steam energy is used to run the turbines, these turbines are coupled with generators which produces electricity.

Heat rate is the heat input required to produce one unit of electricity (kWh). 1 kW = 3,600 kJ/h

But practically no energy conversion is 100% efficient, considering the conversion efficiency of 31.6% in a power plant heat input of 3600 ÷ 31.6% = 11395 kJ/kWh is required.

So, to produce 1kWh electrical energy 11395 kJ of steam energy is required.

Electric power generation = Steam energy ÷ 11395kJ/kWh

Electric power generation = (8,582.483 ÷ 11395) kWh/kg

Electric power generation = 0.753179728 kWh/kg

Total weight of solid waste collected from Mumbai city =1000 tons/day

Total electric power generation = (0.753179728×1000000) kWh/day

Total electric power generation = 753179 kWh/day = **0.75 MU/Day.**

9.1 TYPICAL STUDY OF PARAMETERS

PLANT	STEAM GEN TPH	RO WATER	MSW	RDF	LAND	CAPTIVE	POWER
CAPACITY	BOILER Pr BaR	Kg/Hr	TPD	TPD	AREA M2	USEAGE	GRID
125 KWH	1TPH 10.5BAR	1600	12	6	300	45 KWH	80 KWH
800 KWH	7TPH 45.0BAR	11200	80	40	800	300 KWH	500 KWH
1500 KWH	13TPH 45.0BAR	20800	150	75	1100	500 KWH	1000 KWH
3000 KWH	25TPH 45.0BAR	40000	290	150	1500	700 KWH	2300 KWH
4000 KWH	34TPH 45.0BAR	54400	394	200	1800	900 KWH	3100 KWH
7500 KWH	63TPH 45.0BAR	100800	740	370	2200	1200 KWH	6300 KWH
NOTE:	MSW Un-Sorted & Dried (30% Moisture)			1800	Kcal/Kg		
	MSW Sorted & Dried (30% Moisture)			3000	Kcal/Kg		
	ASH Generation			5 to 25	%		

10.0 SUMMARY

A growing interest in utilizing waste to energy facilities is being driven by the need to conserve landfill space, minimize environmental liabilities, reduce greenhouse gas emissions, and obtain renewable sources of energy. None of the single solution is capable of solving the entire solid waste management problem, although by favourable use of methodology of combined technologies decrease at source, reutilizing, composting and incineration can be supportive. Recycling & reprocessing new materials from used matter like paper, plastics, metals, glass, etc. By decomposing organic matter like kitchen waste, food waste in aerobic or anaerobic way compost can be prepared which further can be utilized as a fertilizer for soil. Combustion of waste in presence of air at high temperatures in Incinerator technology, it lowers the volume of waste up to 90%. Therefore landfill can be avoided completely by above technologies. But from decades in India definition of energy means electricity and scarcity of electricity creates hindrance to growth and development so Waste to Energy Incineration technology should be used for solid waste management as it provides all kind of process- reduce, recycle and regeneration.

10.1 Currently Working and Under Construction Plants in India

a) Okhla plant Okhla WTE plant in Delhi is currently under operation, which uses the method of direct combustion of MSW, produces 16 MW/day of power with an input of 1350 TPD of waste. The waste is segregated before combustion process. Air Pollution Control Systems such as Turbo-reactor and Fabric Filtration Air Quality Control System are equipped to prevent the hazardous gases coming out after combustion.

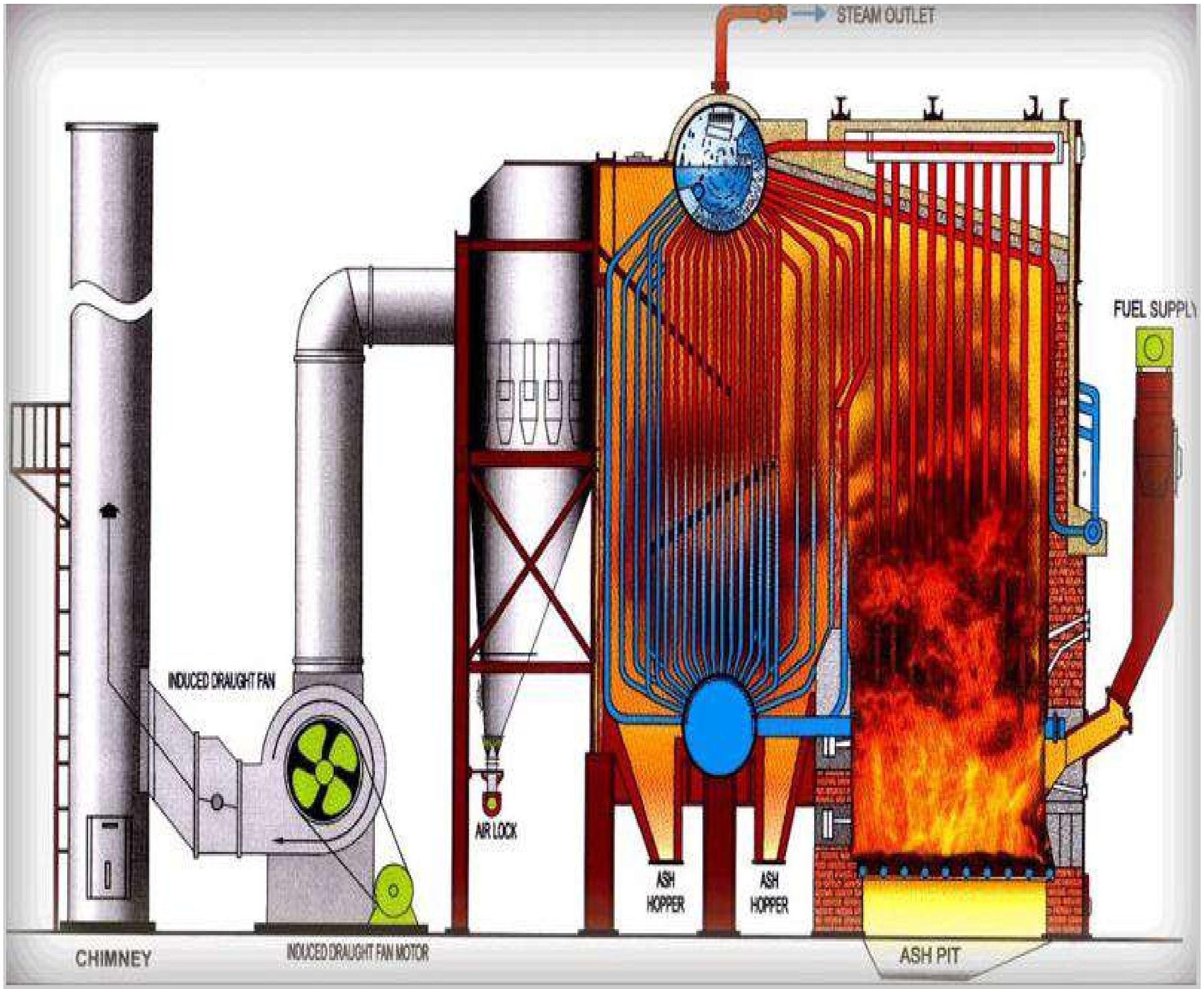
b) Vijayawada Plant A power plant at Vijayawada utilizes wastes from vegetable market and slaughterhouse by generating 0.15 MW power per day.

c) Gazipur Plant This plant at Gazipur is under construction and is expected to produce 12MW/day power with the input volume of 1300TPD of waste.

11.0 CONCLUSION

The alarming rate of increase in the waste materials in India can no more be acceptable. Hazardous wastes poison our country and negatively affect the health of millions of people. Also, conventional sources of energy like fossil fuels are depleting at a faster rate which will lead us to energy crisis. The concept of '**Electricity from wastes**' gives us a way to manage energy as well as waste. Conducted literature survey included several research papers and categorized them in three areas that are Bio-energy, Thermal Energy and Miscellaneous sources of energy.

In bio energy we encountered many methods like incineration, anaerobic digestion, plasma gasification etc. useful in generating electricity by mitigating the bio waste. While in Thermal energy we focused on saving waste heat energy and converting into electricity. Miscellaneous sources of energy consists many waste sources like electronic waste, plastic waste etc. Every energy source has its own indispensability in its area. Hence, we conclude from our work that by effective waste management we can keep India green forever and save ourselves from energy crisis.



स्वच्छ भारत
एक कदम स्वच्छता की ओर

Abbrevations Used:

CEA	: Central Electricity Authority
MSW	: Municipal Solid Waste
WTE	: Waste to Electricity
MOEF&CC	: Ministry of Environment, Forest, and Climate Change
GHG	: Green House Gases
SPM	: Suspended Particulate Matter
PM	: Particulate Matter
MT	: Metric Tonne
TPD	: Tonnes Per Day
MSPGCL	: Maharashtra State Power Generation Company.

Economic Grid Interactive Hybrid Energy Storage Solution in Renewable Energy specifically for India

Dr. Rashi Gupta -Vision Mechatronics Pvt Ltd

Introduction:

The electrical grid is not something most people think about. Flip the switch, the lights come on. If it doesn't work, make a phone call to the electric company. End of story. But the grid is actually a hugely complex organism, one that requires close attention to keep the electricity flowing at the right voltage and frequency. It is common to hear people say that renewables like solar and wind disrupt the grid because they vary in voltage and frequency depending on wind speed and cloud cover. There are also concerns about microgrids disrupting the stability of the larger utility grid.

Millennials are far more likely to express interest in energy usage reports, app-based savings suggestions, prepaid billing and energy usage tracking than previous generations. Across the board they're also far more interested in community solar, electric vehicles, energy storage, smart appliances and the smart home concept than the baby boomer generation. Millennials also want their utilities to invest heavily in smart grid infrastructure upgrades and renewable energy generation (even if it means they have to pay more), and compared to older generations, they're more willing to jump ship if their current utility doesn't meet their needs. This brings us to the next point of focus, i.e., energy storage in such applications

Key Roles of energy storage:

Balancing grid supply and demand

Peak shaving and price arbitrage opportunities

Storing and smoothing renewable generation

Deferring large infrastructure investments

Reducing end-use consumer demand charges

Back-up power

Smoothening of RE power

With the current rate at which the renewable energy market is spreading through India, we cannot overlook the importance of the role energy storage would play in the whole situation. If we look at the current situation of energy storage in India, Lead-Acid and its variant are the dominant technology and the new and upcoming Lithium-Ion and its variant are lesser prevalent, but are now picking up. With more and more awareness being created about Lithium batteries, it's likely that we will see a major segment of energy storage in India dominated by it.

The current market demands for energy storage are huge, on the back of growing demand for automobiles, continuous expansion of telecommunication infrastructure, increasing number of solar power projects, and growing IT industry. Growing awareness among the consumers to opt for high quality batteries would result in paradigm shift in sales of unorganized batteries to organized batteries.

There has been growing shift towards other forms of batteries, particularly lithium ion batteries. Lithium ion batteries are environmentally friendly batteries and last longer than lead acid batteries. The decline in prices of lithium ion batteries has helped in increasing its consumption, as such batteries are used as substitute for lead acid batteries.

However, rise in technological developments and increasing need for cleaner energy sources have brought Li-ion batteries on the forefront across various industries as well as end-use sectors. As of now, India predominantly depends on China, South Korea and Taiwan for Li-ion batteries since the country does not have indigenous manufacturing operations for these batteries. However, to offset this challenge, companies are planning to start production of advanced Li-ion batteries in India itself.

Under the new policies taken up by the government, adoption of Li-ion batteries is anticipated to grow at a tremendous pace in the coming years. Rising penetration of electric vehicles, substantial investments in clean and renewable energy sources, and the recently launched Make in India campaign are expected to boost the demand for Li-ion batteries in the country through the forecast period. Government of India has launched New Electric Mobility Mission Plan 2020, which projects to have 6-7 million electric vehicles running on Indian roads by 2020. Smart city projects and Green Energy Corridor for power generation from renewable sources would add to the overall installed capacity, thereby increasing the demand for energy storage batteries.

Primary Objective:

Given the current stability situation of the grid, smart city and green corridor developments and the rural electrification challenges, low cost Long duration energy storage for backup of 8 hours or more is the primary requirement.

Problem Statement:

As we know every objective has its own set of problems, the aforementioned objective faces a problem on the economic and the technological front, that is, Economical long duration energy storage solution is required for many application which with one given technology becomes expensive and non-viable.

We are looking at the energy storage requirements ranging from a couple of MegaWatts to hundreds of MegaWatts. Battery costs also depend on technical characteristics such as generating capability, which for energy storage systems can be described in two ways:

- Power capacity or rating. Measured in megawatts, this is the maximum instantaneous amount of power that can be produced on a continuous basis and is the usual type of generator capacity discussed
- Energy capacity. Measured in megawatt hours (MWh), this is the total amount of energy that can be stored or discharged by the battery.

A battery's duration is the ratio of its energy capacity to its power capacity. For instance, a battery with a 2 MWh energy capacity and 1 MW power capacity can produce at its maximum power capacity for 2 hours. Actual operation of batteries can vary widely from these specifications. Batteries discharged at lower than- maximum rates will yield longer duration times and possibly more energy capacity.

In situation like this, and with the current economic situation of lithium batteries in India, we can expect lithium batteries of such tune to be expensive and non-viable at times. But in all when we are to talk about the life of such storage systems and the initial investment, levelized cost of operation, we would find that it's rather economic to use these energy storages.

Short-duration batteries are designed to provide power for a very short time, usually on the order of minutes to an hour, and are generally less expensive per MW to build. Long-duration batteries can provide power for several hours and are more expensive per MW. On the revenue side, batteries have relatively low capacity factors because of charging duration and cycling limitations for optimal performance. Nevertheless, they can uniquely capture a range of value streams, which can sometimes be combined to improve project economics. Let's have a look at the variations in the Energy Storage Technology that exists

	supercap	SMES	flywheel	lead-acid	lithium-ion	NaS	redox-flow	hydrogen	pumped hydro	CAES
energy density in Wh/l	2-10	0,5-10	80-200	50-100	200-350	150-250	20-70	750/250bar 2400/liquid	0,27-1,5	3-6
installation costs in €/kW	150-200	high	300	150-200	150-200	150-200	1000-1500	1500-2000	500-1000	700-1000
installation costs in €/kWh	10000-20000	high	1000	100-250	300-800	500-700	300-500	0,3-0,6	5-20	40-80
reaction time	<10ms	1-10ms	>10ms	3-5ms	3-5ms	3-5ms	>1s	10min	>3min	3-10min
self-discharge rate	up to 25% in first 48h	10-15 %/day	5-15 %/h	0,1-0,4 %/day	5 %/month	10 %/day	0,1-0,4 %/day	0,003-0,03 %/day	0,005-0,02 %/day	0,5-1 %/day
cycle life-time	>1Mill.	>1Mill.	>1Mill.	500-2000	2000-7000	5000-10000	>10000	>5000		
life-time in years	15	20	15	5-15	5-20	15-20	10-15	20	80	ca. 25
system efficiency in %	77-83	80-90	80-95	70-75	80-85	68-75	70-80	34-40	75-82	60-70
short-term (<1min)	XXX	XXX	XXX		X		X			
mid-term (>1min,<2d)			X	XXX	XXX	XX	XX	X	XX	XX
long-term (>2d)				X		X	XX	XXX	XXX	XX

The primary point of focus for this paper is to introduce a different approach to energy storage consideration in cases where the requirement for the energy storage is huge. The paper proposes use of multiple technologies in combination to achieve the said goal. As we all know that no technology is perfect and has their pros and cons, this approach aims to combine pros of multiple technology in way that would make the cons, in the combination, seem negligible.

In the global market, energy storage has many other technologies that India is yet to witness. Lithium Titanate being the closest to being exposed in India, there are also energy storage systems that have life expectancy of more than 25 years and rely on different kinds of raw materials. For ex., Vanadium Redox batteries have been prevalent in the global market since quite some time, but has some significant shortcomings that heavily overshadow its advantages. These batteries have a life of 25 years and can be effectively utilized over its lifespan. With such technologies and mix and match of the prevalent technologies, such shortcomings can be overshadowed by merits of the other and viceversa.

Other technologies like Compressed Air Energy Storage operate at a completely different scale and uses air as a raw material. Here we need to focus on the part where we can make sure that the raw material required for such energy storage systems should be present in abundance so as to have a sustainable solution to the problems at hand. For example, zinc air batteries use Zinc as the raw material which is more easily found as compared to lithium, could be a possible way of creating more economical solution as compared to lithium. Research on zinc air batteries is still in the laboratory phase and would take some time to appear as a readily available solution for the general market.

Research & Solution

What India's Power Sector Needs?

HESS : Hybrid energy storage solution is way forward for combing different types of storage to get the optimum economics of energy storage. Hybrid energy storage systems (HESS) merit a closer look for stationary applications as part of comprehensive energy storage deployment strategies. If HESS technology can achieve double-digit percent decreases in capex and opex, increase system operating life, and boost revenues by simultaneously providing multiple services, these hybrid solutions may provide an optimum solution. Of course, the energy management hardware (inverters, converters, etc.) and software needed to manage two different storage technologies for multiple use cases are not trivial.

We have used two different types of energy storage technologies to cater to this long duration energy storage requirement which may include Lead batteries, Lithium batteries and flow batteries based technology. This requires an intelligent controller which perform the following functions:

1. maintain the battery health as per the individual technology requirement
2. Inter-balancing between the two different technology

3. Intra-balancing the batteries with intelligent BMS

4. Sending alerts to the user for the faults

5. Interfacing with the battery for the protection mechanism

6. Grid interactive storage (For charging as well as Grid feed)

7. Renewable energy management (For charging)

8. Data logging and reporting

9. Internal Switching from one storage technology to other and vice versa as per load demand

10. Remote/local monitoring

Being grid interactive energy storage solution it can cater to many objectives like

1. Peak load management

2. Demand management

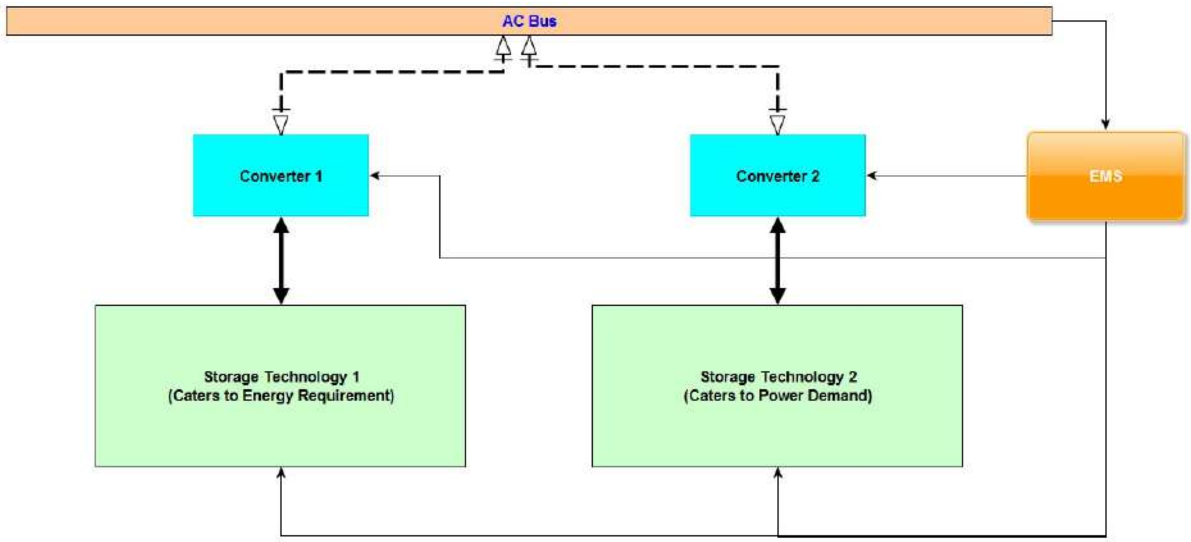
3. RE smoothening

4. Long duration Backup

5. Diesel Generator replacement solution

6. Can cater to the Instantaneous power requirement

7. Handling of heavy inductive loads



Effectively utilizing the storage technologies in combination, a type of power need and the other for energy needs, this is the ideal research segment for the electronics industry of India. With such research, we can expect the power instability and the concerns that currently affect the operations of renewable energy power plants to be taken down to a level that would be least bothersome. The illustration above shows the kind of system that we have developed to have a completely synchronized system that would take care of the load demand. During the situation where the load demand is excessively high, for example an inductive load is turned on, Storage Technology 2 would be used to provide the output power owing to its capabilities of being a storage for Power Demand. This would essentially be done by the EMS, which is a self-learning type of a controller which is capable of adapting to the load profile and patterns throughout the day. Irrespective of the learning of the EMS, the basic function of determining the load current on the AC bus is trivial. As soon as the power demand subsides, the EMS now intelligently switches the source from the Storage Technology-2 to Storage Technology-1. This keeps the utilization of each technology optimum. It also helps reduce the overall size required for each technology, essentially optimizing the financial model of the proposed system. The situation just explained could be during a grid failure or during the presence of the grid as well i.e., applications like peak shaving. Once the peak demand subsides and reduces below the threshold, the storage systems can be supplied with energy to keep it ready for the next occurrence. The priority will be given to the Storage Technology that supports Power Demand, to replenish itself, and then the other. Though all of this may seem trivial, a very important fact that must not be neglected is the time to switch from one source to the other. This only implies that the switch from one source to other either be made well within 10ms or there be continuous operation of the Storage technology 2 in order to have a flicker free transition from one source to another. This in fact, is another decision that the EMS takes to prevent the load from facing a power loss. As we can decipher, the EMS is the brain of the whole HESS system and would be essential to have a customized priority learning and power transfer algorithm for each kind of application chosen.

The integrated energy management system allows the full control to the user to analyse their energy requirement even on a daily basis to utilize their RE assests at the most optimum level and use the energy storage to its utmost benefit.

An important point to be focused upon is the segmentation of such systems for varied applications and varied infrastructure levels. It's only wise to realize that the cage must be built only as big as it is needed.

Implementation Issues that may occur at the MW scale level:

1. The system may be very complex to implement at the MW scale level

2. May not be a completely maintenance free solution

3. Regulatory and policy barriers may pop up in the due course

Conclusion

With this hybrid energy storage solution (HESS) we aim to resolve the long duration backup and energy requirement issues economically taking the advantages of latest Lithium based technology coupled with the various other storage technologies to based on the applications.

Note: This paper is based on the experience that the author has in this industry alongwith the products developed by the company over a period of time.

Case Study: Battery Energy Storage System for Optimum Solar Energy Integration and Enhancement of Grid Security at Andaman Island.

S S Mishra, (AGM) and Subir Karmakar (DGM) NTPC Ltd

(Cell No- 9650991145, 9650992419, Email- ssmishra@ntpc.co.in,subirkarmakar@ntpc.co.in)

Abstract:- Presently South Andaman demand is catered majorly through existing DG capacity as well as NTPC Gharacharma Solar PV Plant (5 MWp). As per Electricity Deptt, A&N, evening peak & day hour demand during 2021-22 would be around 50 MW & 35 MW respectively. 24x7 Power For All document of Andaman & Nicobar aims to reduce the diesel generation in the island by installing Gas plant and enhancing share of renewable energy in a phased manner. Considering above, by 2021-22, South Andaman energy mix should be primarily free from Diesel generation. Cloud movement is a routine phenomenon in Islands of Andaman & Nicobar. Regular cloud movements have tremendous impact on generation variability on existing Solar PV capacity (5 MW). In Andaman during May to October month in addition to normal cloud movements, there is full dark cloud observed, 2 to 3 times in a month. Due to this, in total around 15 days solar radiation is extremely low and at times solar plant/Inverter automatically goes into sleep mode. In Andaman, monsoon season is almost around 8 months. Based on the information submitted by Electricity dept., A&N regarding seasonal load profile and NTPC 5MWp Gharacharma Solar plant generation data a detailed analysis has been carried out for FY21-22 time frame duration for Optimum Solar Energy integration, Smooth operation of Gas Plant and enhancement of Andaman Grid Security with the help of Battery Energy Storage System.

I. Introduction:-

Typical month wise load demand curve for South Andaman during FY-2016-17 is shown in Fig. 1. Typically day time load (base load) demand is around 20MW to 25MW and evening (peak) demand is around 35MW during FY-2016-17 time duration. Cloud movement is a routine phenomenon in Islands of Andaman & Nicobar. Regular cloud movements have tremendous impact on generation variability on existing Solar PV capacity (5 MW) as shown in Fig. 2.). In Andaman during May to October month there is full dark cloud, 2 to 3 times in a month. Due to this, in total around 15 days solar radiation is extremely low and at times solar plant/inverter automatically goes into sleep mode. Further, even during summer season, cloud movements are a regular phenomenon resulting in intermittent generation output, necessitating availability of spinning/balancing reserves on a continuous basis. In Andaman, monsoon season is almost around 8 months. Therefore in monsoon season, Solar PV generation may not be relied upon.

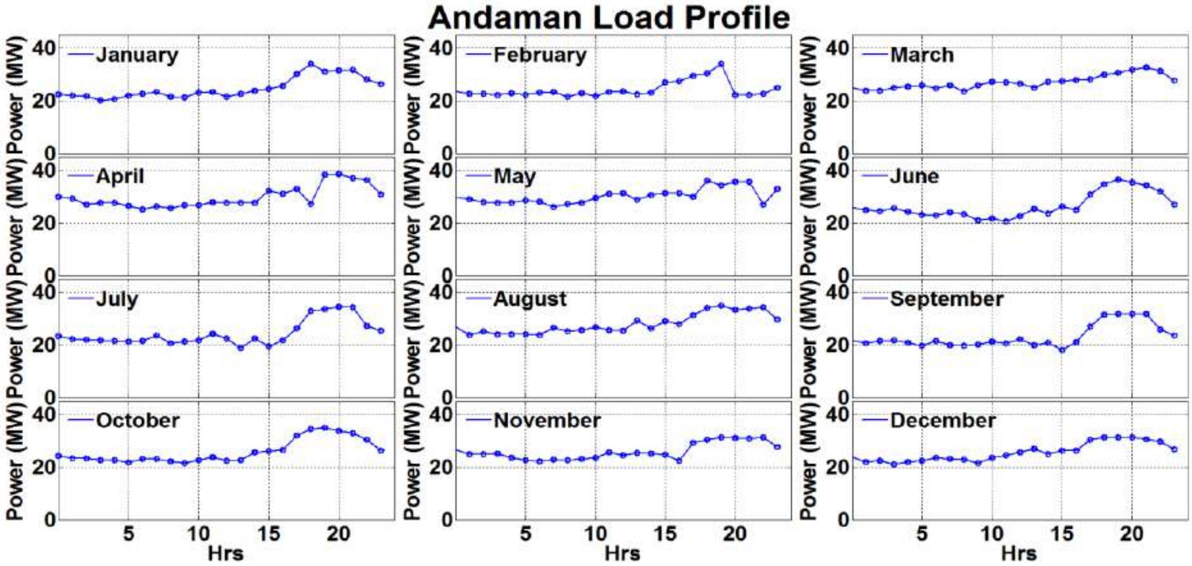


Figure-1 Typical moth wise load demand curve for south Andaman during FY 2016-27

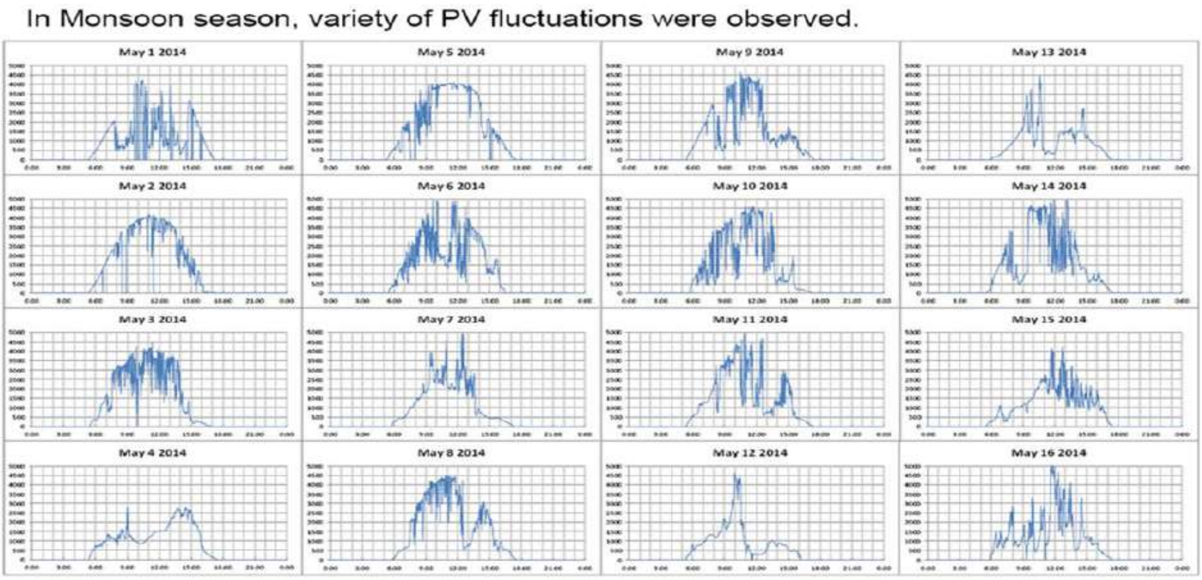


Figure-2 Generation variability during Monsoon season on existing NTPC 5MWp Gharacharma Solar plant.

Following are the Andaman future energy generation scenario:

(i) Gas Plant for based load and peak load requirement.

(ii) Optimum Solar Power Plant for better energy security.

(iii) Power type Battery with Solar Plant in order to cater the day time cloud intermittencies requirement.

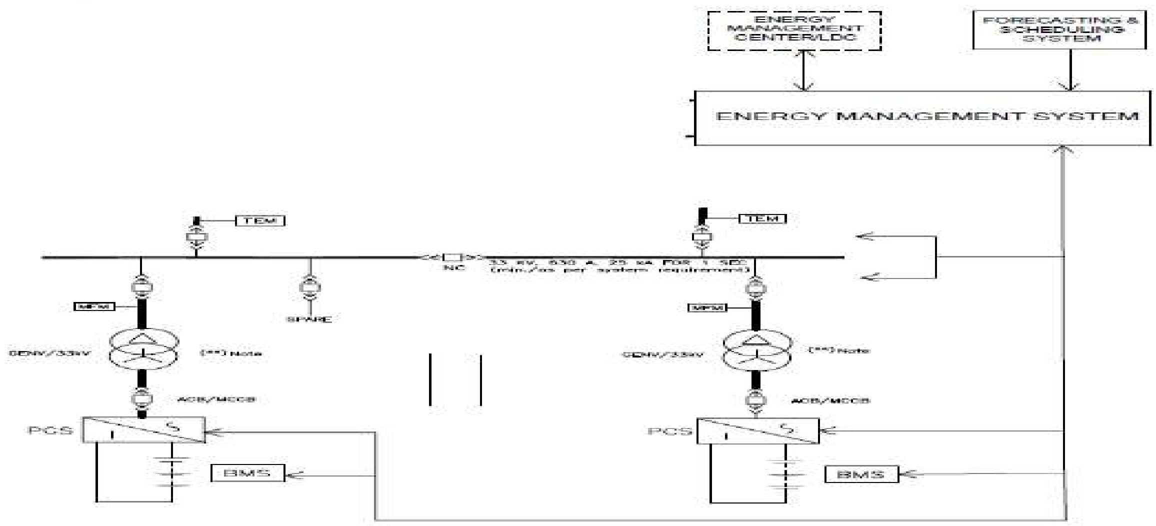
(iv) Energy type Battery with Solar Plant for peak shaving and energy time shifting application for Optimum Solar Integration and mitigation of peak load demand with Solar Power.

II. Battery Energy Storage System (BESS):-

Battery Energy Storage Systems (BESS) may prove to be very useful for power as well as energy application for Andaman grid. However, from the point of view of catering to cloud intermittency, power rated BESS system may be useful while for energy time shift or energy firming, BESS energy application may be useful. It is to mention that Power & Energy Application BESS have distinct characteristics. Power Application BESS have High Power/Energy Ratio, high ramp rate and high Charge/discharge-rate.

Typical single line diagram of battery storage system is shown in Fig.3. Major components of Battery Energy Storage Systems as shown are as follow:

- Battery
- Battery Management System (BMS)
- Power Conditioning System (PCS)
- Power Transformer
- HT & LT Switchgear
- Energy Management System



24MWh, 6MW BESS System

Figure-3 Typical Single Line Diagram for Battery Storage System.

A. **Battery:**

The energy storage system may consist of one or more type of batteries to meet the application requirement. Battery shall be electrically interconnected in any desirable series and parallel configuration to achieve the overall system storage and power rating requirements. The dc voltage of battery system shall be selected to suit the PCS and battery efficient and safe operational requirement.

The batteries are made of stacked cells where-in chemical energy is converted to electrical energy and vice versa. The desired battery voltage as well as current levels are obtained by electrically connecting the cells in series and parallel. The batteries are rated in terms of their energy and power capacities. For most of the battery types, the power and energy capacities are not independent and are fixed during the battery design. Some of the other important features of a battery are efficiency, life span (stated in terms of number of cycles), operating temperature, depth of discharge (batteries are generally not discharged completely and depth of discharge refers to the extent to which they are discharged), self-discharge (some batteries cannot retain their electrical capacity when stored in a shelf and self-discharge represents the rate of discharge) and energy density.

Some of the Battery Technology Used in Large Scale Battery Energy Storage Plant

- Lithium-ion Family of Batteries
- Sodium-Sulfur (NaS) Battery
- Sodium Nickel Chloride Battery
- Flow Battery
- Advance Lead Acid (Ultra Battery)

B. **Battery Management System (BMS):**

The BMS to provide for automatic, unattended operation of the battery storage system. The BMS shall provide the necessary monitoring and control to protect the cells from out of tolerance ambient or unsafe operating conditions. The BMS shall automatically control the charge and discharge of the individual cells, balancing between cells to optimize energy consumption and range, monitor cell heath and provide critical safeguards to protect the batteries from damage.

C. **Power Conditioning System (PCS):**

The Power Conditioning System (PCS) is the interface between the DC battery system and the AC system and provides for charging and discharging of the battery. It may consist of one or more parallel units. The PCS shall consist of solid state electronic switch along with associated control & protection, filtering, measuring instruments and data logging devices. The PCS shall be bi-directional inverter with four quadrant operation.

D. **ENERGY MANAGEMENT SYSTEM (EMS):**

Energy Management System (EMS) system shall be a computerized system for real time monitoring, operation, control, reliable & efficient operation and optimization of performance of the BESS system. SCADA system shall be part of EMS system. EMS shall be able to acquire real time data of various equipment of BESS system and have in logic/programming to of BESS as per specification. The EMS &SCADA system to have all accessories, auxiliaries and associated equipment's and cables for the safe, efficient and reliable operation of entire BESS and its auxiliary systems.

Battery Energy Storage System Application for Andaman

1) Solar Generation Smoothening
2) Peak Shaving/Peak Shifting
3) Micro-Grid Operation with PCS Black Start Feature.
4) VAR Support

A. Solar Generation Smoothening:-

BESS is required to mitigate the intermittent fluctuations of solar power generation due to cloud intermittency by smoothen Solar PV output power to grid. The BESS to absorb short term power variations in Solar PV plant output by fast charging or discharging the battery and generate a smoother generation curve that can be absorbed in the grid in an easier way.

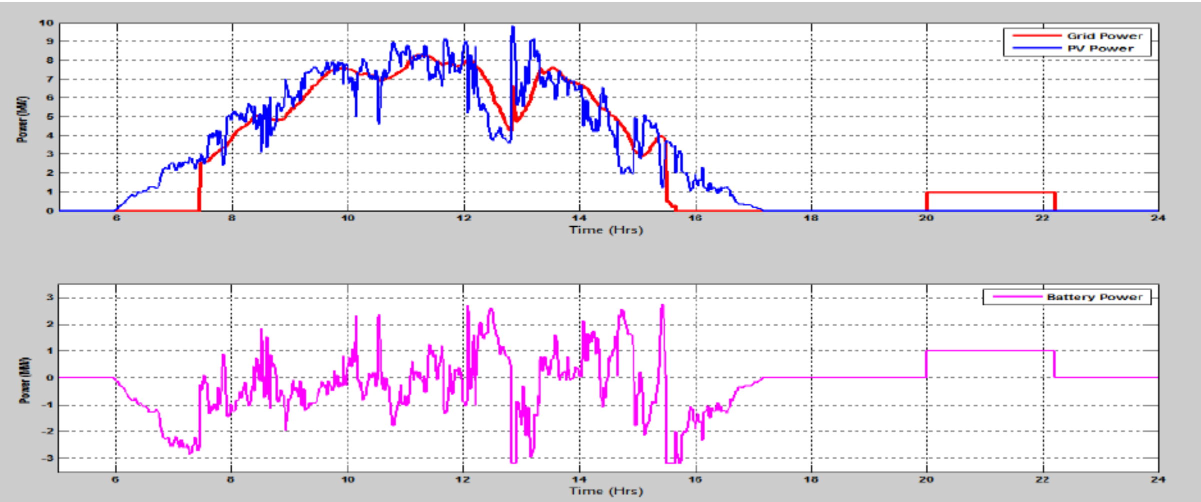


Figure-4 BESS Application: Solar Generation Smoothening.

B. Peak Shaving/Peak Shifting :-

For energy time shift application the BESS shall time-shift the excess Solar PV plant output power and make it available to gird when needed. BESS shall automatically charge the battery with power from solar PV plant during solar generation hours and discharge the battery by supplying power to grid during peak load periods or as per grid operator requirement.

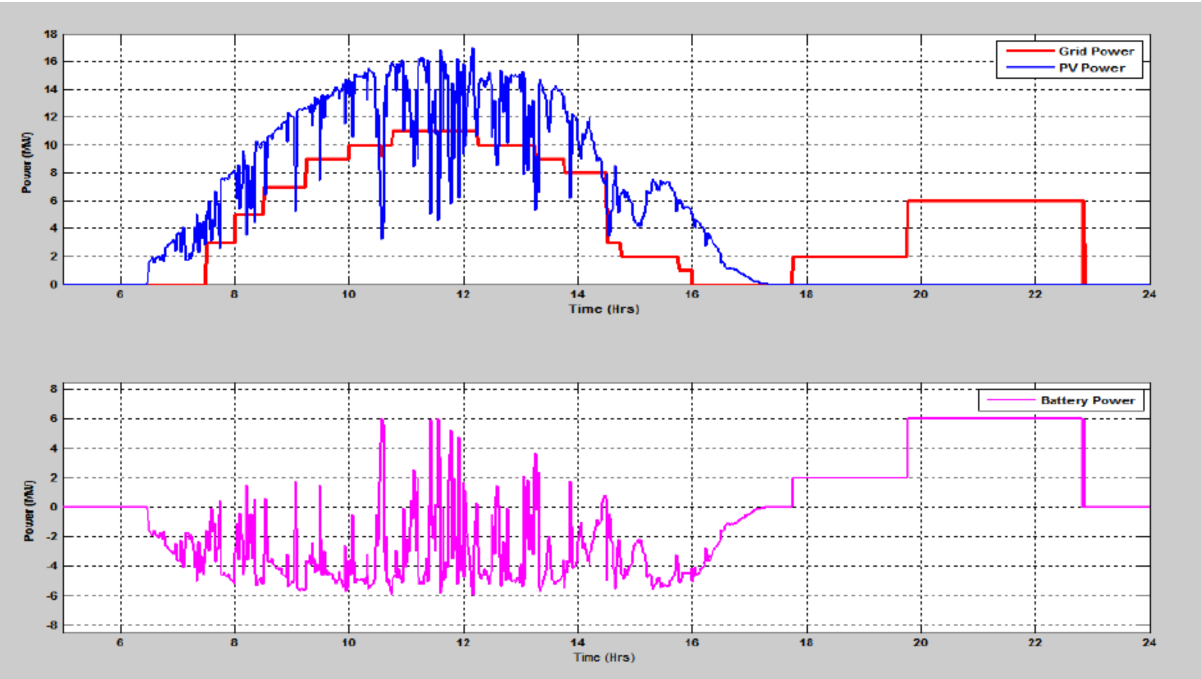


Figure-5 BESS Application: Peak Shaving and Energy time shifting.

C. Micro-Grid Operation with PCS Black Start Feature:-

BESS shall have black start operation feature and shall be able to form a micro-grid with solar PV plant & local loads. BESS shall set and automatically control the micro-grid voltage & frequency within acceptable limit and shall charge or discharge the battery based on micro-grid requirement.

E. VAR Support:-

The BESS will be required to provide VAR support to grid for voltage regulation purpose. The VAR output of the BESS may be limited based on remaining capacity left after providing real power output. The VAR support mode shall be controllable through selectable set point in energy management system (EMS).

III. Case study- Simulated Result and Discussion:-

A. Solar Power Generation Smoothening

Some of the methodology used for Solar Power generation smoothening are as follow,

(1) Moving Average Strategy
(2) Battery SOC Control
(3) Ramp Rate Control

Simulation study has been carried out to study the effect of Moving average method and Battery SOC control method for battery storage requirement and characteristic of injected solar power to grid during high cloud days and also during sunny day. Fig.6 shows the simulated curve for solar generation smoothening of different days based power moving average method.

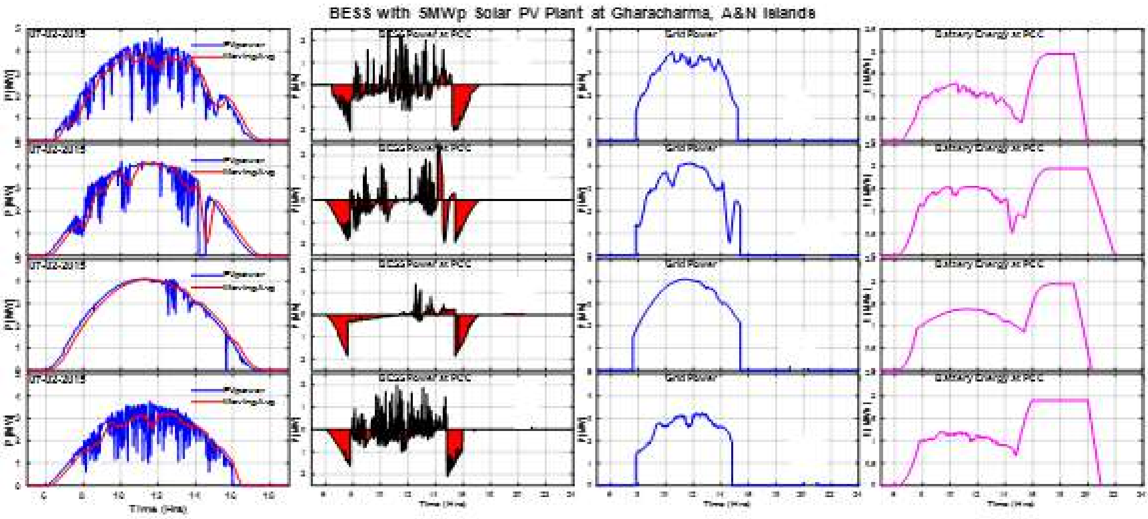


Figure-6 Simulated curve for different days for Solar Generation Smoothening based on moving average method.

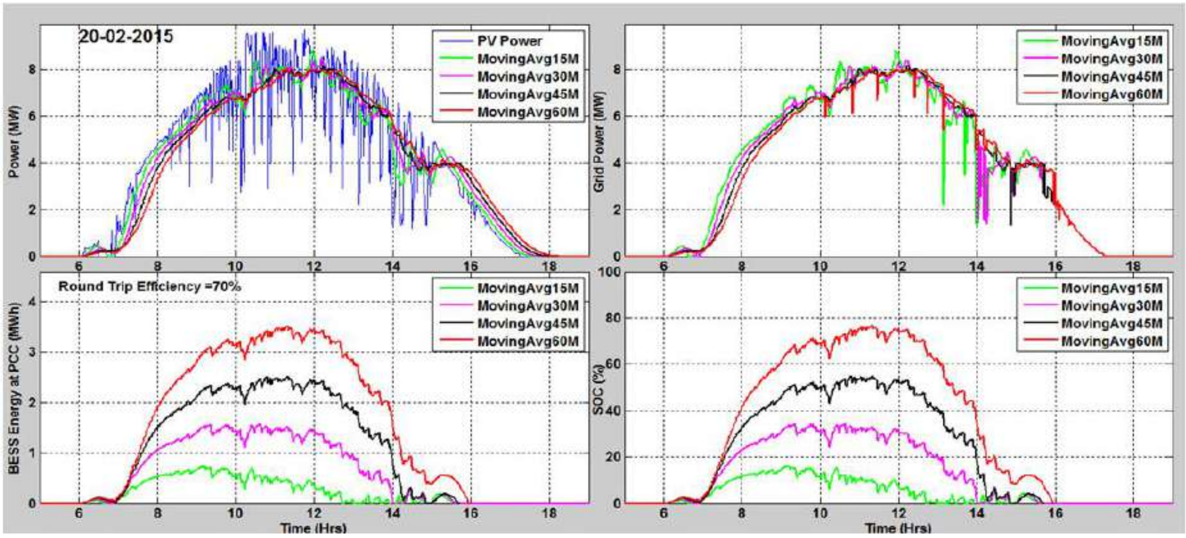


Figure-7 Simulated curve for Solar Generation Smoothening based on different moving average value.

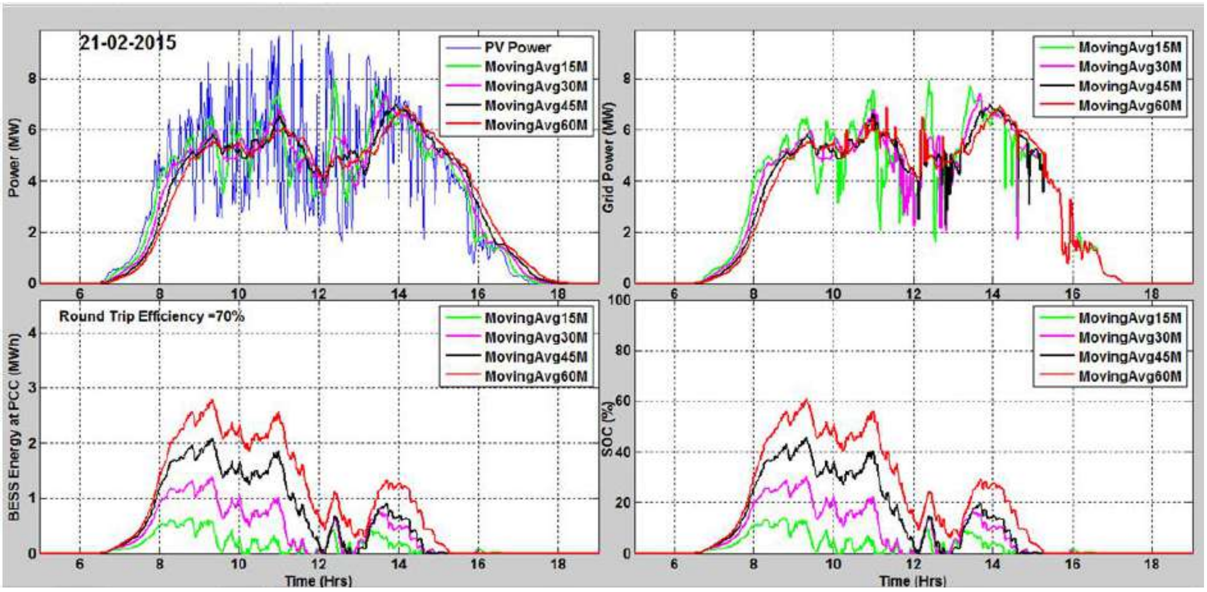


Figure-8 Simulated curve for Solar Generation Smoothening based on different moving average value.

Fig. 7 & 8 shows the simulated solar generation smoothening curve with different moving average value. Higher moving average value shall have better smother solar generation power curve for smooth injection to grid. However, as the moving average value increases the storage energy sizing requirement also increasing. Fig.9 shows the comparative simulated curve for battery sizing and ramp rate (1 minute) of injected power to grid. Figure shows that without BESS the maximum ramp rate of the injected power to grid is around 50% and whereas with BESS is comes down to 3% with 30 minutes moving average value and around 5% with 15 minutes moving average value. Battery energy sizing requirement with 15 minutes much lesser than 30 minutes average value methods. However, considering Andaman small grid, the 30 minutes moving methods is more suitable for grid stability point of view.

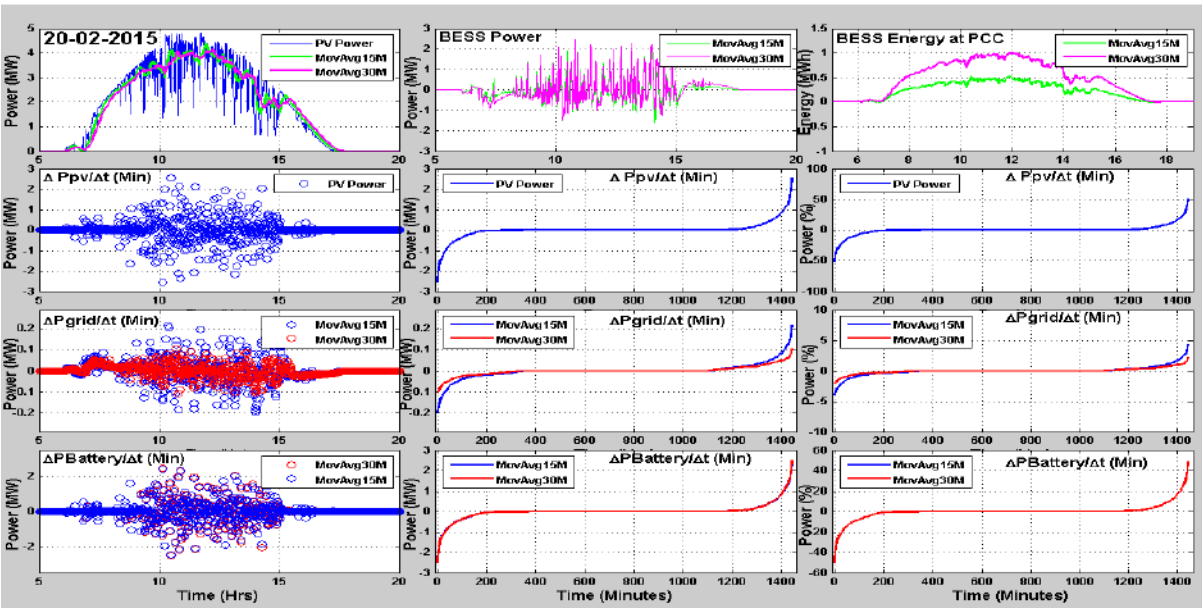


Figure-9 Simulated curve for Solar Generation Smoothening based on different moving average value.

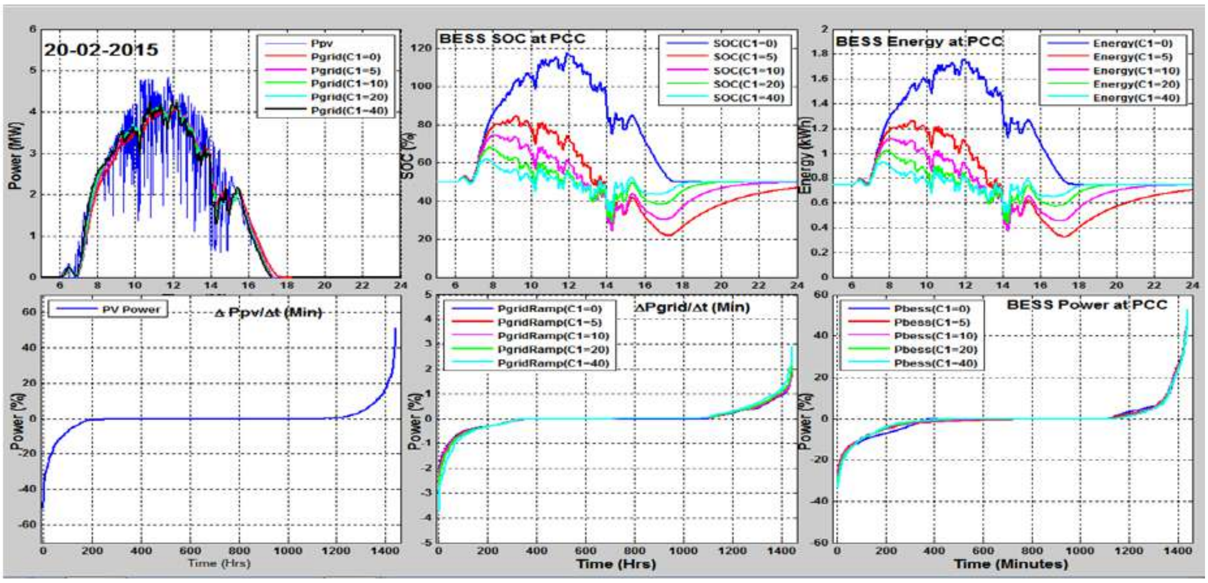


Figure-10 Simulated curve for Solar Generation Smoothening based on Battery SOC Control algorithm.

One major disadvantage with moving average method is that during clear sunny day also the BESS shall charge during 1st half solar generation hours and discharge during 2nd half of solar generation hours. With Battery SOC control algorithm for solar generation smoothening as shown in Fig.10 the battery energy sizing requirement shall significantly reduce without compromising the ramp rate of injected solar power to grid.

B. Peak Shaving/ Peak Shifting

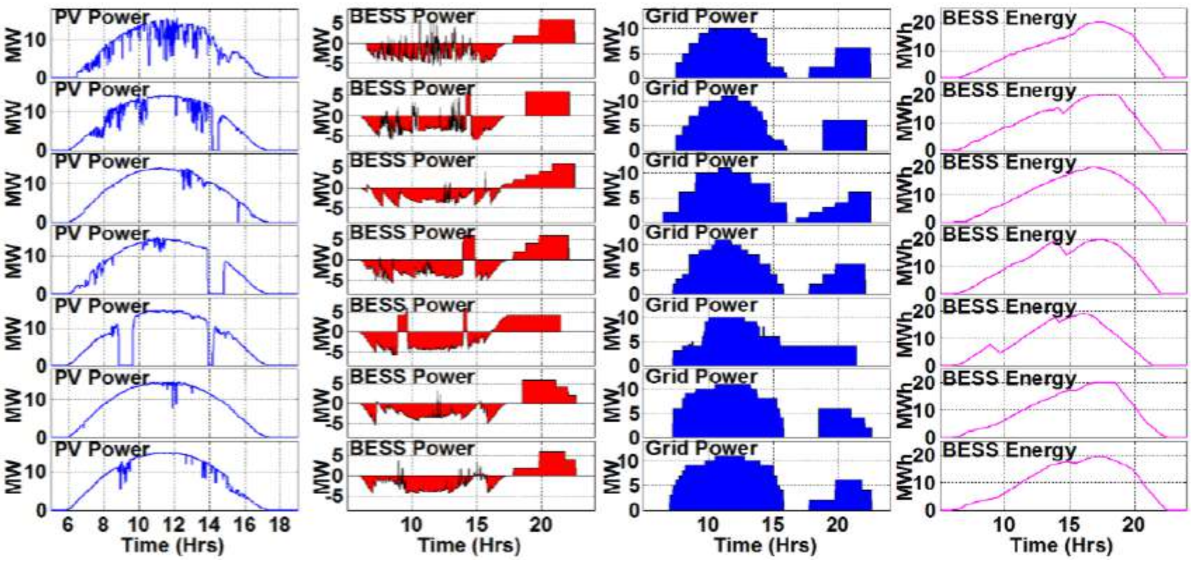


Figure-11 Simulated curve for Solar Generation Peak Shaving/Peak Shifting

Fig.11 show the simulated curve for application BESS for Peak Shaving and Peak Shifting for different days with day ahead solar generation for casting and generation scheduling. BESS with Energy type are required for this application. 0.2C type battery with 4 to 5 hours of storage capacity are suitable for this application. As per the figure the BESS time-shift the excess Solar

PV plant output power and make it available to gird when needed. BESS automatically charge the battery based on prior charging schedule with power from solar PV plant during solar generation hours and discharge the battery by supplying power to grid during peak load periods or as per grid operator requirement. As shown in figure the solar plant power injected to into grid is constant during schedule time. BESS completely absorbed the intermittent power fluctuation of solar plant generated power due to cloud intermittence issue. The energy store in Battery can be used to offset the peak load power demand requirement. Fig. 12 and 13 shows the Battery utilization for two different size of BESS capacity (i.e. 6MW, 24 MWh and 13MW, 52MWh) for complete one year duration for FY 2021-22 time frame. Majority of the Day the BESS is fully utilized.

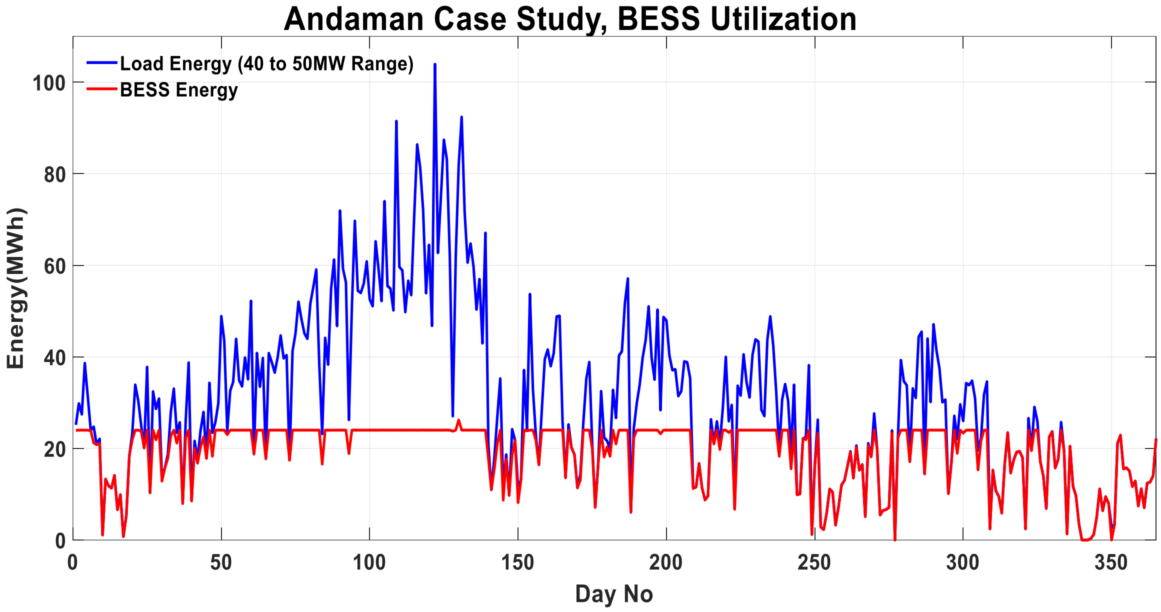


Figure-12 Simulated curve for Battery Utilization (BESS size 6MW, 24MWh) for Andaman peak load power demand (40 to 50MW range) supply for complete one year period for FY 21-22 time frame.

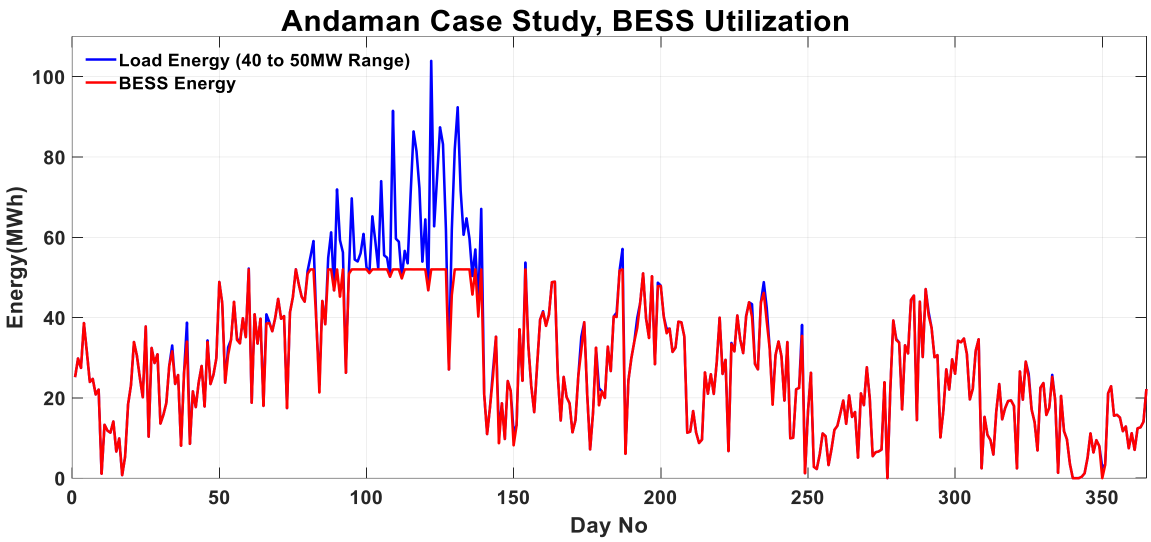


Figure-13 Simulated curve for Battery Utilization (BESS size 13MW, 52MWh) for Andaman peak load power demand (40 to 50MW range) supply for complete one year period for FY 21-22 time frame.

C. Case study-Hybrid Solar and Gas Plant Operation During Cloud Intermittence with BESS and without BESS Scenario :-

Fig. 14 and 15 show the simulated typical one day load and solar & gas plant generation operation curve with and without BESS system. It's clear from the figure that without BESS system the injected grid power from solar plant are highly distorted/intermittent and causing the Gas plant to operate with high ramp rate and that my reduce the service life of the Gas plant machine. With power type BESS the injected grid power from solar plant is smooth and the ramp rate requirement of Gas plant has significantly reduces. Total solar capacity considered in this case is 35MW (i.e., 10MW existing and 25MW additional solar capacity)

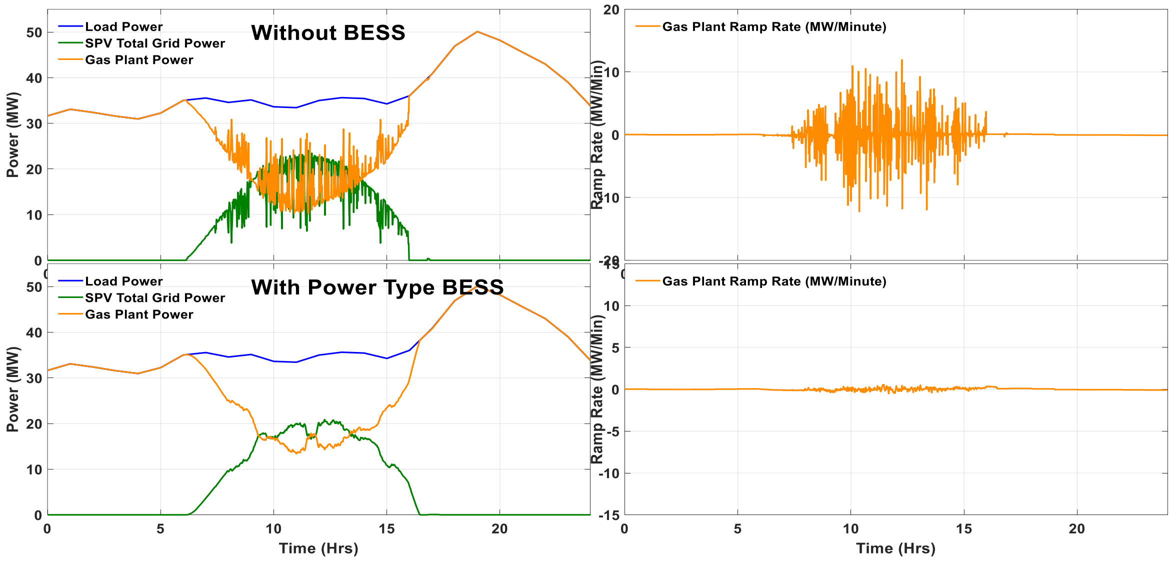


Figure-14 Simulated One Day generation curve for Gas Plant ramping requirement with and without BESS system during high solar intermittence

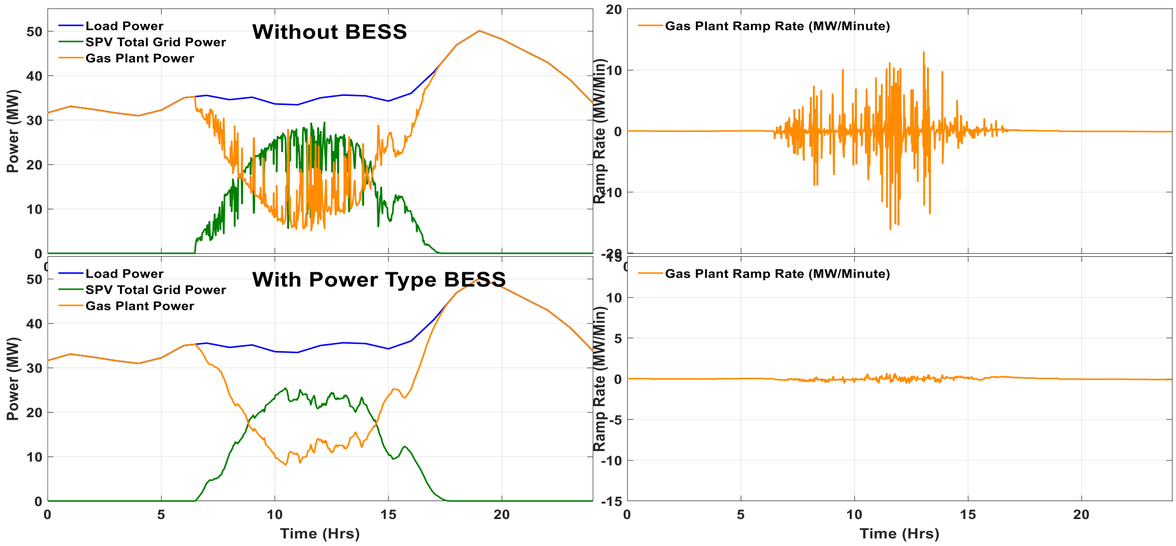


Figure-15 Simulated One Day generation curve for Gas Plant ramping requirement with and without BESS system during high solar intermittence.

Fig. 16 show the simulated typical one day load and solar & gas plant generation operation curve with 55MW solar capacity (i.e., 10MW existing and 45MW additional solar capacity). From the figure its clear that without any Battery Storage System the grid has surplus solar power even with zero power from Gas plant. In order to integrate the large solar power capacity during day time, the energy type BESS is must. With energy type BESS with additional 35MW solar plant has the capability to absorb the surplus solar energy and supply the store energy during evening peak hours. The Gas plant operated in technical minimum level and the ramp rate requirement from Gas plant also minimum and can be cater with single machine running, hence significantly enhance the engine average loading (i.e. Individual machine PLF can be obtained 75-80%).

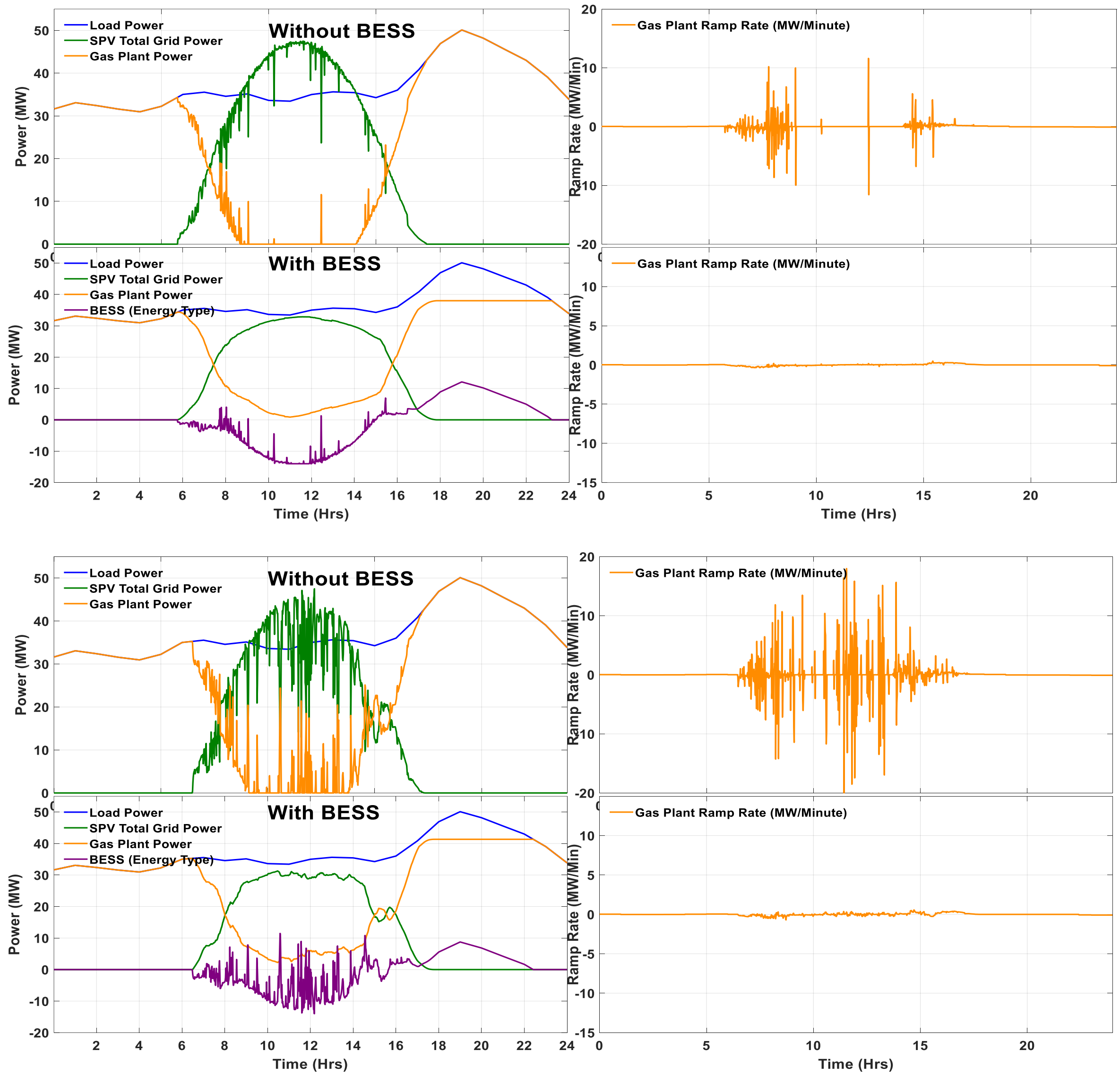


Figure-16 Simulated One Day generation curve for Gas Plant ramping requirement with and without Energy type BESS system

IV. **Conclusion:-**

This paper presented the case study of uses of Battery Energy Storage System for optimum solar integration and smooth grid operation in Andaman. Estimated peak load demand in South

Andaman shall be 50MW in FY2021-22 and off peak day demand is around 35 MW. 24x7 Power For All document of Andaman & Nicobar aims to reduce the diesel generation in the island by installing Gas plant and enhancing share of renewable energy in a phased manner. Cloud movement is a routine phenomenon in Islands of Andaman & Nicobar and shall have tremendous impact on generation variability and thus grid operation. Simulation study also suggest that without BESS (power or energy type BESS) the grid operation will be very difficult as the Gas plant required frequent start/stop and ramping up & down in order to offset the solar generation variability due to frequent cloud intermittence which lead to lowering of operating efficiency and higher maintenance. BESS system with Solar Plant shall significantly reduce the frequent start/stop and ramping up & down requirement of Gas plant. Gas plant spinning reserve capacity requirement also reduces and single machine can be sufficient to cater the ramping up/down requirement. The Gas plant unit can be operated in technical minimum level and the ramp rate requirement from Gas plant would get considerably reduced due to BESS. Optimisation of no of running Gas machine in association with Solar plant can be achieved as per grid requirements thus significantly enhance the engine average loading (i.e. Individual machine PLF can be obtained 75-80%).

The estimated solar generation potential for South Andaman is around 55MW. In order to exploit the full solar potential in optimal manner combination of Power type and energy type battery are required. As a measure of cost optimisation, out of total 55MW Solar capacity, 20 MW can be provided with Power type battery and balance approx.35 MW need to be provided with Energy type Battery to save the day time surplus solar generation and supply the same during evening peak time. The Energy type battery considered for peak shifting shall also support energy security (for Portblair) from Renewable and may become attractive in case LNG price goes high.

DAY 2: 21[ST] FEB 2018

SESSION 1:

TRANSMISSION

Power Quality Measurement-Importance, Gaps and Technologies

February 12, 2018

Erik Sperling (Deputy Head R&D, PFIFFNER Instrument Transformer Ltd., Switzerland)

- Convenor-**IEC TC33 MT20**
- Working Member-**CIGRE B3.39**
- Working Member- **IEC TC 38 WG37**

Email ID: erik.sperling@pmw.ch, Ph: + 41 (0) 62 739 28 11

Address: PFIFFNER Technology Ltd. Lindenplatz 17, CH-5042 Hirschthal / Switzerland

Mr. Roman Röthlisberger (Vice President, Head, India Sales, PFIFFNER Instrument Transformer Ltd., Switzerland)

Email ID: roman.roethlisberger@pmw.ch, Ph: +41 79 377 74 00

Address: PFIFFNER Technology Ltd. Lindenplatz 17, CH-5042 Hirschthal / Switzerland

Kumar Mukund (Technical Sales Manager, Klovertel Pvt. Ltd., India)

Email ID: kumar.mukund@klovertel.com, Ph: +91 9650024146

Address: Klovertel Private Limited, 251, Okhla Industrial Estate Phase III, New Delhi-110020, India

ABSTRACT

The importance of measuring Power Quality (PQ) is gaining traction like never before. The electricity grid of the country is becoming extremely complex on account of addition of various renewable energy sources (Solar, Wind etc.); increasing level of transmission voltages (765 kV, 1200 kV etc.); HVDC links and addition of complex loads comprises of semiconductor devices. The conventional Instrument Transformers have limitations to measure various disturbances arising in the modern grid as they are unable to measure high frequency disturbances accurately. Resistive Capacitive Voltage Divider (RCVD) has a unique circuit design to measure such high frequency disturbances. This paper is an attempt to highlight the irregularities/deficiencies in various power quality regulations in India, the need to measure various Power Quality parameters more accurately and to explain the ability of Resistive

Capacitive Voltage Divider to measure disturbances of wide range frequencies up to 10 kHz precisely.

INTRODUCTION

In India, the issue of Power Quality has been typically looked at from the viewpoint of power factor, frequency, reliability of supply (i.e. duration of interruptions), restoration of supply (indices like SAIFI, SAIDI CAIDI etc.) and voltage regulations. While we have a strong system of frequency regulation, issues of voltage regulations, transients, and harmonics are hardly cared about. These critical PQ issues results in many problems. Increasing use of semiconductor based electronic equipment, non-linear loads and rapid integration of renewable energy sources into the grid network throws new challenges for the PQ environment.

An earlier study carried out by Asia Power Quality Initiative (APQI) shows that the direct costs of downtime in India are in the tune of USD 3128 million per annum. About 57% of these financial losses are due to voltage sags and short interruptions, while about 35% of the losses are due to transients and surges. However, the cost of prevention for these may be less than 10% of the cost of problems. Both the consumer and the distribution utilities suffer from equipment /process failure and high cost of operation and maintenance due to compromised equipment quality and poor monitoring of consumer establishments.

CURRENT REGULATIONS ON POWER QUALITY IN INDIA

In India, we have various regulations for quality of electricity supply which apply to the generation, transmission and distribution companies. These regulations have been specified by the Central Electricity Authority (CEA) and the Central Electricity Regulatory Commission (CERC) at central level and the State Electricity Regulatory Commissions (SERCs) at state level as per the provisions of the Electricity Act, 2003, to help maintain the stability of the electricity grid.

However, electricity being a concurrent subject in the Indian Constitution, the State Commissions has come up with their own independent sets of regulations. These regulations vary in approach, construct and applicability. Therefore, there is lack of consistency in the way PQ is dealt with in various States in India. This has inevitably fostered an ambience of misplaced understanding and subdued awareness of the economic importance of PQ in the entire Power Sector value chain.

A brief study conducted by the International Copper Association India (ICAI) under its flagship program Asia Power Quality Initiative indicates that the awareness and sensitivity towards the issues of PQ in India is moderate at best, which leaves a lot of scope for improvement.

Though, the voltage variation, harmonics distortion and voltage unbalance are discussed in the regulations by SERC’s for DISCOMs; monitoring, management and control of these parameters are not widely covered with clearly defined framework. Also, the implementation of PQ of electricity distribution, supply and utilisation are not very structured, nor they are strictly enforced by the Regulators. The Regulators, so far, have largely focused only on the

Frequency and Power Factor (mostly classical definition oriented i.e. average PF and not true RMS PF suitable for non-linear load environment) of the electricity supply.

Frequency regime is implemented through CERC Regulations and consistently followed across the country. Power Factor (PF) is also largely maintained at similar levels and implemented through incentives and penalties in tariff determined by the SERCs. Reliability indices like SAIFI, SAIDI, CAIDI, and MAIFI are almost invariably specified by the SERCs but there is no evidence to demonstrate that these reliability indices are strictly monitored and implemented by the SERCs.

Power Quality Standards Prescribed in CEA and CERC Regulations

The below mentioned table summarises PQ standards prescribed in CEA and CERC Regulations:

Power Quality Parameters	**Limits prescribed in the regulations**		
	CEA-Grid Standard Regulation	**CEA- Technical Standard for Grid Connectivity**	**CERC – Indian Electricity Grid Code**
Voltage Variation			
765 kV	+5% and-5%	Maximum 3% and Minimum -1.5% for step changes	+5% and-5%
400 kV	+5% and-5%		+5% and-5%
220 kV	+11% and -10%		+11% and -10%
132 kV	+10% and -8%		+10% and -8%
110 kV	+10% and -10%		+10% and -10%
66 kV	+9% and -9%		+9% and -9%
33 kV	+9% and -9%		+9% and -9%
Harmonics	THD – 5% with single harmonic content not exceeding 3 % for 33 to 132 kV THD – 1.5% with single harmonic content not exceeding 1 % for 765 kV THD – 2% with single harmonic content not exceeding 1.5 % for 400 kV THD – 2.5% with single harmonic content not exceeding 2 % for 220 kV	THD – 5% with single harmonic content not exceeding 3 %	
Voltage Unbalance	1.5% for 765 and 400 kV 2% for 400kV 3% for 33 to 132 kV	3% for 33 kV and above	

Inconsistency in Standards for Harmonics

Many differences were observed in the standards for harmonics specified by the various States Regulators as listed below.

1) **At 11 kV level**

Tamil Nadu, Gujarat and Maharashtra specifies THDv as 5% with individual harmonics content not exceeding 3% whereas Karnataka specifies THDv as 3.5% with individual harmonics content not exceeding 2.5%. Andhra Pradesh and Madhya Pradesh specify the cumulative THDv as 8% for 11 kV.

2) **At 33 kV level**
   Karnataka specifies THDv limit as 3% with no individual harmonic content higher than 2.5% whereas Tamil Nadu, Gujarat and Maharashtra specifies THDV as 5% with individual harmonics content not exceeding 3% for 33 kV level. Andhra Pradesh and Madhya Pradesh specify the cumulative THDv as 8% for 33 kV.
3) **Inconsistency in Karnataka's Regulations**
   Karnataka specifies THDv limit as 5% for 11kV and 33 kV in one regulation and 9% in another regulation. There are three different limits for single state.
4) **Difference from Central Regulations**
   For EHT voltage levels, some states (such as Karnataka and Maharashtra) have harmonics limits different from the central regulations. Madhya Pradesh regulation recommends following IEC Std 1000-4-7 or IEEE limit and Delhi doesn't specify any harmonics limits so far.

Deviation in Harmonics with IEEE-519 Standard

In comparison with IEEE-519 standard, it is observed that harmonics limits prescribed by CEA Grid Standard Regulations are slightly on the higher side at 220 and 400kV voltage level. CEA Grid Standard Regulations recommends 5% THD with single harmonic content not exceeding 3 % for 33 to 132 kV, however IEEE recommends the CEA advised limits only up to 69 kV level and it suggests having 2.5% THD with individual harmonic content not exceeding 1.5% for 132 kV. This indicates the scope to narrow down the harmonics limits advised in Indian regulations. Also, most of the states which specified voltage harmonics limits have not specified the limits for current harmonics.

Most of the states are referring to IEEE519 -1992 standards for harmonics limits. In contrast, the cumulative THDv of 11 kV, 33 kV and 132 kV level in Andhra Pradesh and Madhya Pradesh are higher than IEEE standards and CEA regulations. Furthermore, there is no clarity on the consequence of non-compliance.

PERFORMANCE ASSESSMENT OF DISTRIBUTION UTILITIES AND BENCHMARKING OF POWER QUALITY IN EUROPEAN COUNTRIES (CEER BENCHMARKING)

Most of the Europeans countries have adopted EN50160 standard as voltage quality legislation, regulations and standardization. In these countries, continuity of supply (transient interruption, short interruption and long interruption) and voltage monitoring are considered as evaluating factor when assessing the DISCOM performance. In addition, indices, such as SAIDI, SAIFI,

MAIFI, ASIDI, ASIFI, CAIDI, CML, ENS, IEEE 1366-2003 indicators, CTAIDI, TIEPI and NEIPI are used to quantify long interruptions.

Standard EN 50160 Summary

The summary of Standard EN 50160 is mentioned below:

Voltage Disturbance	Voltage Level	Voltage Quality Index (Limit)
Supply Voltage Variation	LV	95% of the 10-minute mean r.m.s values for 1 week (±10% of nominal voltage). 100% of the 10-minute mean r.m.s values for 1 week (+10% / -15% of nominal voltage).
	MV	99% of the 10-minute mean r.m.s values for 1 week below +10% of reference voltage and 99% of the 10-minute mean r.m.s values for 1 week above -10% of reference voltage. 100% of the 10-minute mean r.m.s values for 1 week (±15% of reference voltage).
Flicker	LV, MV, HV	95% of the Plt values for 1 week.
Unbalance	LV, MV, HV	95% of the 10-minute mean r.m.s values of the negative phase sequence component divided by the values of the positive sequence component for 1 week (0% - 2%).
Harmonic Voltage	LV, MV	95% of the 10-minute mean r.m.s values for 1 week lower than limits provided by means of a table. 100 % of the THD values for 1 week (≤8%).
	HV	95% of the 10-minute mean r.m.s values for 1 week lower than limits provided by means of a table.
Mains Signaling Voltage	LV, MV	99% of a day, the 3 second mean value of signal voltages less than limits presented in graphical format.

ECONOMIC IMPACT OF POOR POWER QUALITY:

1) Voltage Dips and Short Interruptions:

The cost of a voltage dip is usually lower than that of a short or long interruption but comparatively, dips are much more frequent. An interruption will affect all (unprotected) processes but a dip may affect only those that are most sensitive.

Voltage dips are mainly a problem in industry. Different surveys studied sensitivity of voltage dips in industry showing that the continuous manufacturing and IT sectors are the most sensitive.

The conclusion of the Leonardo Power Quality Survey [1] was that the most sensitive industries, representing 20% of European turnover and around 30% of industry, experience power quality costs equivalent to about 4% of their turnover. 24% of this cost is due to the effects of voltage dips while 19% is due to short interruptions. The cost per voltage dip event is between 2.120 and 4.682€. Short interruptions are, on average, 3 times more-costly for industry and over 9 times costlier for services. All users reported, on average, 13 voltage dip events and 6 short interruptions per year.

According to EPRI's investigations, voltage dips were responsible for 48% of PQ problems excluding interruptions[2].

2) Harmonics:

Harmonics is a PQ problem, directly related to the increasing use of non-linear loads, mainly associated with the increasing penetration of power electronics. Voltage distortion and, to a greater extent, current distortion may cause immediate loss by initiating a power interruption. If a transformer or power cable fails due to excessive heating caused by harmonics, the consequence will be an interruption. Non-outage related effects include the following:

- Current effects:
  - ✓ Erroneous tripping of circuit breakers due to higher crest factor
  - ✓ Overheating of neutrals in 4-wire circuits feeding single-phase loads
  - ✓ Overheating of transformers due to excess eddy current loss
  - ✓ Failure of capacitors due to high harmonic current
- Voltage effects:
  - ✓ Increased losses in directly connected induction motors
  - ✓ Over stressing of PFC capacitors due to resonance effects
  - ✓ Erroneous operation of controls based on zero-crossing.

EPRI's survey indicated harmonics as the root cause of 22% of all power quality problems (excluding interruptions)[3].

Recently the adverse effect of supra-harmonics (>2 kHz and < 150 kHz) came under scrutiny. These harmonics are generated by different types of electronic devices and can – among other effects – affect power line communication signals, on which automated power distribution grids are heavily relying.

[1] Power Quality Survey – conclusions for industry: http://www.leonardo-energy.org/european-power-quality-survey-results
[2] Primen, "The cost of power disturbances to industrial & digital economy companies," EPRI - CEIDS, June 2001
[3] ECI Publication No Cu0145: APPLICATION NOTE-THE COST OF POOR POWER QUALITY-Roman Targosz, David Chapman, October 2015-www.leonardo-energy.org

3) **Transients:**

Transients are voltage disturbances of very short duration (up to a few milliseconds) but high magnitude (up to several thousand volts) with a very fast rise time. Due to the involvement of high frequencies, they are considerably attenuated as they propagate through the network so that those occurring close to the point of interest will be much larger than those originating further away.

Causes include switching or lightning strikes on the network and switching of reactive loads on the consumer's site or on sites on the same circuit. Transients may have magnitudes of several thousand volts and so can cause serious damage to the installation and the equipment connected to it.

Electricity suppliers and telecommunications companies go to some effort to ensure that their incoming connections do not allow damaging transients to propagate into the customers' premises. Nevertheless, even non-damaging transients can cause severe disruption due to data corruption.

Although they do not occur very often, once they do happen very close to a site, the consequences are severe. EPRI identified transients as the second most visible event reported by users.

4) **Voltage Swells:**

Voltage swells are less frequent than dips but may also cause damage, particularly if voltage rise is relatively high. The consequence is usually equipment damage which is rather rare in case of dips.

MEASURING HARMONICS ACCURATELY- A PROBLEM

Apart from the limitations in various Regulations, there is also a limitation with availability of adequate equipment. Mr. Erik Sperling (R&D Head, PFIFFNER Instrument Transformer Ltd., Switzerland) along with some of his colleagues presented a research paper at **CIRED** (21st International Conference on Electricity Distribution, 6-9 June 2011) on, "***Accuracy of Harmonic Voltage Measurements in the Frequency Range up to 5 kHz using Conventional Instrument Transformers.*"** The findings of the report are summarised as mentioned below.

Summary of Research Report on "*Accuracy of Harmonic Voltage Measurements in the Frequency Range up to 5 kHz using Conventional Instrument Transformers.*"

The number of sources of low as well as high order harmonics in distribution and transmission grids increases continuously (e.g. wind parks, HVDC links). Hence, it is imperative that the network operators and regulators should carry out more and more power quality measurements including harmonics in all voltage levels from LV to EHV. IEC 61000-4-30 defines methods and accuracies for the measurement instruments itself, but explicitly excludes the accuracy of instrument transformers. It is therefore not possible to specify an overall accuracy for such harmonic measurements.

The factors with influence to the frequency behaviour of instrument transformers, namely VTs, are broadly classified into three categories:

1) Construction-specific (e.g. rated primary value)
2) Operational-specific (e.g. burden)
3) Test signal-specific (e.g. test-waveform)

The construction-specific characteristics have the most significant influence on the frequency behaviour of VTs. It mainly defines the capacitances and inductances, which are responsible for the resonance effects within the instrument transformer.

Main general findings:

a) The critical frequency up to the point where accurate measurements are possible decreases with voltage level.
b) Even for VTs with same primary voltage the critical frequency f_{crit} can vary in wide ranges due to the different design. The specification of a single f_{crit} only per voltage level is not adequate.

Some specific findings:

a) Block-design VTs are usually used up to 35kV. The critical frequency varies in a wide range from $f_{crit} \approx 3500$Hz for 10-kV-VTs down to $f_{crit} \approx 600$Hz for 35-kV-VTs.
b) The accuracy of capacitive VTs is guaranteed within a very small frequency range around the nominal frequency only. These VTs are not suitable for harmonic measurements in standard cases.
c) For 66-kV-GIS VTs, the critical frequency is about 500Hz higher compared to the inductive outdoor VTs of same voltage level.
d) 110-kV combined transformers show in most cases a better performance compared to the inductive outdoor VTs for same voltage level.
e) No significant difference exists between inductive outdoor type for 110kV and 220kV. Both are suitable for measurements up to the $f_{crit} \approx 500$Hz (10th harmonic).

The paper was a contribution to the discussion on the accuracy of harmonic measurements using standard VTs, especially at higher voltage levels. It should be defined reasonable accuracy classes for HV and EHV voltage transformers. The influence of transformer ratio accuracy on the harmonic measurements according to actual standards (e.g. EN 50160) was verified. It shows that attention has to be taken to the interpretation of such measurements, especially at voltage levels above 20kV. This is of special importance, if regulatory rules should be introduced in future dealing with harmonics.

Only instrument transformers of two different manufacturers were analysed in the project. Due to the high sensitivity of the frequency dependent behaviour from transformer design the results may be different to other manufacturers.

Finally, the paper should give impulses for the ongoing standardization work. Adding requirements for frequency dependent behaviour of instrument transformers to future standards can improve the quality of harmonic measurements significantly in long-term.

As short-term solution for the network distributors that carry out measurements in HV and EHV networks at least the frequency dependent transformer ratio of the used VTs should be known.

To meet the new challenges encountered by Electricity Grid we need new modern measuring equipment. A research paper on, "***Modern Inductive Instrument Transformers for New Challenges"*** is written by Mr. Erik Sperling. The finding of the paper is summarized below:

Modern Inductive Instrument Transformers for New Challenges

Erik SPERLING, PFIFFNER Instrument Transformers Ltd. Switzerland

This report describes measuring technology for high voltages and high currents in conventional applications. Some theoretical aspects on how to design a measurement transformer are presented and, also, an overview is presented on current and future international standards. The main purpose of this paper is to describe new challenges posed on modern electric grid. The two of the main challenges are - power quality measurement and ferro-resonance.

Design criteria for voltage and current transformers

Today, the requirements placed on measurement transformers are standardised. The most widely known standard is IEC 60044. (IEC = International Electrotechnical Commission) This standard consists of 8 different sub-standards, depending on the instrument transformer type. Based on the international standard, three main criteria must be met when designing an instrument transformer:

1) Transformation ratio
2) Magnetization curve
3) Accuracy requirements

Characterisation of New Challenges

Due to the dynamic changes resulting from continuous developments in modern power transmission networks with respect to increased flexibility, power transfer and feed-in options, the requirements placed on instrument transformers have changed considerably. While the requirements for insulation coordination, accuracy and electrical dimensioning (as given in the current 60044-X) are still important for the design of instrument transformers, new, demanding influences can be observed. They can be divided into two main categories:

1) Transient phenomena
2) Continuous phenomena

These two categories have different impacts on the design and construction of instrument transformers. Therefore, it is very important to identify these phenomena. For the protection of an electricity network, information on the current situation is necessary in order to be able to take the correct countermeasures. On the other hand, other phenomena may cause some stress on the equipment, but have no influence on the network or on its stability or safety.

1) Transient Phenomena

Transient phenomena are becoming increasingly important. A transient impact is defined as a phenomenon which occurs for a short time without periodically returning. Three main requirements and their characteristics are defined as follows:

a) High number of switching operations
b) Compact system installation combined with GIS-type or conventional SF6 insulated outdoor types
c) Reduction of secondary loading (eventually leading to three-phase ferro-resonance)

Regarding points a) and b): As a result of much more flexible network situations, the number of switching operations is increasing more and more. During each operation, one or more high voltage peaks are superimposed on the basic voltage level. The typical frequency range involved is between kHz and MHz frequencies. Combinations of different types of systems are becoming increasingly common. For example, older systems are upgraded with GIS-type systems to save installation space and to increase their power transmission capabilities. When a switching operation occurs, the high voltage impulse can have a frequency spectrum of up to several MHz. Typical discharge times in SF_6-gas are in the range of 1ns to 5ns.

These switching impulses travel via the connection link to the inductive transformers. They stress the high voltage insulation, and are comparable with typical lightning impulses. Another important issue is the strain placed on the internal electrical connections and on the shielding electrodes. The skin-effect is very pronounced and must not be neglected.

Because of the transient impulses and the higher numbers of switching impulses, special tests become more and more important. 600 consecutive chopped impulses at a test level of 70% of the rated lightning impulse withstand voltage should be applied to the instrument transformers. The intention of this is to check the internal connections and to detect any high impedance loops. In the case of a non-optimal design, small discharges occur and influence the properties of the insulation oil. This test is now integrated as special test in the new international standard for instrument transformers IEC 61869-1, which is to replace the current standard IEC60044-X.

Modern substations with appropriate secondary instrumentation require very low loads. This leads to low damping characteristics. Three-phase ferro-resonance is characterised as a transient phenomenon, because it only occurs during the switching-on of a part of a network system or at an extinction of a single-phase earth-leakage fault. Its typical frequency is the second subharmonic of the fundamental frequency. The resulting amplitude can rise up to twice the rated voltage or more and is easy to detect. This failure has to be detected as fast as possible to protect the instrument transformers against loss of insulation performance, which may lead to an internal arc.

Technical Influences

The transient characteristics have a significant influence on the internal design of instrument transformers. Therefore, more attention should be paid to the following design-specific characteristics. The shielding electrodes and grounding systems must be designed for HF-signals (MHz range). Internal connections on the high-voltage side as well as on the low-voltage side must be of low impedance up to certain frequencies. The voltage distribution along the HV-insulator must be as linear as possible. The design of the bushing has to be carried out accordingly. The primary winding of a high voltage transformer has to be designed for an optimal field distribution to prevent impermissible transient over-voltages.

2) Continuous phenomena

Continuous stress is defined as a phenomenon which occurs permanently or periodically. The main phenomena are listed according to their characteristics.

a) Harmonic waves
b) Proximity effects, heating, shielding in compact network systems
c) Decrease of secondary loading (single phase ferro-resonance)
d) Magnetic coupling because of very low phase spacing

All phenomena listed above have similar effects on the transformers. They can be mainly interpreted as long-term phenomena. As opposed to the transient phenomenon, the main effect is increased temperature. The consequence is faster aging of the insulation material and a possible shorter service life.

Due to the increasingly compact design of substations and increases in power transmission, electric and magnetic fields may affect the measuring instrument transformers in the direct neighbourhood. Two typical examples related to ring cores demonstrate these problems:

i. For an increase of primary current values in combination with a decrease of phase spacing, the magnetic coupling and part-saturation in the iron cores may lead to thermal destruction. Typical generator current transformers are specified for a primary current between 15kA up to 35kA. Higher values are foreseeable.
ii. The interacting accuracy measurement in a three-phase system during a short circuit on one phase (GIS-CT). It is very important that the security system of the network detects the fault correctly and initiates the appropriate reaction. Because of the high importance of this issue, an ad-hoc working group (IEC TC 38 AHG 43) is now involved in finding out the dependencies and in the study of the physical aspects of this issue.

Technical Influences

With respect to the characteristics of continuous phenomena, a deeper understanding of high voltage insulation material and its components is very important.

It is crucial to understand the influence of the long-term impact of voltages or currents with frequencies up to 10 kHz in order to prevent an untypical aging or a shorter service life. Due to the higher frequencies involved, the skin-effect within the primary winding causes higher thermal power losses and therefore higher thermal stress.

The insulation materials used have a large impact. The well-known dielectric dissipation factor, $\tan\delta$, defines the relation between the dielectric power losses and the capacitive reactive power. It is an indication of the quality of the insulation material. A high $\tan\delta$ value is an indication of high power losses in the case of higher frequencies.

As discussed above, in order to prevent partial saturation in current ring cores and to avoid high temperatures, a protection against magnetic fields, in the form of an electrical shield, is one of the possible solutions. Another possibility is the use of compensation windings. These are connected as a special circuit and unify the saturation behaviour within the whole iron core.

Power Quality

For the last 15 years, the number of power sources and the way in which they are connected to the electrical power network (on-site power generation) has been increasing continuously. Alternative energy produced or supplied by wind farms, small hydropower plants, solar power stations or HVDC links are becoming more and more popular. For operators, customers and regulators, information on the actual status of the system is very important. The stability of the power network is very important for all customers. Accelerated aging has to be avoided in any cases. Typical causes for harmonic frequencies up to several kHz can be listed as follows:

1) **Power electronics such as**
   - HVDC links
   - Wind parks
   - Traction converters
   - Drive converters

2) **Electric arc furnaces**
3) **Non-linear loads**
4) **Coupling between different grids**

The consequences on the electrical power networks and their equipment are manifold. The main aspects are listed below:

a) Increase of power losses in the system
b) Higher strain on HV insulation
c) Higher thermal power losses within the HV equipment connected
d) Intensified acoustic emissions (transformers, line traps capacitors etc.)
e) Incorrect control of the HV equipment
f) Incorrect function of protection devices

A current question concerns the possibility of measuring the harmonic waves with conventional instrument transformers. A second important aspect is the accuracy of the measuring equipment depending on the frequency. First results for current transformers for MV and HV show no significant resonance effects in the frequency range up to 5 kHz. Voltage transformers, on the contrary, exhibit a significant dependency of the accuracy range on the ratio.

Ferro-Resonance Phenomena

A ferro-resonance oscillation is defined as a complex, non-linear oscillation which occurs if a main iron core of an inductive voltage transformer goes into periodical saturation. This phenomenon can occur if an inductive component with a nonlinear inductance, a capacitance and a power source form an oscillating circuit. Two main forms of ferro-resonance oscillation can be defined. One of the characteristic oscillations is the stationary behaviour. This can be a power frequency oscillation, a sub-harmonic oscillation or chaotic oscillation. The second characteristic oscillation is the non-stationary behaviour, and is defined as a transient oscillation.

The characteristic of the oscillations and their impact on the transformer can be divided into three main categories.

a) Amplitude of the voltage increases to a higher level; this leads to dielectric destruction of the HV insulation (very fast)
b) Unchanging amplitude of the voltage; this leads to thermal destruction of the HV insulation (slow process)
c) Self-damping; if oscillating conditions are no longer fulfilled (uncritical)

Modern instrument transformers are optimized to keep their internal power loss as low as possible. In the case of ferro-resonance, the electrical power has to be converted into thermal power. To prevent ferro-resonance oscillations, the following main measures can be taken:

1) **Transformer design**
    - flux density as low as possible
    - appropriate iron core materials
    - air gap iron core
2) **Additional external auxiliaries**
    - damping resistance and/or damping coil
    - resonant damping circuit (1-phase)
    - open-delta winding (3-phase)
    - electronic damping devices
    - additional load

Conclusions

This paper is a contribution to the discussion on modern instrument transformers that meet advanced requirements. Modern transmission networks show dynamic changes with respect to more flexibility, power transfer and feed-in options. As discussed in this paper, the requirements placed on instrument transformers are becoming more complex as defined in the relevant IEC60044-X standards. It is very important to understand these additional requirements. A classification in two main parts like transient and continuous will help answer the questions posed by the challenges of the future. Experience gained will have to be considered in the design and construction of the latest instrument transformer generation. Additional tests could possibly become a necessity.

The current IEC 60044-X standard represents a guideline for transformers, but without taking the above-mentioned facts into consideration. Actually, the technical committee TC38 of the IEC, which is responsible for measurement transformers, is creating new standards for instrument transformers. The IEC 60044-X will be substituted by the IEC 61869-X, consisting of one standard for general requirements and 14 further standards covering specific requirements. The new standard will take the newly observed phenomena in modern power networks into account.

Until now, there are no instructions on how to deal with harmonic waves and the corresponding accuracy of the transformer ratio at frequencies higher than the fundamental frequency. If purely inductive VT's are to be used as measuring devices, reasonable accuracy classes for high voltage and extra high voltage transformers should be defined as well as the possibility to check the accuracy of the ratio in higher frequency ranges.

With respect to the aspects mentioned in this paper, a modern inductive instrument transformer should be able to withstand and handle these new challenges. The transformers have not yet reached their physical limits. On the other hand, physical relationships can't be easily surmounted and require further investigation.

A POSSIBILITY TO MEASURE POWER QUALITY WITH RC-DIVIDER

Power quality in modern networks is becoming more and more important. The results of first measurements made with conventional instrument transformers in MV, HV and EHV networks show that frequency response is dependent on system voltage. Based on these results and the necessity of correct measurement results up to a higher frequency range, other more precise measuring systems have to be looked at. Only such equipment will be able to guarantee the correct measurement of power quality parameters up to the EHV-level.

Within the last decade, existing power networks are in the process of changing very dynamically. The production of electrical energy using alternative sources of energy is becoming more and more important. The power quality is highly affected by, for example, HVDC links, wind parks and non-linear electrical loads. As a result, high frequency voltage affects the high-voltage insulation of the installed equipment. Due to the skin effect, thermal overload on conductors may occur. Therefore, it is important to know the level of harmonic voltages and currents in the system. Appropriate measuring instruments with a high accuracy up to higher harmonics of the fundamental frequency are needed. Network operators have to have this data in order to be able to start analysis and be able to initiate appropriate countermeasures. IEC61000-4-30 defines the measuring methods, measuring ranges and the accuracy of the measurement system. The instrument transformers are considered in standard IEC61869-1 "General requirements" and in the appropriate standards which define additional requirements. (IEC61869-3 VT's, IEC61869-5 CVT's). The IEC standards cover only the fundamental system frequency. So far, no studies or information exists on higher frequency ranges, but this knowledge is necessary for reliable and secure network operation.

First publications on the frequency response of HV voltage instrument transformers investigated the dependency of the accuracy of the system voltage up to 245kV. External influences such as temperature, burden, transformer design and manufacturing variations are published for MV-voltage transformer in Technical report IEC/TR 61869-103 is published in 2012. This gives guidance on the use of HV instrument transformers for measuring power quality parameters. All the published results show a system voltage dependent behaviour of the frequency response of instrument transformers up to EHV system (see figure 1).

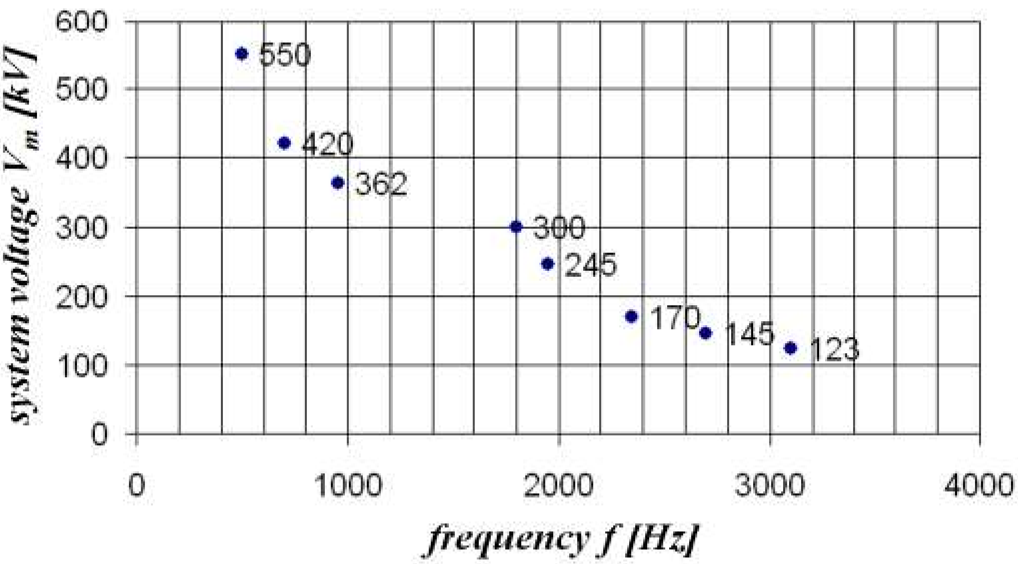


Figure 1: First resonance peak depending on the system voltage Vm

The following aspects have a significant influence on the capacitive part of the resonance circuit and are relevant when considering the frequency response of MV, HV and EHV instrument transformers.

1. Voltage dependency (e.g. HV insulation coordination)
2. Dependence on ambient conditions (e.g. creepage distance, external service conditions at altitude)
3. Basic design (e.g. design for gas or oil insulation)
4. Type of measurement (e.g. capacitive "CVT", inductive "VT")

In general, the resonance frequency f_R of an instrument transformer depends on a capacitive and an inductive part.

$$f_R = 1/(2\pi\sqrt{L}.C) \qquad (1)$$

If the capacitive part C is increased, the resonance frequency f_R will decrease if the inductive part L does not change. The frequency response of an instrument transformer is typically characterised by several resonance frequencies. Multiple resonance circuits (parallel circuit as well as series circuit) exist with different capacitances and inductances. An example of a resonance curve for conventional inductive instrument transformers is presented, which illustrates this behaviour.

<u>Resistive-Capacitive-Voltage Divider</u>

The capacitive part of the instrument transformer depends on the voltage level as a result of the dimensioning of the insulation system. It cannot be reduced by a large amount. With reference to equation (1), the inductive part L is the second factor that can be modified in order to change the resonance frequency. The main inductance L_H of a typical inductive voltage transformer can range over several kH. A possible solution to these problems is a resistive-capacitive voltage divider, known as a RC-divider. This non-conventional voltage measurement system has no significant inductance.

RC-Divider Fundamentals

An RC-divider consists of a capacitor divider together with a resistive divider, which are electrically connected in parallel. The simplified equivalent circuit diagram is shown in figure 2. Expected stray capacitances are not considered.

The complex transfer function $k(j\omega)$ of the secondary voltage V_2 divided by the primary volt age V_1 is:

$$\frac{V_2}{V_1} = k(j\omega) = \frac{C_1}{C_1 + C_2 \cdot \frac{\left(1 + \frac{1}{j\omega C_2 R_2}\right)}{\left(1 + \frac{1}{j\omega C_1 R_1}\right)}} \quad (2)$$

or

$$\frac{V_2}{V_1} = k(j\omega) = \frac{R_2}{R_2 + R_1 \cdot \frac{(1 + j\omega C_2 R_2)}{(1 + j\omega C_1 R_1)}} \quad (3)$$

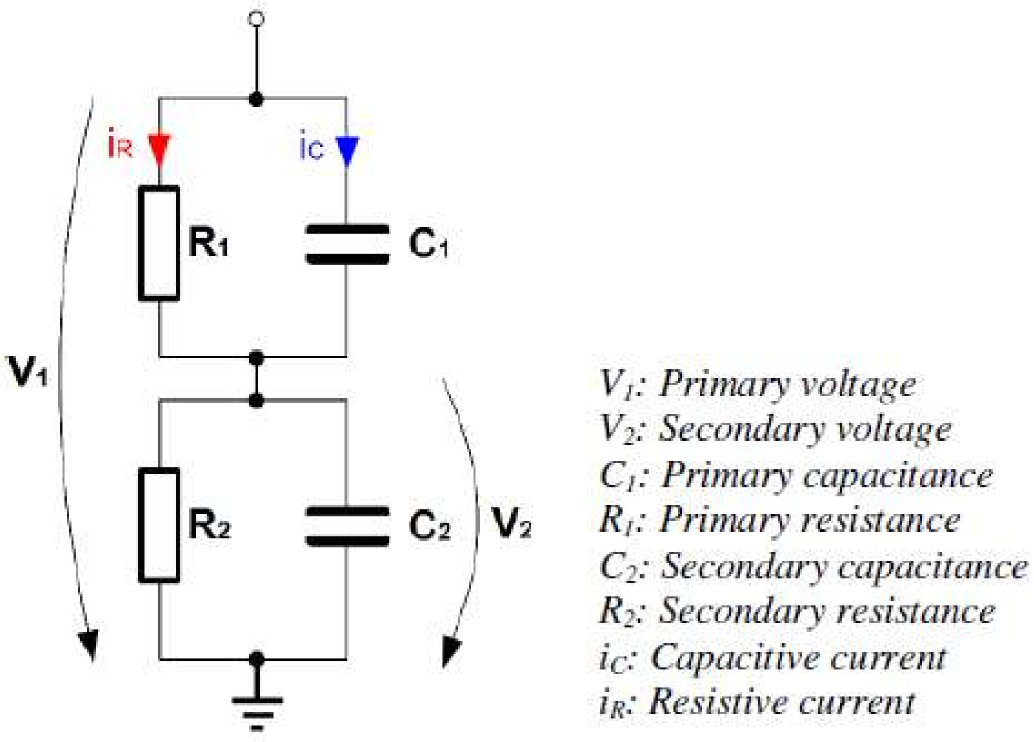


Figure 2: Simplified equivalent circuit diagram of a RC-divider

Both formulas indicate that the transfer function characteristic is frequency dependent.

Depending on the angular frequency $\omega = 2\pi f$, the following conclusions can be made:

$$f \to \infty \qquad \frac{V_2}{V_1} = \frac{C_1}{C_1 + C_2} \qquad (4)$$

$$f \to 0 \qquad \frac{V_2}{V_1} = \frac{R_2}{R_2 + R_1} \qquad (5)$$

For high frequencies ($f \to \infty$), the capacitive divider is the dominant part of the transfer function; for very low frequencies down to DC ($f \to 0$), the resistive divider dominates the transfer function.

As shown in figure 2, the system current consists of a resistive part and a capacitive part. Depending on the selection of the resistance values R_1 and R_2 (R-divider) and the capacitance values C_1 and C_2 (C-divider) and also under consideration of frequency and voltage, one of both divider ratios is more dominant than the other. At the crossing point of the current curves, the influence of both dividers on the ratio is equal. At this crossing point the probability of incurring the highest inaccuracy is the highest compared to both extreme points at $f = 0$ and $f = \infty$.

Another very important condition can be derived from formulas (2) or (3). The compensation condition demands that the resistive divider ratio has to correspond to the capacitive divider ratio. The time constant τ is defined as an RC term. For a frequency-independent divider ratio of V_2/V_1, up to very high frequency values, the time constant τ_1 of the primary part has to be identical to the time constant τ_2 of the secondary part.

$$\tau_1 = \tau_2 \quad \to \quad R_1 \cdot C_1 = R_2 \cdot C_2 \qquad (6)$$

Three main system states can be distinguished. Figure 3 shows the system response in the time domain depending on the ratio of the time constants τ_1 and τ_2.

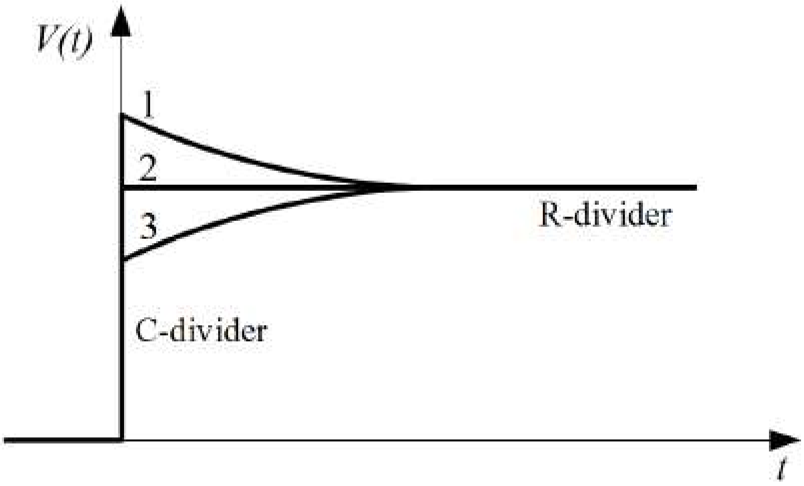


Figure 3: Transient response

1.	$\tau_1 > \tau_2$, Undercompensation
2.	$\tau_1 = \tau_2$, compensated
3.	$\tau_1 < \tau_2$, Overcompensation

In the case of system state 2, the secondary voltage follows the primary voltage with a constant frequency independent time delay. The divider ratio V_2/V_1 is constant at all times.

Determination of resonance frequency

From the theoretical point of view, there seems to be no limit on the measurement of voltages up to several MHz. With respect to the non-ideal behaviour of the capacitive part C_1, the inductive part L will limit the frequency response behaviour. A method with which the natural frequency can be determined is described in IEC60358. To avoid an additional parasitic inductance, caused by the measuring circuit, a coaxial measuring circuit design should be used. Figure 4 shows the behaviour of the main impedance with respect to the applied frequency.

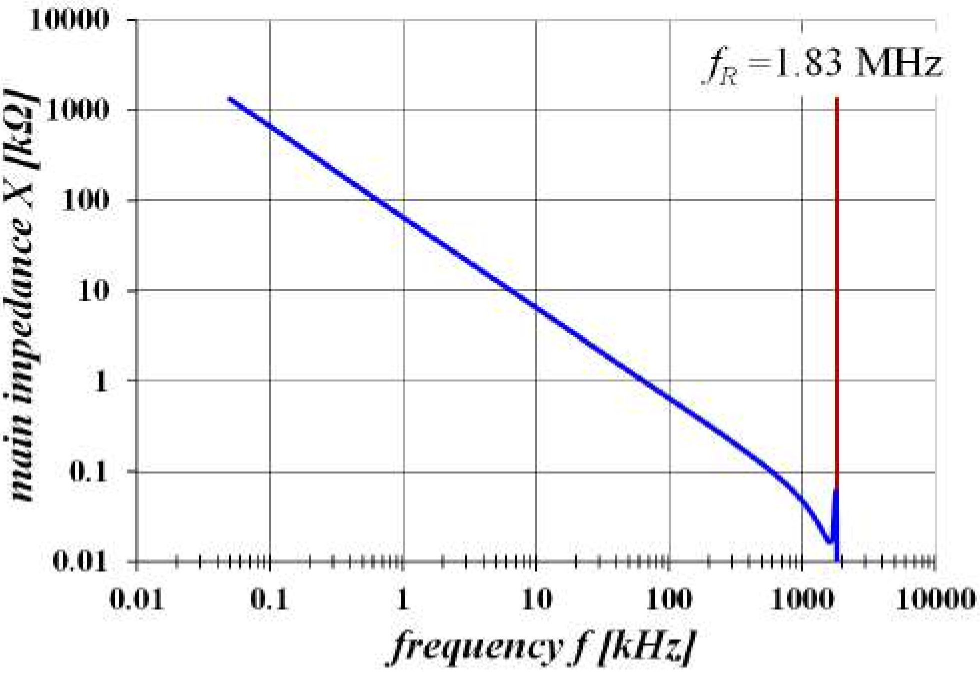


Figure 4: Main impedance curve for a 420kV RC-divider

At resonance frequency, the impedance part X_C is compensated by the impedance part X_L. Only the resistance component is still measurable. According to formula (1) and under consideration of the result obtained for the natural frequency $f_R = 1.83\,MHz$ as well as the main capacitance $C_1 = 2400pF$, the calculated parasitic inductance within the primary part of the RC-divider is $L_{Para} = 3.3\,\mu H$.

Calculation of Voltage Error and Phase Displacement

In the case of non-equal time constants τ_1 and τ_2, formulas 2 and 3 have to be used for the final calculation of the voltage error ε_U and the phase displacement $\Delta\varphi$.

$$\left|\frac{Z_{ges}}{Z_2}\right| = 1 + \frac{C_2}{C_1}\sqrt{\frac{1 + 1/(\omega C_2 R_2)^2}{1 + 1/(\omega C_1 R_1)^2}} \tag{7}$$

$$\left|\frac{Z_{ges}}{Z_2}\right| = 1 + \frac{R_1}{R_2}\sqrt{\frac{1 + (\omega C_2 R_2)^2}{1 + (\omega C_1 R_1)^2}} \tag{8}$$

The formula for the voltage error ε_U calculation is defined in IEC61869-3, sub-clause 3.4.3 as:

$$\varepsilon_U = \frac{\left|\frac{Z_{ges}}{Z_2}\right| \cdot V_2 - V_1}{V_1} \cdot 100[\%] \tag{9}$$

The definition of the phase displacement $\Delta\varphi$ can be found in IEC61869-1, sub-clause 3.4.4. It is defined that, in the case of positive phase displacement, the secondary voltage leads the primary voltage.

$$\Delta\varphi = \varphi_2 - \varphi_1 \tag{10}$$

The phase displacement calculation is defined as:

$$\Delta\varphi = -\arctan\left(\frac{1}{\omega C_2 R_2}\right) + \arctan\left(\frac{1}{\omega C_1 R_1}\right) \tag{11}$$

or,

$$\Delta\varphi = \arctan(\omega C_2 R_2) - \arctan(\omega C_1 R_1) \tag{12}$$

Technical Design

The technical designs of RC-dividers are shown in figure 5 below.

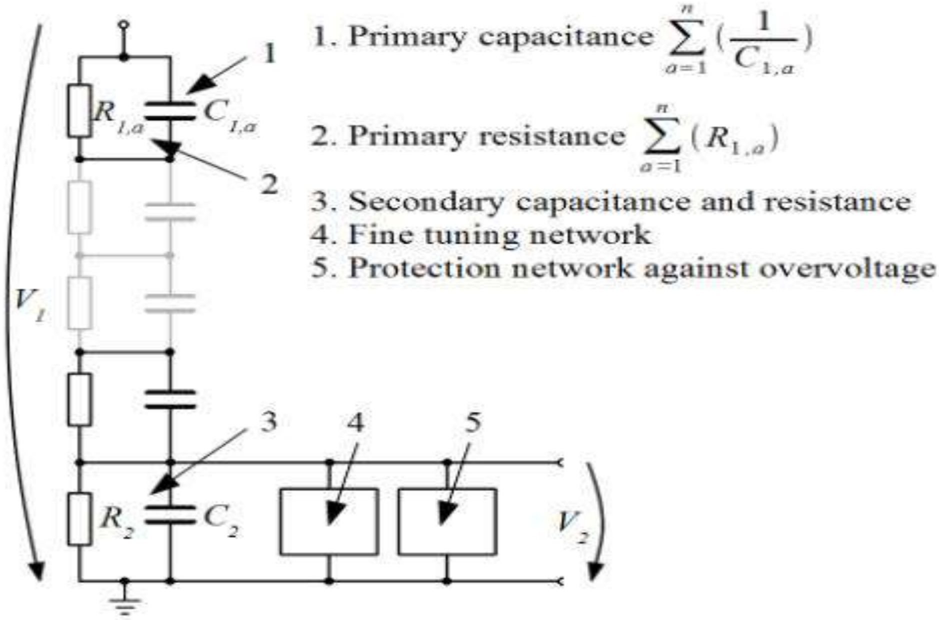


Figure 5: Electrical circuit diagram of a real RC-divider

The primary part consists of single capacitor elements connected in series. Depending on the system voltage the number of single capacitor elements varies. The same requirements are valid for the resistance part. Additionally, power losses during service or during test have a significant influence on the divider design and the number of resistors needed. It is essential to avoid a temperature-dependent inaccuracy. With respect to the divider formula, the resistors on both the primary and secondary sides should have the same temperature coefficient. The same condition is also valid for the capacitance. High temperature differences between the primary and secondary parts of the RC-divider have to be avoided.

Measurements and Results

Experimental setup

A single-phase power amplifier provides a test signal up to a voltage level of 280V (RMS) in a frequency range of 15Hz up to 10kHz. The sinusoidal signal was generated by an external generator and transmitted to the power amplifier. The data acquisition was realized using ADC-boards with a sampling rate of 2MS/s.

Test method

The test starts at a predefined frequency of 15Hz with incremental steps up to the maximum frequency of 10kHz. Initially, the step width was changed in an adaptive manner in order to determine possible resonance frequencies. Later, with respect to the initial results and the analyses of the data, more efficient frequency steps were used. Test conditions were:

1. A 420kV RC-divider in an upright position
2. Test voltage, applied to the primary terminal was realized using a coaxial cable
3. Rated burden connected to the secondary terminals.
4. Test voltage directly measured at the primary terminal
5. Coaxial conductors used for all measurement cables
6. Earthing was realized as a star-point connection to prevent inductive loops.

For each frequency, the primary voltage V1 divided by the nominal ratio n (green curve in figure 6) and the secondary voltage V2 (red curve in figure 6) were measured simultaneously.

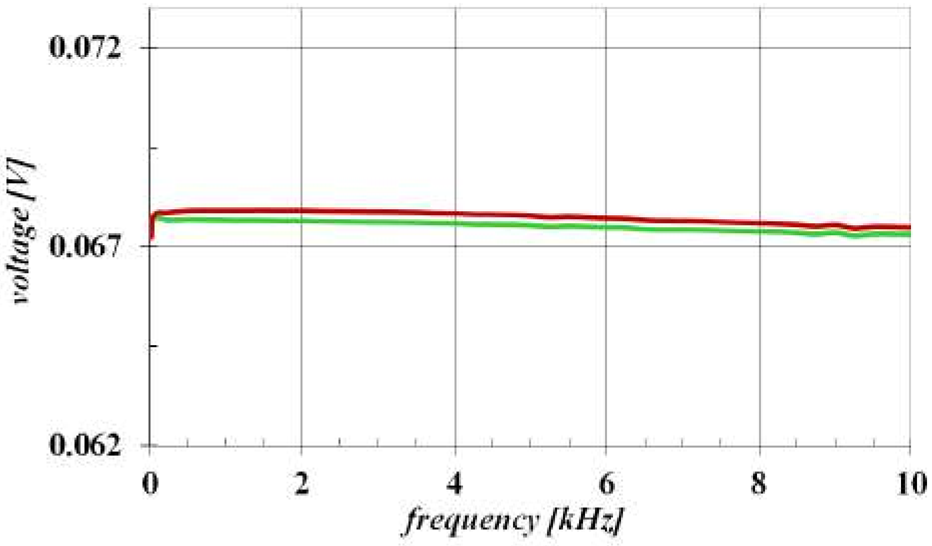


Figure 6: Magnitude of measured voltage V_1/n (green), V_2 (red)

<u>**Results**</u>

Based on international rules on the display of accuracy for instrument transformers (see formula 9), the frequency-dependent voltage error and phase displacement are shown in figure 7.

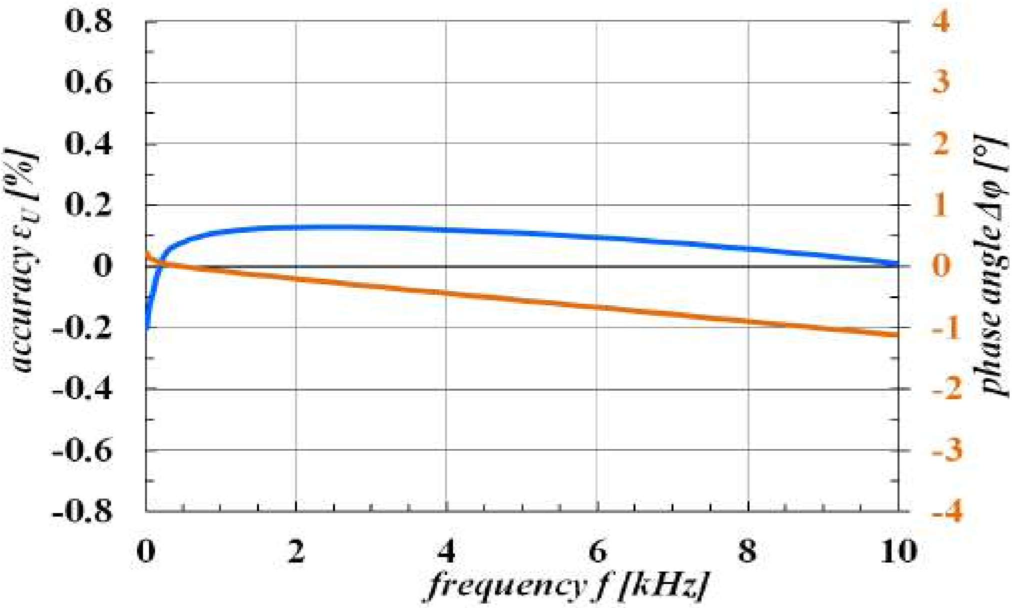


Figure 7: Frequency response of voltage accuracy ε_U (f)(blue) and phase displacement Δφ(f)(orange)

The characteristic of the voltage error ε_U (blue curve), shows that the RC-divider has no resonance frequency in the measured frequency range. The accuracy obtainable is within ±0.2% over the complete range. The phase displacement over the frequency range is displayed in orange. The phase displacement error is low enough for the identification of the direction of the spurious signal sources. Several series of measurements confirmed the findings stated. The accuracy achievable in comparison to conventional inductive instrument transformers is very high and stable up to a frequency of 10 kHz.

The frequency response of different instrument transformers for HV and EHV voltage levels is shown in figure 8. All conventional instrument transformers have resonance frequencies with very high accuracy errors in the frequency range up to 10kHz. Only the RC-divider shows a linear frequency response (see blue line in fig 7). The accuracy results were measured with the same test system, test method and under the same test conditions as described above. No burden was connected to these conventional instrument transformers.

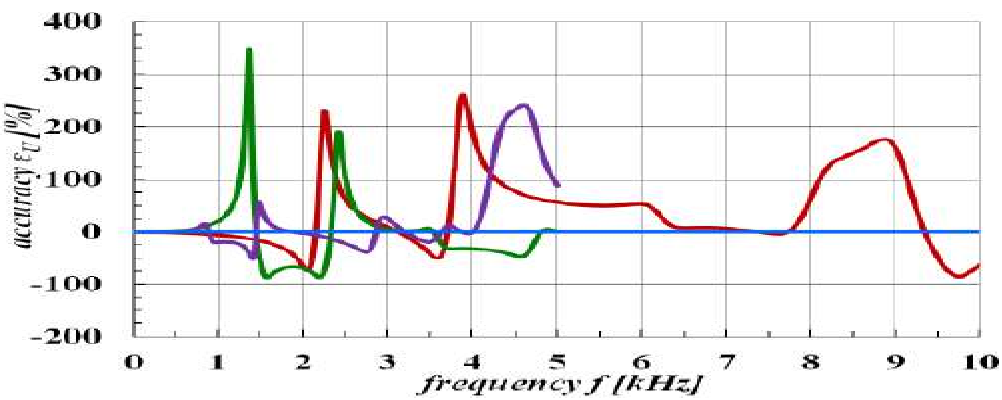


Figure 8: Frequency response of voltage accuracy $\varepsilon_U(f)$ for 123kV-VT (red), 245kV-VT(green), 420kV-CTVT(purple) and 420kV-RC-divider (blue); measured at the PFIFFNER company

Comparison with Conventional Voltage IT's

	Conventional inductive voltage transformer	Conventional capacitive voltage transformer	Non-conventional RC divider
Method of measurement	Magnetic principal Galvanic separation	Divider & magnetic principal Galvanic separation	Divider principal no galvanic separation
Accuracy at stationary power-line frequency	till class 0.1 Very good	till class 0.2 good	till class 0.1 Very good
Burden range	0VA ... to several 100VA; specified burden range may not be exceeded	0VA ... to 100VA; specified burden range may not be exceeded	low burden values 0VA ... 3VA (kΩ-range) re-adjustable
Secondary voltages	100V; 110V; 115V factor (1; √3; 3)		1.625V; 2V; 3.25V; 4V; 6.5V (√3) 100V; 110V; 115V factor (1; √3; 3)
Dependence of secondary windings to each other	Winding physically separated		No separation
Measurement of harmonics	20Hz till max 1.5kHz (depending on voltage level) bad	50/60Hz ±1% Very bad	0Hz till 1MHz Very good
Accuracy at harmonics	Only at rated frequency OK, otherwise big deviation Very bad		10Hz ... 10kHz Amplitude accuracy 0.2% possible Very good
Behaviour at impulse voltage or transient phenomena	Voltage distribution because of control electrodes within the bushing Good	Interne linear voltage distribution because of identical capacitor windings Very good	Interne linear voltage distribution because of identical capacitor windings Very good
Ferro Resonance performance	Only with additional investigations possible Very good - Bad		No Very good
Discharge of cable and overhead lines	Only thermal limits Very good	Not possible Very bad	Because of very high resistance values, long discharge times good
No-load on secondary winding	Very good		Very good
Short-circuit on secondary winding	Protection with fuses Very bad		No influence Very good

Additional Field Application

I addition to the standard measuring function, because of its performance RC-divider can be used also in case of:

- Measurement of DC offset in AC networks
- Measurement of harmonic frequencies (Power quality)

- Measurement of ferro-resonance in AC networks
- As an alternative measuring device at ferro-resonance critical network point. (no saturation)
- As an alternative measuring device on networks with high or very high transient voltage peaks
- As an alternative measuring device on networks for CVT's in case of natural frequency variation (CVT's are frequency dependent)
- As an alternative measuring device on networks including multiple line/cable discharge (not possible with CVT's)

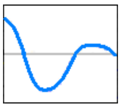
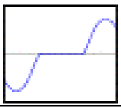
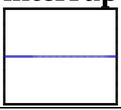
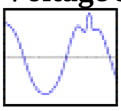
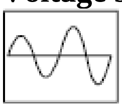
CONCLUSION

The total installed capacity of India is around 330 GW. Out of these, around 68% is constituted by thermal, 14% by hydro, 2% by nuclear and rest 16% by renewable energy sources (wind, solar etc). India's per capita electricity consumption which is at around 1000 kWh is amongst the lowest in the world. As a matter of fact, the global average per capita electricity consumption is at around 3100 kWh while our neighbour country China's per capita electricity consumption is at around 4000 kWh. Also, considerable population of India does not have access to electricity and those who have the access hardly get the desired quality. To bridge these gaps and to meet India's ambitious future growth target, the Government of India (GoI) has set a mission with objective to provide "24 × 7 Affordable Environment Friendly Power for All by 2019." To achieve this objective the GoI has launched many ambitious schemes viz. Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) for Gramoday Se Bharat Uday, Integrated Power Development Scheme (IPDS) for Smart Infrastructure in Cities, Ujwal DISCOM Assurance Yojana (UDAY) for Demolishing DISCOMS' Difficulties etc. India has very aggressive power generation target to achieve its growing needs with increased emphasis on renewable energy. It is evident from the fact that the GoI has already increased the renewable energy addition target from earlier 20 GW to 175 GW by 2022, a whopping 9 times increase. These additional capacity additions along with the intermittent nature of renewable energy is going to create many Power Quality challenges and thus precise monitoring at injection point and load point is vital for all players in power sector.

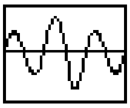
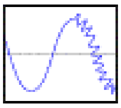
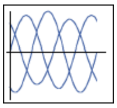
India's power transmission infrastructure is amongst the most complex in the world owing to its diverse geography, widespread area, considerable ambient temperature differences in all the five regions, diverse load, long distances, HVDC links etc. As per the data of Ministry of Power (Upto 30.11.2017) the power transmission infrastructure in India comprises of 15, 556 CKM +500kV HVDC link, 33,286 CKM 765kV link, 166,947 CKM 400kV link and 165,882 CKM 220kV link[4]. They all add up to 381,671 CKM. Furthermore, if we talk about the capacity of substations, India has capacity of 22,500 MVA/MW +500 kV HVDC Converter/BTB stations; 177,500 MVA/MW 765 kV stations; 266,599 MVA/MW 400 kV substations and 324,973 MVA/MW 220kV stations. In other words, India's total sub-station transmission capacity is

[4] http://powermin.nic.in/sites/default/files/uploads/Growth_in_Transmission_sector_Eng.pdf

791,570 MVA/MW[5]. This huge capacity would be further augmented in future owing to growth in power generation capacity. In addition to that India has an ambitious plan of grid linking (like European Nations) with neighbouring countries like Nepal, Bhutan, Bangladesh, Pakistan, Afghanistan, Myanmar, the Philippines, Singapore, Thailand, Vietnam etc. for better asset utilization. This would further add to the complexity of the present grid. Some of the common power quality problems arises in the transmission network, their causes and consequences are mentioned below:

1. Voltage sag (or dip) 	**Description:** A decrease of the normal voltage level between 10 and 90% of the nominal rms voltage at the power frequency, for durations of 0,5 cycle to 1 minute. **Causes:** Faults on the transmission or distribution network (most of the times on parallel feeders). Faults in consumer's installation. Connection of heavy loads and start-up of large motors. **Consequences:** Malfunction of information technology equipment, namely microprocessor-based control systems (PCs, PLCs, ASDs, etc) that may lead to a process stoppage. Tripping of contactors and electromechanical relays. Disconnection and loss of efficiency in electric rotating machines.
2. Very short Interruptions 	**Description:** Total interruption of electrical supply for duration from few milliseconds to one or two seconds. **Causes:** Mainly due to the opening and automatic reclosure of protection devices to decommission a faulty section of the network. The main fault causes are insulation failure, lightning and insulator flashover. **Consequences:** Tripping of protection devices, loss of information and malfunction of data processing equipment. Stoppage of sensitive equipment, such as ASDs, PCs, PLCs, if they're not prepared to deal with this situation.
3. Long interruptions 	**Description:** Total interruption of electrical supply for duration greater than 1 to 2 seconds **Causes:** Equipment failure in the power system network, storms and objects (trees, cars, etc) striking lines or poles, fire, human error, bad coordination or failure of protection devices. **Consequences**: Stoppage of all equipment.
4. Voltage spike 	**Description:** Very fast variation of the voltage value for durations from a several microseconds to few milliseconds. These variations may reach thousands of volts, even in low voltage. **Causes:** Lightning, switching of lines or power factor correction capacitors, disconnection of heavy loads. **Consequences:** Destruction of components (particularly electronic components) and of insulation materials, data processing errors or data loss, electromagnetic interference.
5. Voltage swell 	**Description:** Momentary increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds. **Causes:** Start/stop of heavy loads, badly dimensioned power sources, badly regulated transformers (mainly during off-peak hours). **Consequences:** Data loss, flickering of lighting and screens, stoppage or damage of sensitive equipment, if the voltage values are too high.
6. Harmonic distortion	**Description:** Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency. **Causes:** Classic sources: electric machines working above the knee of the magnetization curve (magnetic saturation), arc furnaces, welding machines, rectifiers, and DC brush motors. Modern sources: all non-linear loads, such as power electronics equipment including ASDs, switched mode power supplies, data processing equipment, high efficiency lighting.

[5] http://powermin.nic.in/sites/default/files/uploads/Growth_in_Transmission_sector_Eng.pdf

	Consequences: Increased probability in occurrence of resonance, neutral overload in 3-phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems, errors in measures when using average reading meters, nuisance tripping of thermal protections.
7. Voltage fluctuation 	**Description:** Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz. **Causes:** Arc furnaces, frequent start/stop of electric motors (for instance elevators), oscillating loads. **Consequences:** Most consequences are common to under-voltages. The most perceptible consequence is the flickering of lighting and screens, giving the impression of unsteadiness of visual perception.
8. Noise 	**Description:** Superimposing of high frequency signals on the waveform of the power-system frequency. **Causes:** Electromagnetic interferences provoked by Hertzian waves such as microwaves, television diffusion, and radiation due to welding machines, arc furnaces, and electronic equipment. Improper grounding may also be a cause. **Consequences:** Disturbances on sensitive electronic equipment, usually not destructive. May cause data loss and data processing errors.
9. Voltage Unbalance 	**Description:** A voltage variation in a three-phase system in which the three voltage magnitudes or the phase angle differences between them are not equal. **Causes:** Large single-phase loads (induction furnaces, traction loads), incorrect distribution of all single-phase loads by the three phases of the system (this may be also due to a fault). **Consequences:** Unbalanced systems imply the existence of a negative sequence that is harmful to all three phase loads. The most affected loads are three-phase induction machines.

The cost of poor monitoring of the above-mentioned power quality parameters is huge. The conventional instrument transformer has limitation to measure such high frequency disturbances. PFFINER's "Resistive Capacitive Voltage Divider (RCVD)" can accurately measure such disturbances up to 10 kHz and above. Many European countries are already using RCVD for better power quality monitoring at strategic location, especially at cross country transaction grids. Indian power sector has the unique opportunity to leverage this technology for better power quality as well as better asset management.

I would like to conclude this paper with the following remarks:

- Inductive VT's have a higher frequency dependent transformation ratio dependency compared to CT's
- RC-dividers have the performance to measure the PQ parameters
- RC-dividers can be used for metering, measuring and protection purposes
- RC-dividers can be used both for AC and DC application, GIS and AIS

Reference:

1. Measurement of transient voltages in a substation-J. Plesch, E. Sperling, G. Achleitner, S. Pack, CIGRE 2015, Paper 0255
2. Power Quality: Basics, standards, measurements, experiences, Jan Meyer and Jako Kilter (Elering AS / Tallinn University of Technology, Estonia), PFIFFNER Day, Hirschthal, 8th June 2017
3. WHITEPAPER_ POWER QUALITY REGULATIONS IN INDIA, Forum of Regulators (FOR), India, Assisted by Asia Power Quality Association_ September 2015
4. CIGRE/CIRED JWG C4.112 – Power Quality Monitoring, M.H.J. Bollen1, J.V. Milanović and N. Čukalevski, International Conference on Renewable Energies and Power Quality (ICREPQ'14), Cordoba (Spain), 8th to 10th April, 2014, Renewable Energy and Power Quality Journal (RE&PQJ), ISSN 2172-038 X, No.12, April 2014
5. Application note, The Cost of Poor Power Quality, Roman Targosz, David Chapman, October 2015, ECI Publication No Cu0145, European Copper Institute (ECI)
6. Experiences with recent Power Quality Measurements in a High Voltage Grid of Westnetz GmbH, PFIFFNER Day, June 8th, 2017 "Future Grid Challenges", Dr. Philipp Werdelmann, Westnetz GmbH
7. International Standards for Power Quality Measurement Systems, P Axelberg, Unipower AB, Sweden, M H. J. Bollen, Chalmers University of Technology, Sweden
8. Ministry of Power, India
9. Central Electricity Authority (CEA)
10. Central Electricity Regulatory Commission (CERC)

Emerging Opportunities and challenges of R&D in Indian Power Sector
15-16 February ,2018 –Vigyan Bhawan , New Delhi

Challenges & Achievements of Indian Transmsission Line Industry and Emerging New Global Technologies

By

Dr. DEEPAK LAKHAPATI

Chief Design Officer
STERLITE POWER TRANSMISSION LIMITED
NEW DELHI , INDIA
deepak.lakhapati@sptlpower.in

ABSTRACT :

Indian transmission sector is continously overcoming various Challenges like Time, Space and Capital and achieved remarkable innovative solutions using the latest globally proven technologies. Pilot projects used as a tool for research and development. On satisfactory confidence these innovative solutions are used in actual lines.Paper describes the Challenges infront of the Industry, technologies and innovation used in the Projects and also emergining Global technologies which can be used in the Indian upcoming projects .Paper covers the case studies on some of the latest achievements.Voltage Up-gradation of the Transmission line by using High Temperature and Low Sag conductors supported on Monopoles to use an existing corridor, in densely populated housing areas In Kerala. Civil Aviation Zone restricted the height of the 400 kV D/c transmission line on the Himalayan Mountains in Srinagar. Innovative solution was developed using Horizontal conductor configurations on a pair of monopoles by reducing the height and the foot print complying aviation regulations. North Eastern states imposed restrictions on the foot print being used in the forest and tree cuttings for two independent lines of 400 and 132 kV lines .Multi voltage Multi Circuit transmission line of 400kV/132kV solution reduced substancially the forest foot print and tree cuttings.Floods in Ganga River is always a Challenge for the Transmission Line crossing towers . A 400 kV Transmission tower washed away shutting down the Power flow for nearly 10 months till a restoration solution was implemented.A Unique GIS Substation has been designed on Three storied Building for the first time in Asia due to space restrictions in NCR. New Emerging Technologies used in Europe, North and South American Countries giving Much higher SIL requirments by using different tower configurations are worth looking at by the Indian transmission sector.

INTRODUCTION :

Today Indian Power sector is going through a difficult time where many of the old transmission lines built in 1950-1970 are on 66/110 /132/220 kV voltage levels, overloaded and cannot serve the current power demand without planned load shedding / power cuts, limited or no access to the tower locations due to development of unplanned houses under the tower foot print, hutments below the transmission lines, many encroachments close to the live conductors. R & D engineers have developed solutions and implemented new upgraded transmission lines which can be used in different states in India.

Engineering challenges were of different dimensions when it comes to building transmission lines in hamalayan mountains in Srinagar, where civil aviation restricts the height of towers around the air strips. Use of Monopoles was developed to overcome the solutions. Social Impact is other important consideration while building new transmission lines like saving the wild life, tree cuttings in forest, protection of environment etc. R & D engineers are also exposed to emerging new opportutines globally and are transfering the knowledge and experence to Indian power sector.

Some of engineering solutions developed and implemented out of the R & D case studies using the latest software are detailed below.

Case Study no 1 :

A Solution out of R&D efforts for Voltage Up-gradation of the Transmission line by using HTLS conductors supported on Monopoles to use an existing corridor, in densely populated housing areas In Kerala.

We were faced with an engineering challenge of upgradation of existing 66kV S/C transmission line which was built in 1960 and overloaded to 110kV D/C line using same locations in the corridor.
Various alternatives were studied as an R&D Project. Because of space constraints only feasible solution was finalized by changing conductor from existing ACSR to HTLS conductor and changing 66kV lattice towers to 110kV D/C monopoles.
Similarly due to difficult access of heavy piling machinery could not reach the locations (backyard of houses), micropiles were designed and installed in transmission line industry for the first time in India. Further aerial technology was implemented for laying conductor.

Some of the pictures are illustrated below:





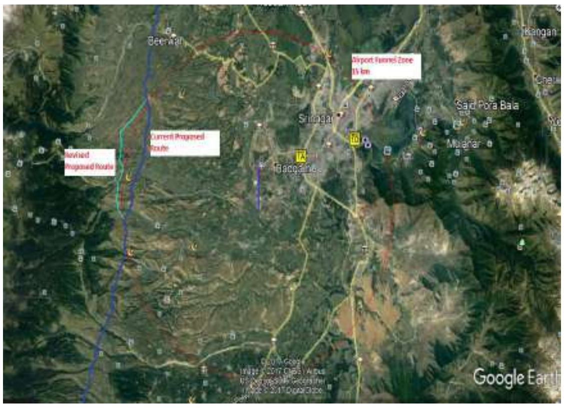


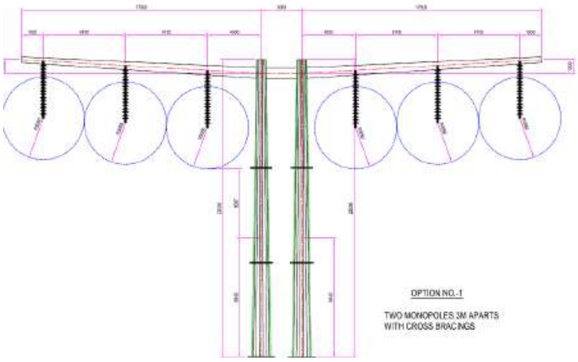


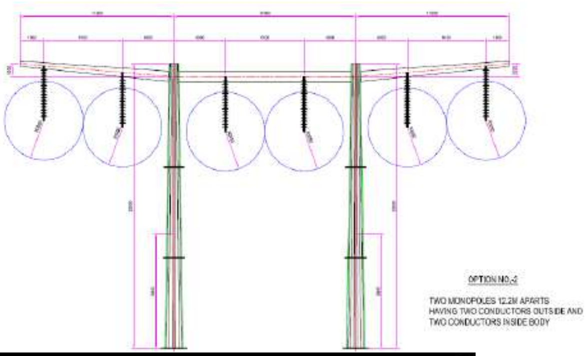
Case Study no 2 :

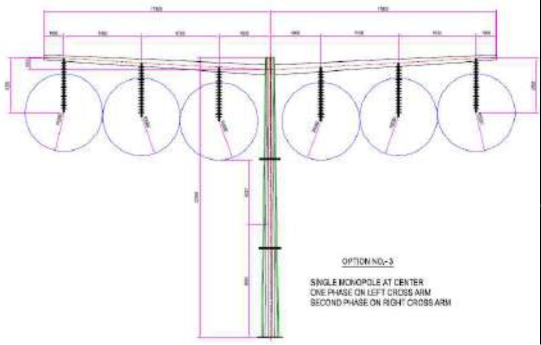
Use of R&D as a backbone for Civil Aviation Zone which restricted the height of the 400 kV D/C transmission line on the Himalayan Mountains in Srinagar. Innovative solution was developed using Horizontal conductor configurations on a pair of monopoles by reducing the height and the foot print complying aviation regulations.

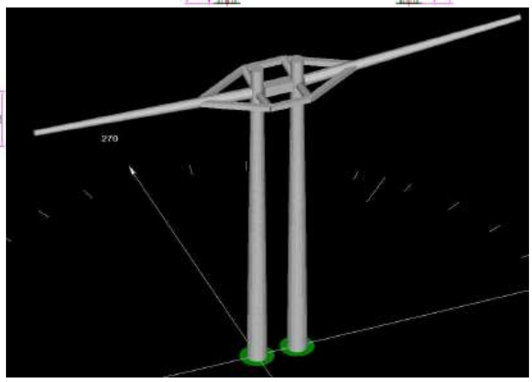
We faced an challenge of a 400kV D/C transmission line passing through a radius of 15km around airport strip in Himalayan mountains of Srinagar. Since there was no alternative route available, only choice was available to reduce geight of towers from 45m to 20m above ground. Situation gave an R&D effort for restriction of height as well as the footprint. A twin poles design got emerged for the most suitable technical solution on the high mountains of Srinagar.











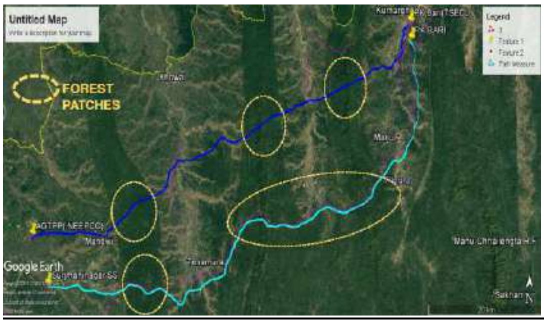
Final Proposal

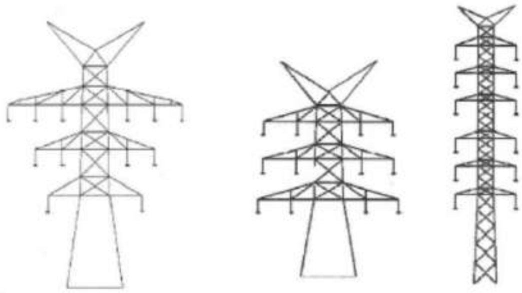
Case Study no 3 :

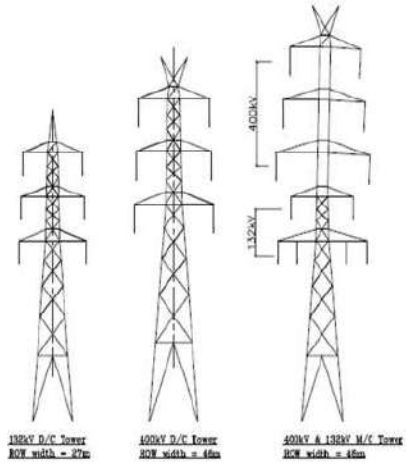
Challenge was given to engineering to find solution to save forests as a social impact.

North Eastern states imposed restrictions on the foot print being used in the forest and tree cuttings for two independent lines of 400 and 132 kV lines. Multi voltage Multi

Circuit transmission line of 400kV/132kV solution reduced substancially the forest foot print and tree cuttings.







Approximate Saving in Corridor				
	Line Length (m)	Length (m)	RoW (m)	Area (sqm)
132kV D/C	100	60	27	1620000
400kV D/C	100	60	46	2760000
		-	-	4380000
400 & 132kV M/C	60	60	46	2760000
Saving in sqm				1620000
Saving in Tree Cutting (nos)				192000

Case Study no 4 :

Restoration Challenge of 400kV Transmission Line which washed away in Ganga river in 2016.

A 400 kV Transmission tower washed away shutting down the Power flow for nearly 10 months till a restoration solution was implemented. 400kV D/C Purnia – Biharsharif transmission line was built in the year 2013 which was crossing Ganga river of width 2km near Begusarai, Bihar. In August 2016 due to unprescedent flood one river crossing pile foundation consisiting of 20 piles was washed away due to sever flood and water velocity causing a distrubtion in power flow for 10 months till the new solution was implemented by designs using 24 piles (group of 6 piles with a pile cap) and the restoration work was completed in May 2017.

Case Study no 5 :

A Unique R&D solution has been developed for GIS Substation on three storied building for the first time in Asia due to space restrictions in NCR.

Due to space constrint in NCR a conventional 400/220kV GIS substation could not be implemented hence very innovative soultion was developed using multi-storied GIS building which leads to reduction in land requirement from typical 10 acres to 4 acres.One of the substations is facing a challenge of liquified sand in an earthquake zone 4 and soil stabilization techniques have been designed in consultation with IIT Delhi experts .

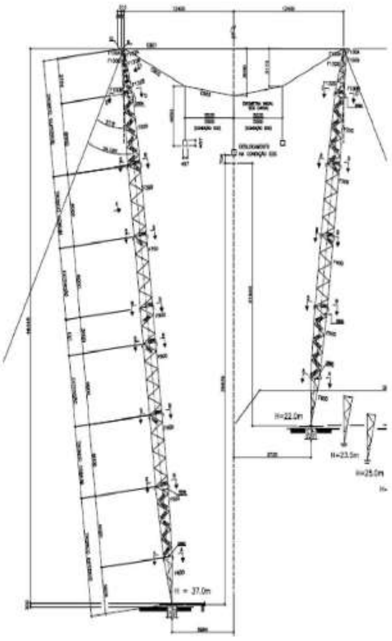
Recommendations :

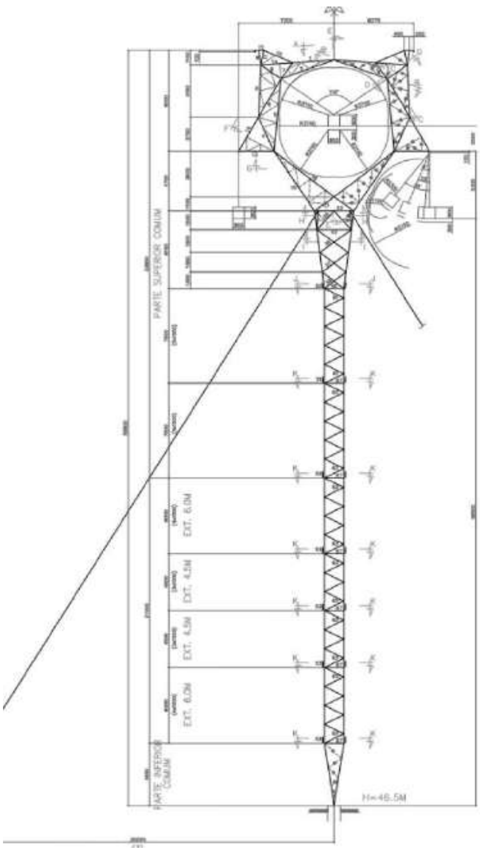
Exposure to Global Emerging Technologies has created a urgent need of inclusion in policies of Indian Power sector for allowing to use .

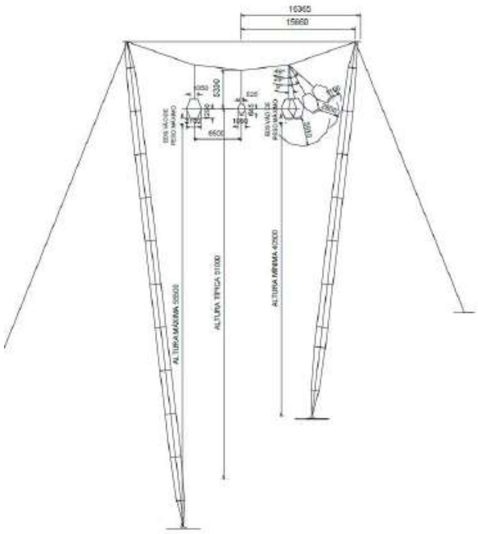
New Emerging Technologies used in Europe, North and South American Countries giving much higher SIL requirments by using different tower configurations are worth looking at by the Indian transmission sector.

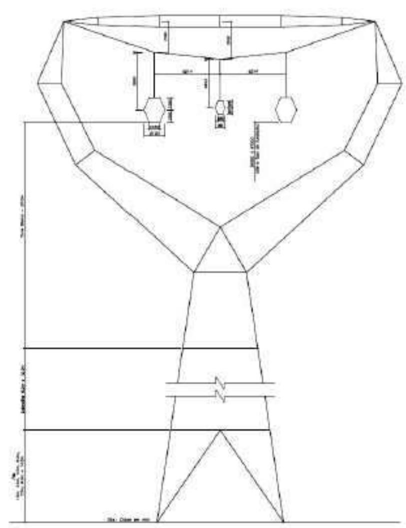
Innovative monopoles are being used in many European countries that require 50-60% less corridor. In Brazil major transmission lines are on guyed towers that reduces the Steel tonnage by more tan 70%.
A typical 500kV hexa bundle tranmssion line has SIL of 1250 MW, however by using assymetrical bundle conductors the SIL value can be increased to 1670MW and are being used in South America.

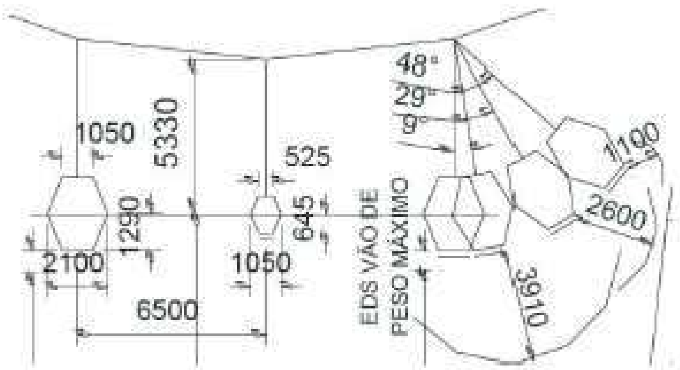
.


H = 27.0m
H=22.0m
H=23.5m
H=25.0m

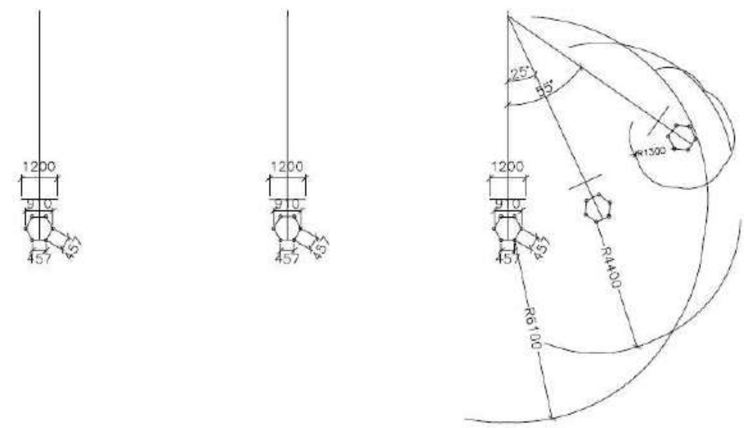

PARTE SUPERIOR COMUM
EXT. 6.0M
EXT. 4.5M
EXT. 4.5M
EXT. 6.0M
PARTE INFERIOR COMUM
H=46.5M







Unsymetric – 1670MW



Symetric – 1250MW

Conclusions :

From the case studies, we feel excited that even though Indian power sector is facing challenges, our Indian Engineers are contineously developing innovative solutions inhouse.

Similarly the global exposure of emerging technologies are helping us to ask a question – Why Not in India? we feel our policy makers should help Indian power industry to allow such globally proven technologies to be implemented in Indian environment.

Acknowledgement :

Author gratefully acknowledge the encouragement given by management to prepare and present the paper. Author is thankful to Mr. Ankit Jain, Engineering Manager, assisted me in preparation of the paper.

Reference :

1) Bystrup, Denmark – Use of monopoles in Europe
2) ANNEL , Brazil - Use of Guyed Cross Rope towers in Brazil

Biodata :

Dr. Deepak Lakhapati, born in Nagpur, India on 2nd June 1953 is gold medallist in Civil Engineering from Nagpur University and also holds Masters and doctoral degree in Structural Engineering. The Professional experience of 44 years includes developing innovative design and engineering solutions for Transmission lines up to 765 kV in various parts of the world and successfully tested large number of proto type towers upto 1200 kV. Have implemented numerous innovative cost effective solutions in transmission lines and travelled extensively at project sites in many countries. Made large number of presentations at various national and international forums including CIGRE Paris, IEEE USA, ASCE USA etc.
Having worked with ABB – SAE, KEC International Ltd, Gammon India, Jyoti Americas, USA, Karamtara Engineering, Currently holding a position as Chief Design officer in Sterlite power Transmission ltd, New Delhi responsible for Global Infra Business Unit.

Power Voltage Transformers

An Innovative Solution for directly tapping power from EHV Lines to reduce diesel consumption for telecom towers

Team: Sanil C Namboodiripad, Head (Asset Mgt. / O&M); NK. Panda, Head (Convergence Business); Sachin Deshpande, Head (O&M – S/S); Vishal Gokhale, Manager (Convergence Business); Vivek Karthikeyan, Dy. Manager (O&M)

Abstract:

With the ever-growing demand of data and voice today, the telecom operators are facing numerous challenges, one of them is the need of energy for their continuous operations. PVT, a power voltage transformer is one of the pioneering steps towards eliminating the use of conventional power and diesel generators, to providing a reliable power to the telecom operators. Sterlite, in such an endeavor has successfully deployed a PVT at one of its power transmission towers to provide that directly usable output power to various applications and specially the telecom antennas. The following paper throws lights on technical details of the PVT and how the whole project was conceived and successfully executed.

SECTION-1

1. 1 Introduction

In recent years, the rise in the world's average ambient temperature has become a matter of global concern and is now recognised as one of the key challenges facing humanity. "Global warming", "Climate Change", "Greenhouse Effect" etc are common expressions used to describe the threat to human and natural ecosystems resulting from enhanced emissions of heat trapping or greenhouse gases (GHGs) arising from the activities of humankind in an increasingly industrialized and globalizing world.

India has the second largest and fastest growing mobile telephone market in the world. Power and energy consumption for telecom operations is by far the most significant contributors of carbon emissions in the telecom industry.

As per Consultation Paper released by TRAI on Approach towards Sustainable Telecommunications in Jan, 2017:

"The CO2 emission level from the Indian mobile telecom sector jumped by more than 70% from 2011-12 and in 2014-2015, it accounted for 58.3 million tonnes and a total of approx 836 giga joules of primary energy was consumed during the specified period, which is equivalent to 73 billion units.

India has about 450,000 telecom sites. As on Dec 2016, at least 360,000 sites are still dependent on diesel generators for power back up.

Going Green has also become a business necessity for telecom operators with energy costs becoming as large as 25% of total network operations costs. A typical communications company spends nearly 1% of its revenues on energy which for large operators may amount to hundreds of crores of rupee."

The telecom industry had briefly overtaken the Indian railways as the country's largest consumer of diesel. As of Jan 2013, it was estimated that the diesel consumption for telecom sites was more than 5.12 billion litres a year.

Aiming to reduce the carbon footprint of the sector, the Telecom Regulatory Authority of India (TRAI), in Oct 2017, has set a target for reduction in carbon emission 30 per cent by year 2019-20 taking base year as 2011-12 and 40 per cent by the year 2022-23.

The solution presented in this paper addresses two issues in one stroke:

- Use of existing power transmission towers to carry the telecom antenna so that new towers need not be built
- Use of power voltage transformers to tap supply power directly from the EHV system so that diesel consumption can be eliminated.
- Sterlite Power has successfully carried out a pilot project at one of its substations and the results are also presented here.

1. 2 Technologies

There are various methods of tapping power from EHV lines:

1) CAPACITIVE METHODS
    i. Capacitive Divider method
    ii. Isolated Shield Wire method
        a. Passive Method
        b. Active Method
    iii. Antenna Method
2) INDUCTIVE METHODS
    i. Current Transformer Tapping method
    ii. Air Core Transformer method

1% <u>CAPACITIVE METHODS - CONCLUSION</u>

- Straightforward principle and good design.
- Power extracted can be from tens of watts up to megawatts.
- Isolated shield wire requires very long distance in order to get relatively high power.
- Capacitive Divider method can provide high amount of power but requires a direct contact with the conductor which brings serious protection problems.
- Capacitive divider method can also help in voltage regulation if placed between two classic inductive Substations

2% <u>INDUCTIVE METHODS</u>

This class of method is based on the magnetic flux which exists around the Transmission Lines and that can induce an electromagnetic force (emf) in an inductor.

Can be divided as:

✓ Current Transformer Tapping method
✓ Air Core Transformer method

a) Current Transformer Tapping method
b) Air Core Transformer method

<u>INDUCTIVE METHODS – CONCLUSION</u>

- Inductive based methods are recommended for a power range of several kilowatts.
- The CT based method can produce even higher power when applied on each phase of Transmission Line.
- The air core transformer method exerts a very small influence on the Transmission line due to the air core coupling.

1.3 Advantages of direct tapping in comparison to other methods

- Highly reliable power source within the substation.
- Independent power supply, more flexible as the user does not have to depend on third parties.
- Cost effective – For large amount of installation.
- Maintenance-free throughout their lifespan.
- Quick and flexible solution

SECTION-2

2.1 Technical challenges

- In India, regulation doesn't allow direct tapping of power from EHV lines.
- As this the new technology, though worldwide used extensively, because of less awareness PVT is not popular in india.
- Awareness in grid and all entities to be enhanced for core purpose and benefits.

2.2 Cost comparison

- Because of new technology, non-standard product, less quantity in production and installation, though the cost is very high can be reduced further when used in large scale.

2.3 Safety

- The protection to be provided on primary side (EHV) is LA and MCB on the secondary side(220V).Any fault on the secondary side would be cleared by the MCB and faults on the primary would be cleared by distance protection of EHV line in which PVT would be tapped.
- Lighting arrestor (LA) to be provided to PVT for protection against the lightning faults.
- Proper earthing of all equipment's and structure to be provided.

2.4 Installations of PVTs across world

Customer	Project Cty.	Nom. Voltage	Ordered in	Qty.	Type
E-Plus	Germany	110 kV	1997	1	PSVS 123
E-Plus	Germany	110 kV	1997	1	PSVS 123
AEG, Weinheim	Germany	110 kV	1997	1	PSVS 123
HTSA	South Africa	400 kV	1999	6	PSVS 420
HTSA	South Africa	400 kV	1999	2	PSVS 420
Mannesmann Mobilfunk	Germany	110 kV	2001	1	PSVS 123
SAG, Gifhorn	Germany	110 kV	2002	2	PSVS 123
HTSA	South Africa	400 kV	2002	3	PSVS 420
HTSA	Namibia	220 kV	2003	3	PSVS 245
LEW	Germany	110 kV	2004	1	PSVS 123
Suncor	Canada	220 kV	2004	3	PSVS 245
Suncor	Canada	220 kV	2004	3	PSVS 245
Transgrid	Australia	330 kV	2004	4	PSVS 362
GE Electric	USA	230 kV	2005	2	PSVS 245
Powerlink	Australia	132 kV	2006	6	PSVS 145
ESKOM	South Africa	420 kV	2006	3	PSVS 420
ABB	Saudi Arabia	400 kV	2007	7	PSVS 420
Powereng Pty Ltd	Australia	220 kV	2007	2	PSVS 245
Powereng Pty Ltd	Australia	220 kV	2007	2	PSVS 245
ABB	Saudi Arabia	400 kV	2007	6	PSVS 420
High Voltage Technology	South Africa	400 kV	2007	3	PSVS 420

Customer	Project Cty.	Nom. Voltage	Ordered in	Qty.	Type
Powereng Pty Ltd	Australia	220 kV	2008	1	PSVS 245
Powereng Pty Ltd	Australia	132 kV	2008	3	PSVS 145
Powereng Pty Ltd	Australia	275 kV	2009	1	PSVS 300
Powereng Pty Ltd	Australia	132 kV	2009	3	PSVS 145
Powereng Pty Ltd	Australia	275 kV	2010	2	PSVS 300
Powereng Pty Ltd	Australia	275 kV	2010	13	PSVS 300
Powereng Pty Ltd	Australia	132 kV	2010	7	PSVS 145
Powereng Pty Ltd	Australia	220 kV	2010	3	PSVS 245
Trench Canada	Canada	230 kV	2010	1	PSVS 245
Trench Canada	Canada	230 kV	2010	6	PSVS 245
Powereng Pty Ltd	Australia	132 kV	2011	6	PSVS 145
LOWER COLORADO RIVER	USA	345 kV	2011	1	PSVS 362
ABB AG	Afghanistan	110 kV	2011	3	PSVS 123
Dynamic Power Soluti	Namibia	400 kV	2011	3	PSVS 420
Powereng Pty Ltd	Australia	330 kV	2011	4	PSVS 362
Dynamic Power Soluti	Namibia	220 kV	2011	1	PSVS 245
Dynamic Power Soluti	Namibia	220 kV	2011	1	PSVS 245
Powereng Pty Ltd	Australia	132 kV	2011	3	PSVS 145
Powereng Pty Ltd	Australia	132 kV	2011	3	PSVS 145
Powereng Pty Ltd	Australia	132 kV	2011	3	PSVS 145
Powereng Pty Ltd	Australia	132 kV	2011	1	PSVS 145
Trench Canada	USA	345 kV	2012	1	PSVS 362
Powereng Pty Ltd	Australia	275 kV	2012	6	PSVS 300
Siemens Ltd.	Australia	275 kV	2012	4	PSVS 300
Cotec SA.	Spain	220 kV	2012	3	PSVS 245
ABB AG	Dominican Repu	138 kV	2012	1	PSVS 245
Trench Canada	USA	230 kV	2012	1	PSVS 245
Trench Canada	USA	345 kV	2013	1	PSVS 362
Trench Canada	USA	230 kV	2013	1	PSVS 245
Powereng Pty Ltd	Australia	132 kV	2013	3	PSVS 145
Powereng Pty Ltd	Australia	132 kV	2013	3	PSVS 145
Powereng Pty Ltd	Australia	110 kV	2013	3	PSVS 123
Trench Canada	Canada	230 kV	2013	8	PSVS 245
Powereng Pty Ltd	Australia	275 kV	2013	1	PSVS 300
Powereng Pty Ltd	Australia	132 kV	2013	2	PSVS 145
Powereng Pty Ltd	Australia	110 kV	2013	1	PSVS 123
Powereng Pty Ltd	Australia	132 kV	2013	3	PSVS 145
Powereng Pty Ltd	Australia	132 kV	2013	3	PSVS 145
Powereng Pty Ltd	Australia	132 kV	2013	3	PSVS 145
Powereng Pty Ltd	Australia	132 kV	2013	3	PSVS 145
Powereng Pty Ltd	Australia	275 kV	2013	3	PSVS 300
Trench Canada	USA	345 kV	2013	2	PSVS 362
Trench Canada	USA	230 kV	2014	1	PSVS 245
Trench Canada	USA	345 kV	2014	2	PSVS 362
Trench Canada	USA	345 kV	2014	2	PSVS 362
Trench Canada	USA	345 kV	2014	2	PSVS 362
Trench Canada	Canada	138 kV	2014	1	PSVS 145
Trench Canada	USA	345 kV	2014	1	PSVS 362
Trench Canada	USA	345 kV	2014	1	PSVS 362
Siemens Spain	Spain	220 kV	2014	24	PSVS 245
Siemens Spain	Spain	400 kV	2014	3	PSVS 420
Siemens Guatemala	Honduras	230 kV	2014	7	PSVS 245
Trench Canada	USA	345 kV	2014	1	PSVS 362

Customer	Project Cty.	Nom. Voltage	Ordered in	Qty.	Type
Siemens Chile	Chile	230 kV	2014	6	PSVS 245
Trench Canada	Canada	230 kV	2014	7	PSVS 245
Trench Canada	Canada	138 kV	2014	1	PSVS 145
Trench Canada	USA	230 kV	2015	3	PSVS 245
Trench Canada	USA	345 kV	2015	1	PSVS 362
Trench Canada	Canada	230 kV	2015	3	PSVS 245
Trench Canada	Canada	230 kV	2015	3	PSVS 245
Trench Canada	Canada	138 kV	2015	3	PSVS 145
Siemens Chile	Chile	220 kV	2015	3	PSVS 245
Trench Canada	USA	345 kV	2015	4	PSVS 362
Trench Canada	USA	345 kV	2015	4	PSVS 362
Trench Canada	USA	345 kV	2015	2	PSVS 362
Trench Canada	USA	345 kV	2015	4	PSVS 362
Siemens Australia	Australia	220 kV	2015	3	PSVS 245
Trench Canada	USA	345 kV	2015	2	PSVS 362
Trench Canada	Canada	230 kV	2015	1	PSVS 245
Trench Canada	USA	345 kV	2015	1	PSVS 362
			Total	279	

SECTION-3

3.1 Pilot Project

The present pilot project is using a capacitive Power VT, which is very similar to a CVT. This is similar to the capacitive divider method explained at 1 a). The details of the equipment which was manufactured by Alstom, India is attached at Annexure.

PVT Pilot Project at BDTCL

Bhopal-Dhule Transmission (BDTCL) project of Sterlite Power consists of four 765 kV Single Circuit and two 400 kV Double Circuit transmission lines that are strengthening the transmission system in the Indian states of Madhya Pradesh, Maharashtra and Gujarat.

The project has been awarded on a 'Build, Own, Operate and Maintain' (BOOM) basis, wherein the transmission lines were commissioned within the timeframe and the Company is operating and maintaining the same for a minimum tenure of 35 years.

Fig 1: Power Voltage

Sterlite had undertaken studies and gathered information from global market to utilize the power transmission towers for telecom applications.

The pilot project was a unique proposal that merges the power and telecom businesses and provides synergy. We believe that this project can be extended towards various other applications also provided the proper commercial mechanism is available.

The pilot project consisted of both installation of the antennae as well as the PVT. The telecom antennae were directly mounted on the transmission tower and the PVT was mounted on the ground. The auxiliary equipment for provision of amplifiers etc. were also mounted on the ground.

The pilot project was successfully carried out for six months from July to November 2017.

3.2 Advantages

High quality clean, green, electrical supply is provided through this scheme for booster antennas in remote locations using a voltage transformer connected to a nearby transmission line.

For Mobile towers located near High Voltage substations in remote areas there is evidently a lack of adequate power source to power the telecom equipment which functions at low distribution voltage. The traditional solution is to use a DG set and a battery backup (UPS) to power the telecom equipment. This requires considerable investment and high maintenance costs in terms of

a. Fuel costs.
b. Maintenance of battery and Air-conditioned kiosk.
c. Area and space to house the DG (Diesel-Generator) set.
d. Manpower required for maintenance and operations.
e. Tower for mounting electronics

PVT solution will allow a direct, convenient and secure connection to the high voltage transmission line (up to 1200kV) in an economic way and convert this high voltage to a lower distribution voltage (110V or 220V) which directly acts as a power source for telecom equipments thus eliminating the need for the existing expensive solutions as mentioned above.

Other Applications of PVT

This technology offers immense possibilities as follows:

a) As a highly reliable auxiliary power supply to substations.
b) For providing clean power supply to telecom equipment by avoiding DG sets.
c) Temporary power supply when building substations, wind farms, etc.
d) Emergency supply during natural disasters
e) Electrification of small villages at remote locations lying adjacent to the transmission line.

Substations auxiliary services power supply:
Power supply in conventional substations where low voltage power is needed as a primary or back-up supply; or in remote areas where building distribution lines is unsafe and with unreliable supply that requires frequent maintenance and high costs. It can also be used as a primary power source in switching substations without power transformers to supply the substation and SCADA control systems.

Power supply for telecommunication and monitoring systems:
High quality electrical supply for booster antennas in remote locations using a voltage transformer connected to a nearby transmission line.

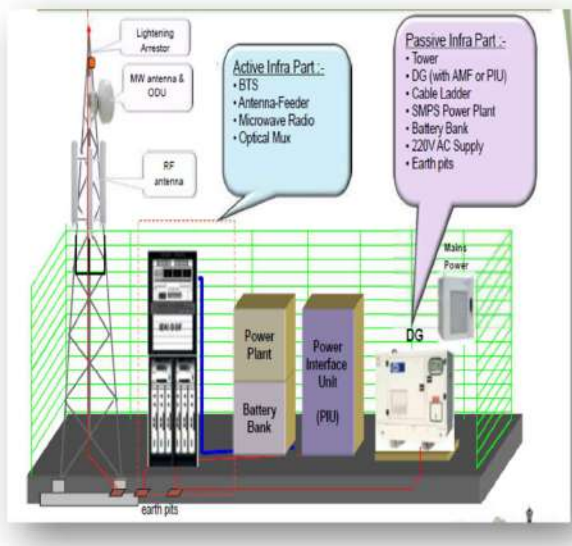
Temporary power supply when building substations, wind farms, etc
Quick and flexible solution upto a few hundred KVA

Emergency supply during natural disasters.
The PVT can be quickly installed at any location and restore power to the affected areas.

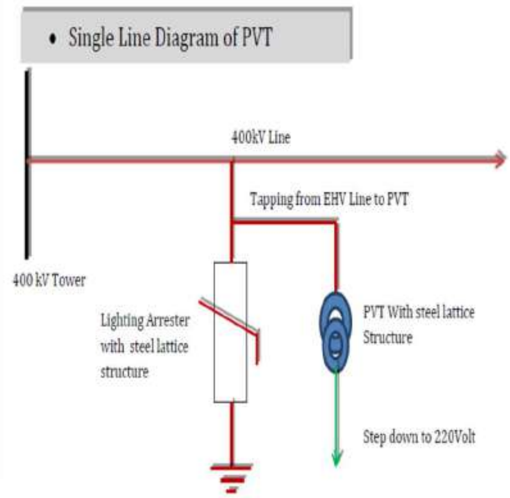
Rural electrification of isolated populations:
As a power source for supplying reliable power to rural populations in isolated areas where there are no distribution lines nearby, but there are transmission lines. This particular application supplies low voltage power directly from HV line in an economical and practical way

3.3 Installation and connection with telecom station

In place of DG set, PVT will be installed for providing Auxiliary supply.



SLD of PVT application on line



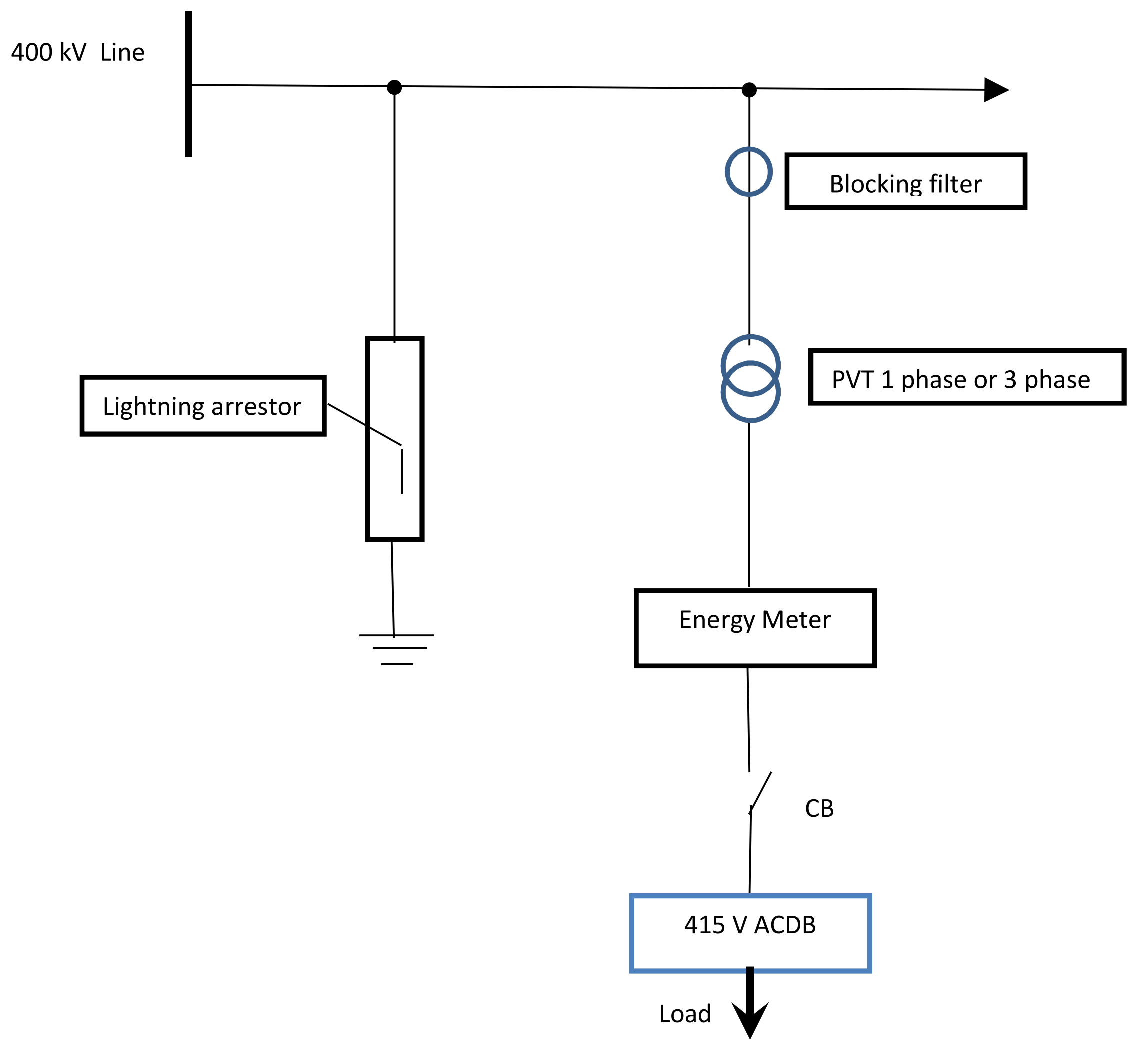
3.4 Conclusion

Power Voltage Transformers are units which are primarily used for auxiliary supply of substations and can be used for other purposes as well, namely for Telecommunication and monitoring systems, rural electrification. The PVT design allows for convenient siting within the less area for simple mounting to single phase supports and the technology ensures uninterrupted, reliable and high-quality power to the connected auxiliary system. By raising awareness that alternative uses for these transformers exist, a positive impact on the global availability of electrical energy in regions with low electrification rates can surely be enticed. To support such unconventional grid topology, transformer in-service reliability should be unconditionally ensured and increased.

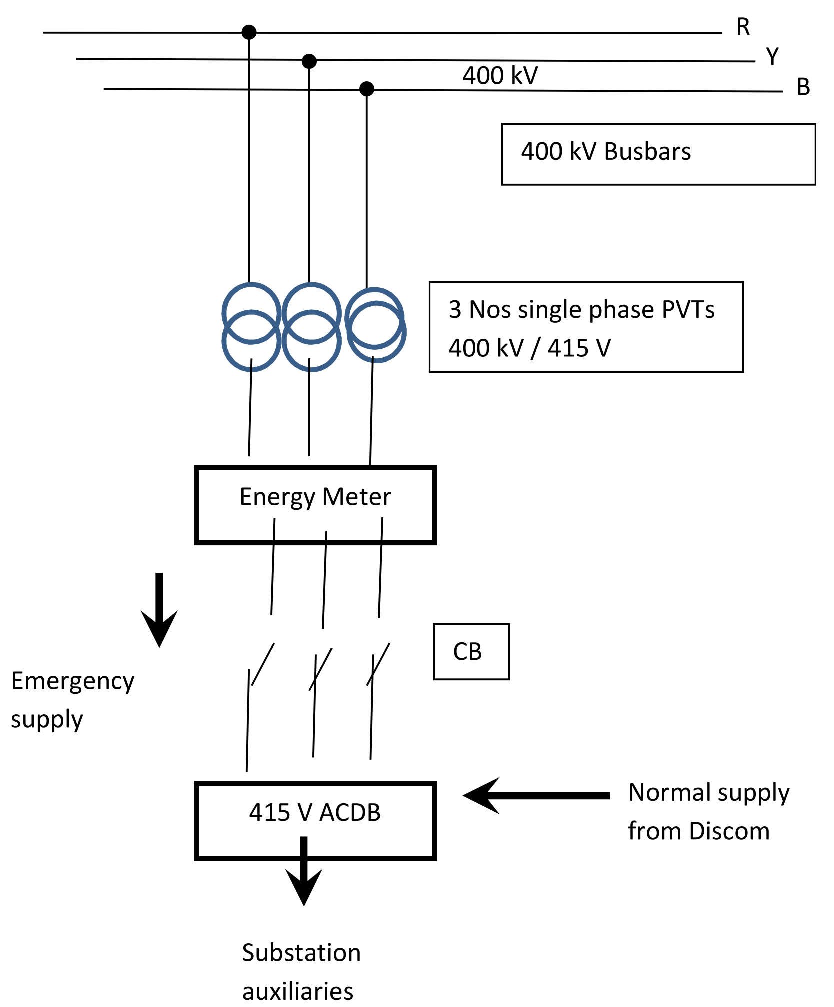
Acknowledgement

The successful completion of this paper reminds us to convey sincere regards to CEA and MPPTL, all the delegates, team members who were involved in the successful commissioning of the PVT at out project site.

Annexure -1: Line Diagram of PVT application- Tapping from line

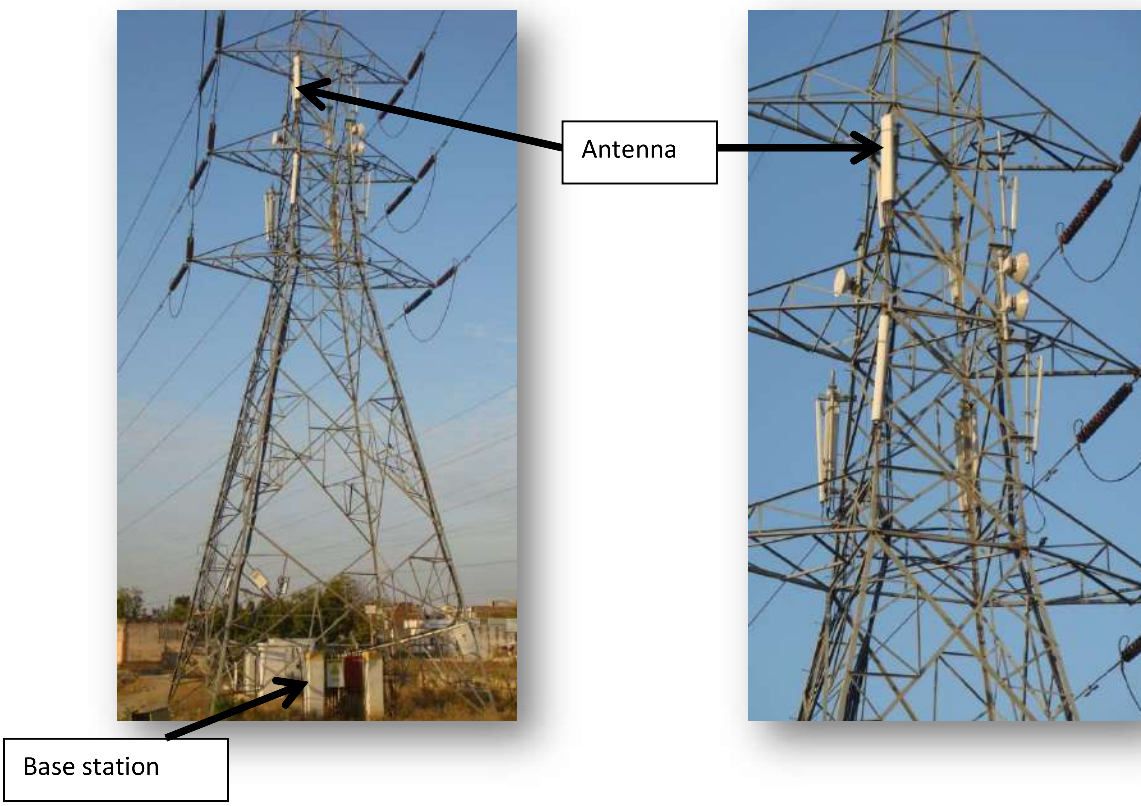


Annexure – 2: Line Diagram of PVT application: Auxiliary supply to the substation

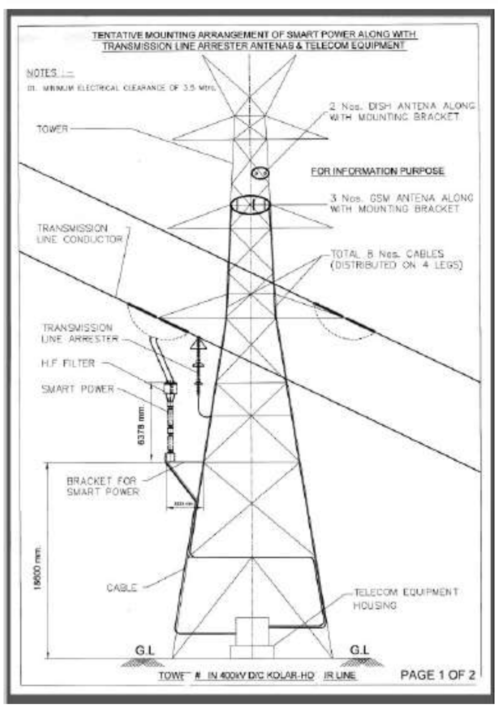


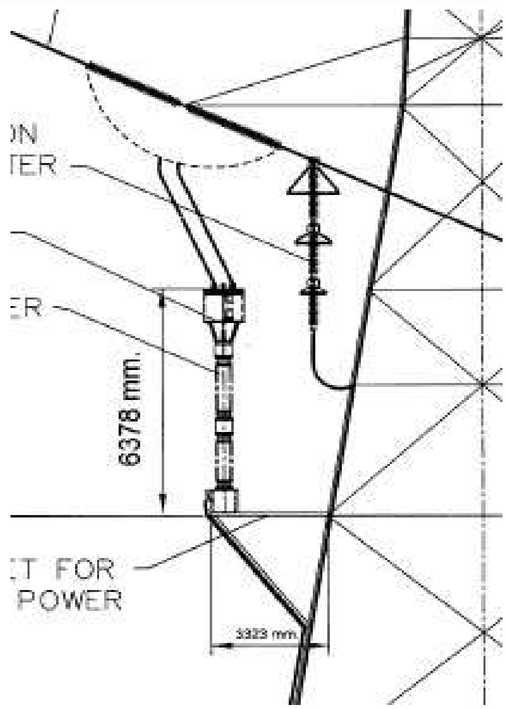
Power Voltage Transformer for Substation Auxiliary – at Coyote Switch (USA)

- **Photographs of antenna mounted on tower**

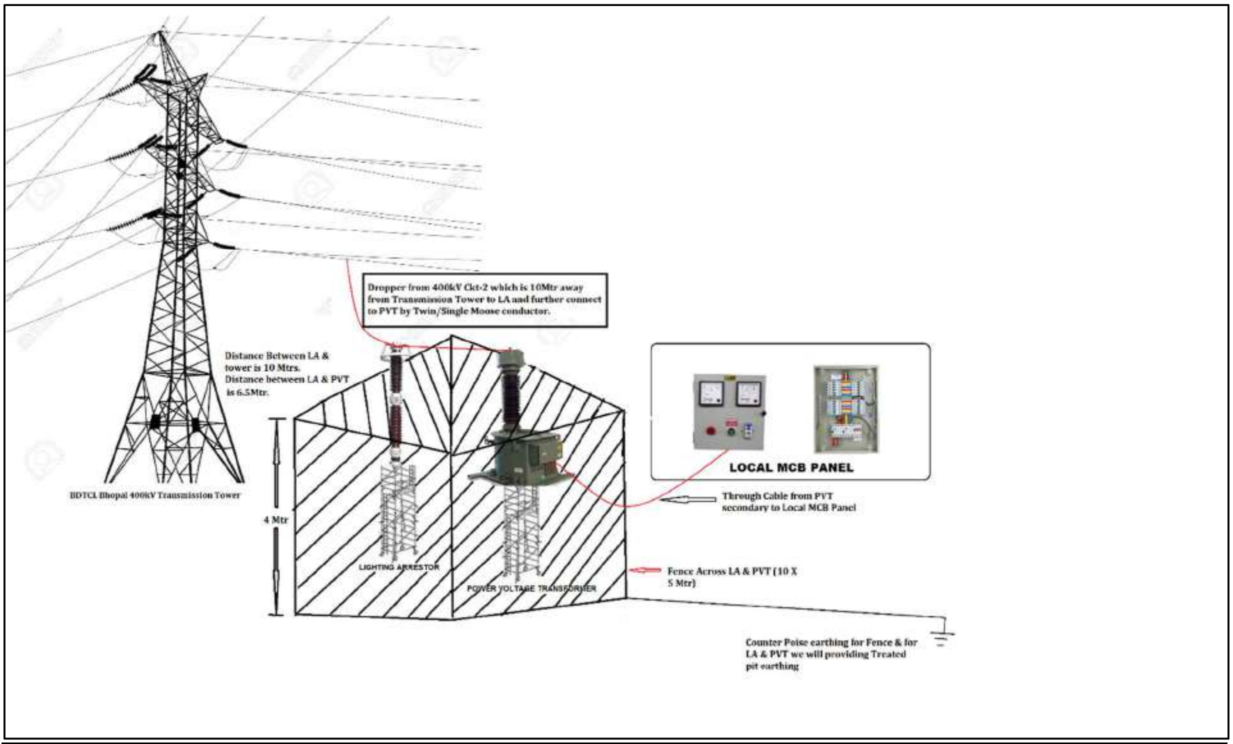


Annexure – 3: PVT GA drawing and mounting arrangement in case of direct mounting on tower





Annexure -4: PVT Connections



Annexure-5: PVT Performance report

Brief about power voltage transformer

- The power voltage transformer is used in high voltage transmission system to provide low voltage energy directly from the line.
- Power voltage transformers ensure high reliability and power availability for any critical load up to 250 KVA rating per phase [Note: KVA ratings depends on the supplier]
- Low cost alternative to small power transformers or distribution feeders
- Compact size and weight as compared to conventional power transformers
- Easy transportation and handling due to light weight
- Output customizable to needs of application site
- Single phase unit, Maintenance free
- Low insulation ageing

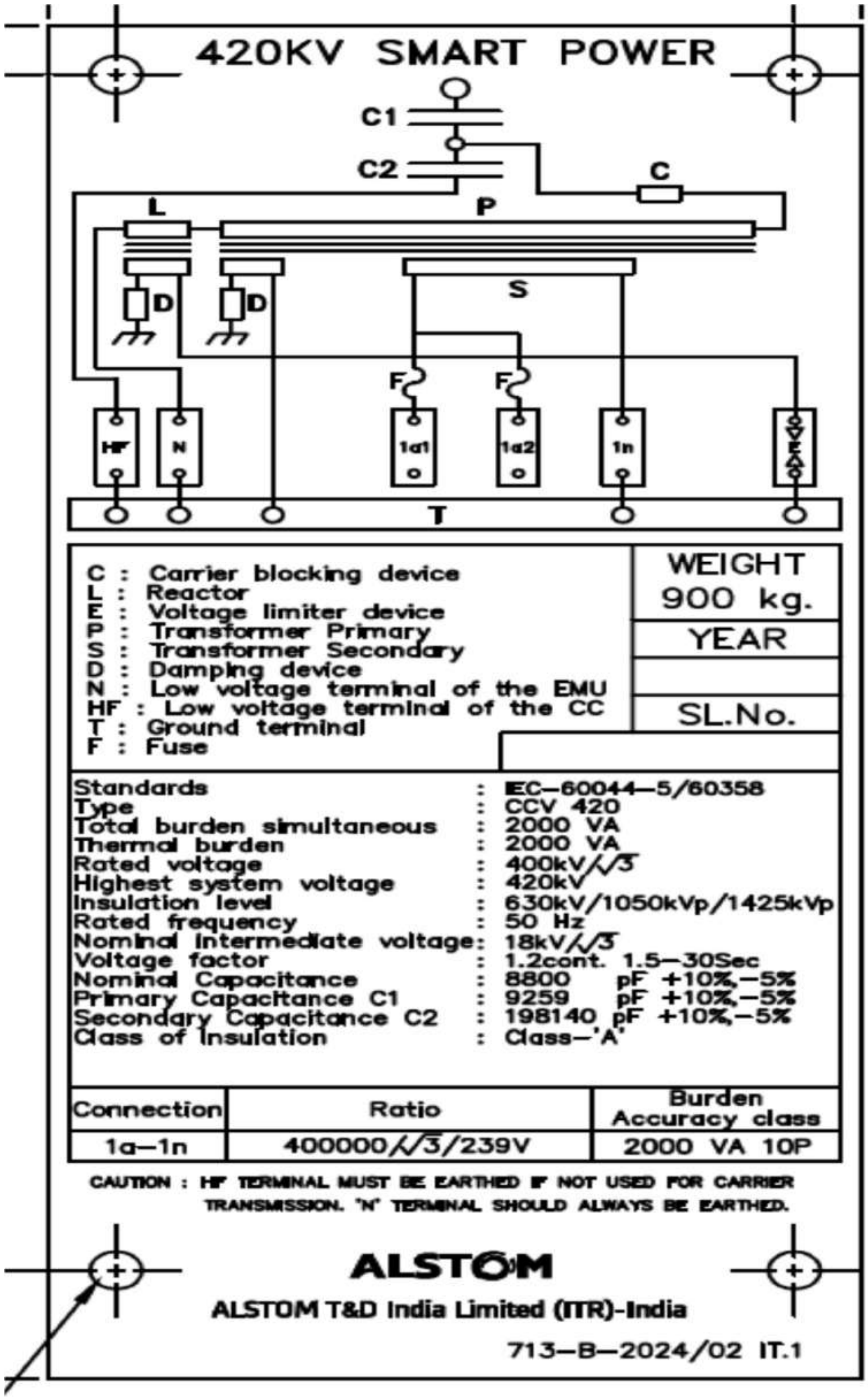
Application

- Temporary constructions of substations, power plants, wind farms or any other emergency use of temporary energy supply.
- Permanent or temporary low voltage supply to infrastructure i.e telecommunications, due to low voltage alimentation in the countryside.
- For substation auxiliary power supply
- Electrification of remote villages
- Power supply to telecom applications
- Emergency supply during natural disasters
- As per regulations alternate source required for Grid substation (other than DISCOM) is essential
- A very stable source
- Many remote villages have high voltage transmission lines passing nearby but it is uneconomical to install standard DISCOM supply system
- High Reliability
- Green Power
- Customized to the needs of the respective consumer

Standards

- There are no specific standards for power voltage transformers. The insulation rules follow the rules of instrument transformers.
  - i. IEEE C57.13 & C57.13.5: Instrument transformers
  - ii. IEC 60044-2: Instrument transformers

Technical Specification



Pre-commissioning test report:-

BHOPAL DHULE TRANSMISSION COMPANY LIMITED	DOC NO. :
	SUB STATION : 765/400KV BHOPAL SUBSTATION
	BAY NO
PRE-COMMISSIONING TEST	EQUIPMENT IDENTIFICATION NO : PVT
POWER VOLTAGE TRANSFORMER	DATE OF TESTING : 02-05-2017

DETAILS OF EQUIPMENT

RATED VOLTAGE	400KV
MAKE	ALSTOM
TYPE	CCV 420
SL NO.	**37992009194**
YEAR OF MANUFACTURE :	2016
FEEDER NAME :	

RATED DATA AND DUTY

CORE	TERMINALS	RATIO	CLASS	BURDEN	APPLICATION
CORE I	1a1-1a2	400KV/√3/239 V	10P	2000 VA	SMART POWER

1 **INSULATION RESISTANCE MEASUREMENT**

BETWEEN CORE	MEASURED VALUE(M OHMS)	APPLIED VOLTS
PRIMARY - SECONDARY WND	>1000	5000
PRIMARY - EARTH	>1000	5000
SECONDARY WND - EARTH	>1000	500

2 **TAN DELTA AND CAPACITANCE MEASUREMENT**

ACROSS STACK	PRE COMMISIONING VALUE	
TOP	CAPACITANCE (pf)	TAN DELTA %
2kV	15860	0.095
5kV	15840	0.073
10kV	15850	0.062
BOTTOM	CAPACITANCE (pf)	TAN DELTA
2kV	20580	0.349
5kV	20580	0.309
10kV	20590	0.288
TOTAL	CAPACITANCE (pf)	TAN DELTA
2kV	8990	0.224
5kV	8979	0.194
10kV	8984	0.175

3 **VOLTAGE RATIO TEST:**

PHASE	PRIMARY VOLTAGE	SECONDARY VOLTAGE		NOMINAL RATIO	ACTUAL RATIO	% ERROR
		BETWEEN	VALUE			
PVT	2000	1a1-1a2	2.050	966.277	975.610	0.966
	5010	1a1-1a2	5.100	966.277	982.353	1.664
	10000	1a1-1a2	10.500	966.277	952.381	-1.438
	12000	1a1-1a2	12.600	966.277	952.381	-1.438

NAME : Vivek Karthikeyan
DESIGNATION : Associate Manager(SPTL)

Installation & Charging Details:-

Date of Installation	10-05-2017
Date of commissioning	27-05-2017 @ 17:16hrs
Condition	In-service with 400kV BDTCL(Bhopal)-MPPTCL(Bhopal) Line2
Period	06 months
End date	27-11-2017
Power flow parameters	
Voltage(V)	242V
Current(A)	0.8A
Energy consumed till date	409KWH
Load connected	a)150W(lamp) b)12W(WiFi antenna)

PVT Performance parameter

Sl.no	Tracking parameter description	Observations	Deviations
1	Secondary voltage levels of PVT	Within limits	None
2	Abnormal noise	No abnormality	None
3	Vibrations	No abnormality	None
4	Burden variations as per the loading	Electrical parameters are within limits	None
5	Tripping of line	No tripping happened	None
6	Grid disturbance	none	None

Equipment healthiness parameters

Tracking parameter description	**Observations**	**Deviations**
Insulation resistance	To be tested after isolating from grid	Verified & No deviation observed
Tan delta test		
Thermography for hot spot measurement	No abnormality	None

PVT Photograph after successful commissioning

Brief CV of Lead Author

Name: Sachin Shyamarao Deshpande

Designation : Head Sub stations (O&M)

DOB : 30 October 1967

Experience :

An Electrical Engineering graduate & energy sector professional with 26+ years of experience in erection, testing, commissioning and operations & maintenance of power plants including Thermal , Gas , Solar, Nuclear, with exposure of heading corporate quality assurance & quality control. Testing, Commissioning and O&M of 765 kV lines and substation. Expertise in driving cost control and enhancing process capabilities and work flow. International exposure in the field, with experience in setting up and maintaining quality system. Adept at training and nurturing teams to build capabilities.

Working with Sterlite Power since four years, he is currently heading O&M of substations. He is also Lead Auditor of ISO 9001-2008 and Six Sigma green Belt holder. Prior to Joining Sterlite worked with GMR Energy, Reliance Energy.

An Innovative Solution for Online Testing of Power Transformers

Manohar Singh, Vishnuvardhan. Telukunta & K.S Meera
Power Systems Disvion
Central Power Research Institute
Bangalore-560080
manoharsingh.cpri@nic.in

Abstract— Type tests are essential to assess short circuit capabilities of transformer windings. The mechanical durability of power equipment is also checked against the mechanical forces developed during their making/breaking short circuit operations. These tests are generally carried out in indoor transformer test laboratories. Testing of Power Transformer for size more than 200 MVA in 765/400 kV class in an indoor laboratory is not economical due to huge investment in procurement of special short circuit testing generator. Power transformer manufacturer are making the power transformers size up to 630, single phase MVA rating. The strong short circuit fault feeding capabilities of the national grids can be utilized for testing these transformer in online manner. However, this may affect the grid operation/control during weak grid operating conditions.

In India, National High Power Testing Laboratory is established for testing power transformer of the order of 630 MVA single phase. This is a unique testing online test facility for testing of 765 kV class power transformers. An offline simulation has been carried out to assess the impact of online testing on the Indian National grid. The simulated results are cross checked with field result and based on confidence gained from the simulation & field results, the safe rating of the power transformer for online testing has been decided during the commissioning of the laboratory.
.

Keywords—power transformer, voltage drop, dynamic stability, protection and online testing**.**

I. INTRODUCTION

Types test of Power transformer are performed in the standalone high power test laboratory [1]. These laboratories are located across the globe like Central Power research institute (India), KEMA (Netherland), CESI (Italy) and KERI (South Korea) Erection of high power standalone laboratory for testing of power transformer for 400kV and above class is not popular due to involvement of huge investment. In few of the European counties like CESI Italy, the short circuit strength of the national grid is utilized for testing of the transformer in online mode. If the available short circuit of the grid is low, like in small countries, the online testing widely affects the power quality and nearby connected customers are severely affected. However, dedicated and sectionalized testing bays may suppresses the impact during online testing, but if the test specimen is in 400 kV or 765 kV class of voltage rating and of order of 500 MVA, the impact is unavoidable and may lead to a serious threat on the operation and control of the relative smaller national grid [2].

Indian grid is largest operational synchronous grid in the world with 330 Gigawatt (GW) of installed power generation capacity as on 30 June 2017 [3]. This huge synchronous generation results in availability of high short circuit fault MVA. Although the availability of highest fault MVA in a national grid depends on the location and outage of generating units/lines. A detailed survey has been carried out and it is observed that Bina 765kV and 400 kV substation (S/S) which are located at Bina, Madhya Pradesh in Central India has highest short circuit availability [4]. Details are given in Table 1.

Table 1: Short Circuit Levels at Bina S/S.

Bus Voltage	3-Phase Fault		
kV	Short circuit current (kA)	Short Circuit Power (MVA)	Actual Source Impedance Zs(Ω)
BINA765	25.59	33906.24	17.26
BINA400	32.82	22737.7	7.04

The availability of this huge MVA of order 34 000 at 765 kV & 23000 at 400 kV encourages the test engineers for establishment for online high power laboratory. This online test laboratory is intended for testing of power transformer in 765 kV and 400 kV class of rating upto 630 MVA without affecting the operation and control of the Indian national grid. Although the required short circuit power for testing of 765 kV and 400 kV class transformers is 83500 MVA and 40,000 MVA. So that, it should not create any observable impact the standard short circuit test source [5].

The eq. (1) describes the transformer test current (i_{ts}) at no load test voltage (u_t) calculated as per IEC 60076-5 [5].

$$i_{ts} = \frac{u_t}{\sqrt{3}} * \frac{1}{(z_{st} + z_{tr})} \qquad (1)$$

Where z_{tr} is transformer impedance in Ω and z_{st} is short circuit impedance of standard short circuit power in Ω. If the test current drawl from the national grid its one tenth of the three phase short circuit fault level, then the testing impact on the national grid may not be severe [5].

Therefore it is vivid, the proposed online testing laboratory has presently not sufficient available short circuit power for testing of power transformer in rating of 500 MVA and above in 400 kV and 765 kV voltage class. The available short circuit MVA is in the range of 34000 MVA for 765 kV and 23000 MVA for 400kV voltage levels.

II. ONLINE TESTING OF POWER TRANSFORMER

A) Methodology

In online testing laboratory, the national grid is the only source of required short circuit power. This short circuit power is utilized to test the power transformers. Single and three phase Power Transformer are most common for voltage transformation/power transmission at higher voltage ratings and their popular ratings are listed in Table.2 [6].The percentage impedance (Z), primary/secondary (U1/U2) voltage level, and no load test voltage at supply side (u_t) are also listed in Table.2 below..

Table. 2. Test Transformer Details

Transformer ID	Transformer Details				Test Parameters	
	Three phase Bank MVA	Individual Rating MVA	U1/U2 (kV)	% Z	No. of phases	u_t (kV)
T1	BINA 400	615	615	400/220/33	12.5	3
T2	BINA 765	630	210	765/400	12.5	1
T3	BINA 400	1500	500	400/765	14	1
T4	BINA 765	1500	500	765/400	14	1
T5	BINA 400	1890	630	400/765	14	1
T6	BINA 765	1890	630	765/400	14	1

From Table 2, it is observed that 630 MVA is the highest rating transformer manufactured in India in 400 kV as well as 765 kV voltage class [7]. As per transformer testing standard IEC 60076-5, any voltage class can be tested from higher available grid voltage level. i. e 220 kV & 400kV class transformer can be tested from 400 kV or 765 kV grid supply respectively [5] The test arrangement is shown in Fig.1. Fig 1(a) is testing scheme for three phase star/delta transformer by using three phase single equivalent test scheme and Fig 1(b) is single phase testing scheme for single phase transformer [6].

If the available short circuit power from grid is at higher voltage level than the test equipment voltage rating, then this surplus voltage is dropped across the additional series reactor banks (x_{ad}) as shown in Fig.1. This x_{ad} also controls the short circuit current feeding the lab. The values of the x_{ad} is calculated based on the test current (i_{ts}) requirement at supply systems voltage (u_t).
Three phase single equivalent test scheme as shown in Fig.1 (a) is popularly used for testing of higher voltage rating three phase transformers [5]. For two phases of test equipment (b & c phases) are shorted and then connected across phase to phase grid supply. The secondary of the test specimen is phase to phase short circuited. Impedance offered by the test transformer ($z_{tr}^{/}$) will be 1.5 times of transformer rated impedance. The value of x_{ad} is obtained as per Eq. (5). $Z_{tr}^{/}$ is z_{tr} on grid supply voltage.

$$z_{tr}^{//} = 1.5 * z_{tr}^{/} \quad (3)$$

$$E_a - 2*z_s*i_{ts} - 2*x_{ad}*i_{ts} - z_{tr}^{//}*i_{ts} \quad (4)$$

$$x_{ad} = \frac{E_a}{2*i_{ts}} - z_s - \frac{z_{tr}^{//}}{2} \quad (5)$$

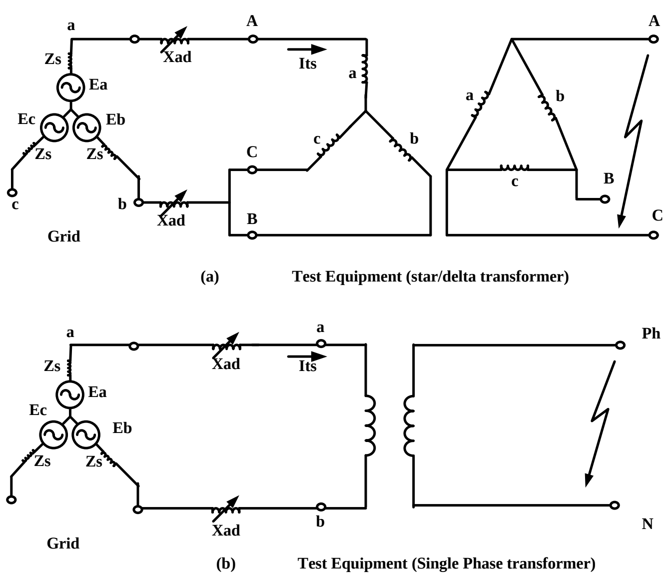


Fig.1 Testing Arrangement

In case of single phase transformer testing as shown in Fig.1 (b), x_{ad} is calculated as per in Eq. (6)

$$x_{ad} = \frac{E_a}{2*i_{ts}} - z_s - \frac{z_{tr}^{/}}{2} \quad (6)$$

As per the power transformer testing standard IEC 60076-5, the actual test current during testing should be within tolerance of 5% of i_{ts} [5]. x_{ad} is also utilized for tuning of the actual test current and test voltage requirements..

B) Grid Impact Assessment

Short circuit withstand tests are carried out for a duration of 250 msec as per the IEC 60076-5. During this interval, the national grid will experience an intentional disturbance. This disturbance may lead to an almost line to line fault condition at grid connected bus, if the test specimen fail [8] (as the impedance offered by test specimen is zero during failure and the value of the additional impedance is also generally low). If these testing conditions remain unattended for a longer duration, it may lead to instability of local generating stations. Therefore adequate protection is designed at lab site to disconnect the testing bay from the national grid immediately after completion of test duration of 250 msec. The designed protection scheme should operate before 350 msec under worst condition considering relaying and circuit breaker operating time of 100 msec [7].

In the proposed online testing laboratory, it is proposed to test the power transformer of rating upto 630 MVA both single phase and three phase, for a test duration of 250 msec. In 2015, the available grid strength was 23,000 MVA& 34000 MVA at 400 & 765 kV buses, which is lesser than the standard short circuit MVA as per IEC 60076-5. Therefore testing of dominant transformers test cases (Transformer ID mentioned in Table.2) with substandard grid condition may affect the voltage stability and rotor angle stability of the nearby synchronous machines during 250 msec test duration or prior activation of set protection scheme [9].

The online testing impact is analyzed in term of bus voltage drop in local area buses & rotor angle recovery of nearby synchronous machines. The magnitude of bus voltage drop may affect/disturb the operation of the electrical drives connected with the local area transmission network [10]. As shown in Fig.1, the online testing for higher rating transformers are mostly done from phase-phase energization from the national grid and this may lead to unbalance in line voltage of the affected phases in the grid. Oscillation in the rotor angle behavior of local area machines is also analyzed and it is observed that there is a direct non-linear relationship between the quantum of short circuit MVA drawn from the grid and swinging of rotor angle.

Voltages and rotor angles of local network generators are widely affected, when the test specimen fails during testing and this leads a direct line to line short circuit fault at the grid bus based on the available x_{ad}. The behavior of grid bus voltage and rotor angle swinging of generating units located close to the laboratory connection bus are observed in offline studies and results are discussed in the simulation results section in this article. It is observed that oscillation in the bus voltage and a sharp deviation in the rotor angle may lead to grid dynamic instability if disturbance is not cleared within minimum fault clearance time, which is 100 msec as per Indian Grid planning criteria [11]. Therefore this is unavoidable in the online testing laboratory where test duration should not be less than 250 msec.

C) Proposed Methodology.

In this research article, a methodology is devised for safe testing of the power transformer without compromising the grid stability. The minimum value of short circuit power drawl from the national grid is identified so that it should not lead to any grid instability during online testing and even if test specimen failed. x_{ad} can limit the short circuit current and the short circuit power drawn by the laboratory from the grid. Depending on the requirement of the test specimen, x_{ad} value will change as per Eq. (5) and Eq. (6).

The calculation of test parameters is an offline process. Before testing of each test specimen, the laboratory operator will request for a power test window to the local grid operator. Then based on the request, national load dispatch center (NLDC) will assess the state of the available short circuit at lab connection bus through phasor measurement unit (PMU). If the available grid strength (SCMVA) is more than minimum required SCMVA, NLDC will issue command to western region load dispatch center (WRLDC) for closure of network laboratory tie line circuit breaker [12]. Before closing tie line circuit breaker the setting of the protection scheme at laboratory side as well on grid side will be reviewed/updated as per test current requirement of each test specimen. A careful observation of primary and backup protection is essential, else if primary protection system fails, it may affect the complete National grid. One level away local grid network is shown in Fig. 2(a), thick shaded buses are 765kV buses and remaining are 400kV buses. The single line diagram of the laboratory connectivity is shown in Fig. 2(b). This includes master breaker (MB) and backup unit (BU) breaker operated by main and backup protection schemes.

The block diagram of online test laboratory from 400 kV test bay and its timing diagram for operation protection scheme is listed in Fig.2(c) below. The laboratory is protection at four zones i.e. Test equipment protection, bus bar protection, feeder protection and protection of grid side. Over current relaying based protection is used at equipment protection, differential protection for bus bar and feeder protection and differential as well as distance relaying for grid protection [13].

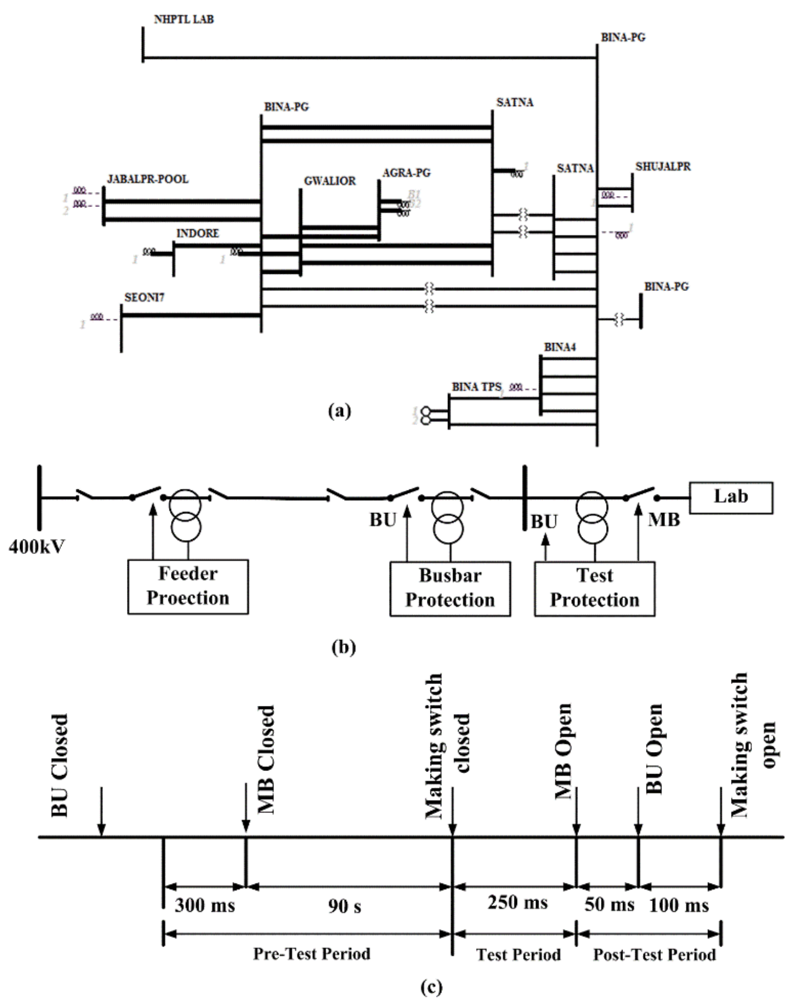


Fig.2 Lab testing and protection system (a) Local Grid Network connected with national high power testing laboratory(NHPTL) (b) Single line diagram of laboratory connectivity (c) Main & backup Protection scheme

If during testing test equipment fails the grid side circuit breaker are opened almost instantaneously and laboratory will be is disconnected from the grid. Otherwise, after successful completion of the test at 300-350 msec to avoid the grid disturbance [14]. The pre-test period corresponds to energization of lab, then test specimen remain under test for 250 msec and laboratory is disconnected from grid during post test period as shown in Fig.2(c).

III. SIMULATION RESULTS

A) Steady State Analysis

Simulation studies are carried out by modelling the complete Indian grid as dynamic model. The grid consisting of large no. of the generating units of installed capacity of 330 GW, highly interconnected a. c transmission lines of 765kV, 400 kV, 220 kV, 132 kV & ± 500 kV direct current lines, capacitor banks, reactor banks, interconnecting, power transformers and loads. These load are modelled at static/dynamic loads at outgoing of 220 kV and 132 kV feeders.

As discussed in the grid impact assessment subsection of section-II, the steady state voltage drop is evaluated for the grid laboratory node (Bina PG 400/765 kV bus). During the testing of most demanding cases (drawing high short circuit current) are listed in Table 2, percentage voltage drop at Grid connected bus Bina PG 400kV are listed in Table 3. During testing if equipment fails, it draws more short circuit current (i_{tsf}) and bus voltage drop further will increase. Percentage voltage drop and short circuit current drawl during equipment failure are also given in Table 3.

Table 3 Bus voltage drop at Grid connected bus

Transformer ID	During Testing			During Testing Equipment failure	
	i_{ts} (kA)	x_{ad} (Ω)	Voltage drop (%)	i_{tsf} (kA)	Voltage drop (%)
T1	3.42	7.65	9.41	18.41	64.89
T2	3.59	30.93	13.56	7.94	34.56
T3	12.2	1.93	42.65	22.3	78.83
T4	7.17	8.55	31.04	14.82	66.93
T5	14.57	0.765	51.37	25.64	90.41
T6	8.77	4.68	38.58	17.43	78.85

Most of the power transformer are tested as per line to line test arrangement shown in Fig.1 and this will lead to large line to line voltage unbalance in the grid. During testing of 500MVA single phase transformer from 400kV and 765kV side, the percentage dip in the Bina PG 400kV and 765 kV bus voltages are shown in Fig.3 for full grid strength, depleted and test equipment failure conditions. Here equipment fails at 100msec during the 250msec testing period. The different grid condition corresponds to a few line outage scenario resulting in depleted grid (1) and depleted grid (2) conditions and corresponding available grid short circuit are listed in Table. 4.

Table.4 Depleted Grid operating conditions

Grid Strength	Lines Tripped	No of Circuits tripped	Grid strength @ 400kV Bina Bus	
			Short circuit current (kA)	Short Circuit Power SC (MVA)
Full Grid strength	Nil	Nil	32.82	22737.70
Depleted Grid(1)	BINA PG 400-SATNA 400	2	30.78	21325.01
Depleted Grid(2)	JABALPUR 756-BINA PG765	1	27.48	19038.70

	SEONI765-BINA PG765	1		
	GWALIOR765-BINA PG765	1		
	AGRA PG-GWALIOR765	1		
	SUJALPUR400-BINA PG 400	2		
	BINA4 400-BINA PG 400	2		

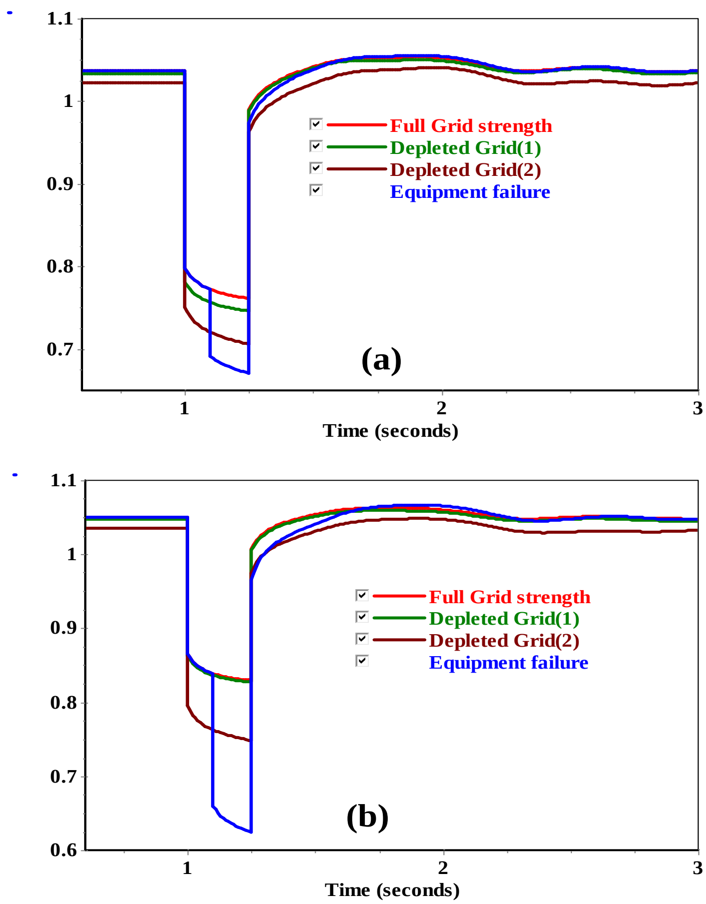


Fig 3: Bina Bus voltages during 500MVA single phase transformer testing (a) 400kV (b) 765kV side.

B) Dynamic Analysis

As reported in above section in Table 3, steady state voltage drop values are higher than permitted limits. Since it is a laboratory of national importance with the aim to test most common standard rating power transformers. Dynamic stability studies are carried out to see the behavior of the rotor angle of the nearby generating units [15]. There are three generating stations, (a) Bina TPS (b) Nigri and (c) Vindhyachal near to the proposed Testing laboratory. The behavior of the rotor angle is observed for different grid short circuit scenarios as well as for normal and test equipment failure testing conditions.

The behavior of the rotor angle for worstly affected Bina TPS (closer to online test Lab.) generator is observed in simulation and plotted in Fig.4 (a), when 500MVA single phase transformer is tested from 400 kV test bay. It is observed that, when full grid capacity is available to NHPTL from WRLDC for testing and test specimen also passes the test(normal test condition), the rotor angle oscillation are well damped and settles to pre-test steady state value within 50 msec after completion of test. The behavior of rotor angle is consistent for all the four testing conditions, i.e. normal test condition, depleted grid (1), depletion grid (2) and test specimen failure. However, recovery of rotor angles of Bina PG is delayed for depleted grid conditions and equipment failure cases [16]. The behavior of rotor angle for Bina TPS are also observed for testing from 765 kV test bay and is plotted in Fig.4 (b). It is observed that rotor angle recovery is not in consistent for depleted grid (2) and test specimen failure as compare to respect to full grid capacity.

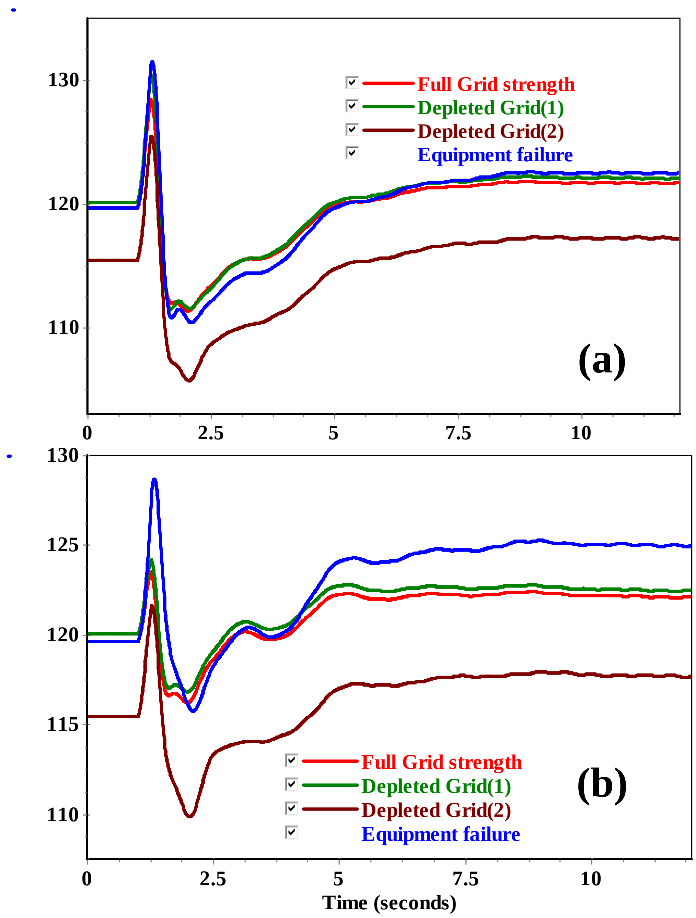


Fig 4 Bina TPS generator rotor angle during testing of 500MVA single phase transformer (a) 400kV (b) 765kV

Fig. 4, above does not indicates loss of network transient stability. Since the Indian grid experienced a grid blackout in July 2012. Indian grid operator, central transmission utility and central electricity authority are of the firm opinion, since it is an online testing facility, there should be fool proof mechanism to avoid any direct short circuit fault condition on the grid network during online testing of transformer in addition to main and backup protection schemes . Therefore as discussed in proposed methodology, x_{clc} is identified. This ensures a safer value of series reactor even the test specimen fail during the online testing. This safer x_{clc} is identified by simulating a series of line to line fault in online lab with increasing value of series reactor as shown in Fig.5. In Fig.5, Bina TPS rotor angle diverge for a $x_{ad} \leq 0.5\ \Omega$ and it well recovered for $x_{ad} \geq 2\ \Omega$. From Fig.5, it is concluded that all power transformer can be tested in the proposed online test lab for which the required $x_{ad} \geq 2$, i.e. value of which the x_{clc}=2.0 Ω can be tested from 400 kV testing bay. However, this value is 4.8Ω for testing from 765 kV testing bay. The finalized pre-requisite criteria for online testing of power transformer is shown in Fig.6. The outer zone represents the transformers and different grid operating condition. Middle layer corresponds to the test cases which are meeting the actual test current in laboratory within ±5% of accuracy desired test current. The inner most layer represents, the transformers that can be safely tested without compromising the grid stability.

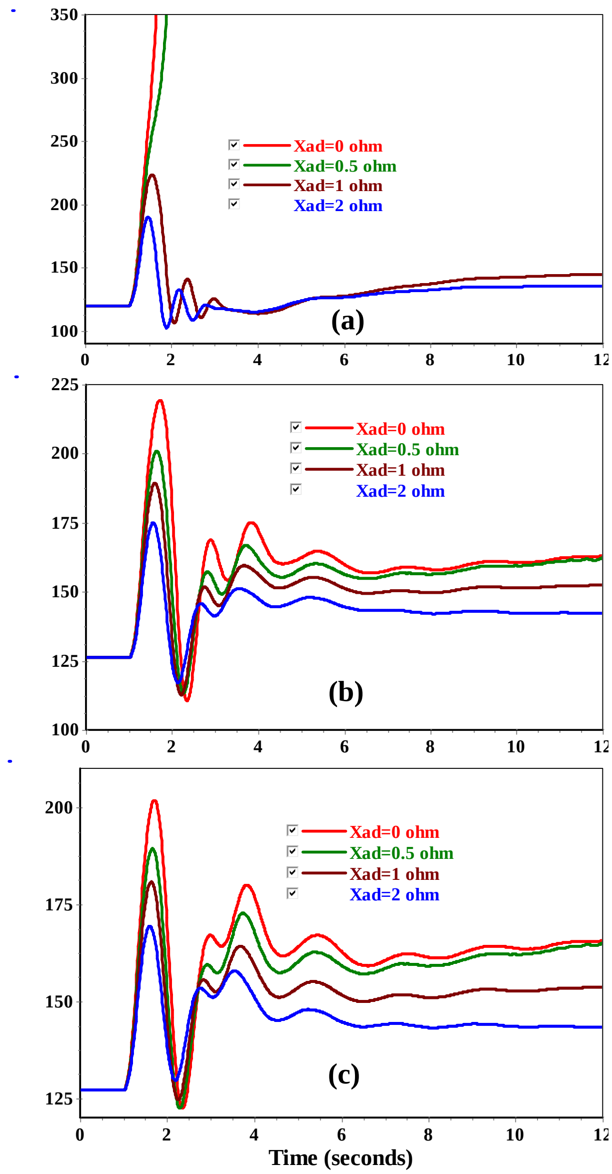


Fig.5. Variation of rotor angle for various value of x_{ad}

(a) Bina TPS (b) Nigri (c) Vindhyachal

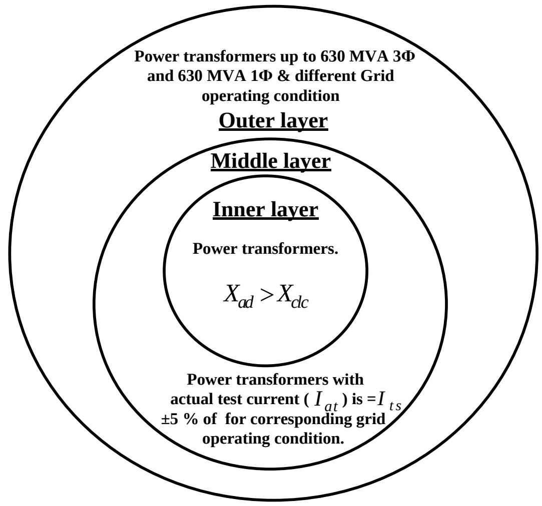


Fig.6. Finalized pre-requisite online test criteria

Considering above pre-requisite, from the simulation studies it is concluded that all single phase power transformers below 500 MVA rating can be safely tested from 400 kV test bay at full grid strength. Similarly, online testing of single phase transformer below 630 MVA is also possible from 765 kV without compromising the grid stability. The cut off test rating for other grid operating condition is also listed in Table.5

Table 5. Cut off transformer test cases.

Test Bay	Grid Strength	X_{clc}	Venerable Test MVA Rating (= >)
kV	kA	Ω	MVA
400	Full Grid	2.0	500 – 3ph& 1-ph
	Depleted Grid(1	4.0	315- 3ph&333.3 1-ph
	Depleted Grid(2)	7.0	200-3 ph& 333.3 - 1-ph
765	Full Grid	4.8	630- 1-ph
	Depleted Grid(1	4.8	630- 1-ph
	Depleted Grid(2)	6.0	500, 630- 1-ph

The effect of online testing is also evaluated for the nearby power customer (Bharat Oman Oil refinery Ltd. (BORL)) connected with the distribution utility drawing power from the laboratory confection point of the transmission utility. BORL consists of drives working at 33/11/6.6/0.433 kV level. In simulation & field results, it is observed/recorded that voltage drop at terminal of these drives is around less than 5% and their operation is not affected.

IV. FIELD RESULTS

Based on the confidence in the simulation results on the impact of online testing on the grid, NHPTL went ahead with pre-commissioning activities of the proposed laboratory. By performing the online testing of three phase, 315 MVA rating of Auto transformers (Test Case Id T1). The field results in terms of test current drawl and voltage drop at 400 kV test bay are recorded by disturbance recorder (DR) located on laboratory & Grid interconnection point. During testing the test transformer is failed due to technical problems and these results are also recorded by the DR. The filed results recorded by relay DR are extracted in the Simulink and DR captured results are shown in Fig.7 for testing of T1 test transformer. The captured Bina 400 kV Bus voltage signals are compared against the corresponding simulated results as shown in Table 6. It is observed that both the results are in close concurrence. This indicates the accurate modelling of a vast Indian grid and gives immense confidence on the simulation results to power systems study team and other shareholder involved in commissioning of this online testing laboratory. The status of the enabled protection schemes is also captured from DR. The status of relay trippings are captured during 250 msec test duration and shown in Fig 8.

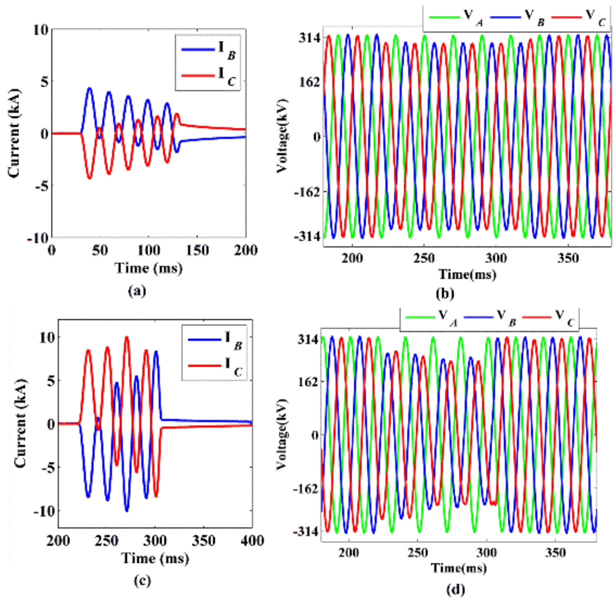


Fig 7 Results for 315 MVA Transformer (a) Calibration Test current (b) Calibration Bina PG DR captured result - Bina PG 400kV bus voltage drop (c) DR captured Test current during failure (d) DR captured - Bina PG 400kV bus voltage drop during failure.

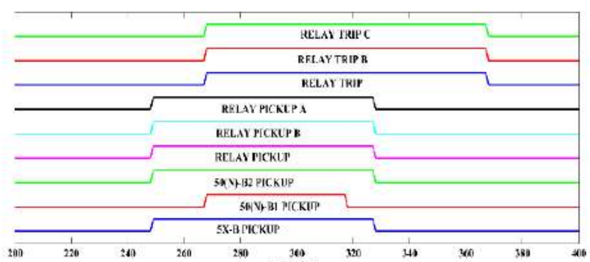


Fig 8. DR captured – Digital Relay Tripping Signals

Table 6. Comparison of Simulation and online NHPTL Lab test results

Test specimen	Shot no	I_{ta} (kA)	I_{ts} (kA)	ΔI_t %	DR %voltage drop	Simulated %Voltage drop
T3(During Testing)	1	3.42	3.19	6.72	10.13	9.41
	2	3.42	3.52	-2.9	11.74	9.41
	3	3.42	3.33	2.63	10.04	9.41

V.CONCLUSION

The proposed online testing facility is unique in nature for testing of upto 765 kV class power transformers. The huge short circuit capacity of the Indian grid is utilized for feeding the short circuit power to the test equipment during the test period. The huge short circuit power drawl during online testing from the grid will affect its operation and nearby connected power customers. A detailed steady state and dynamic simulation studies are carried out for assessing the impact of online testing on the Indian national grid. The steady state voltage drop, voltage recovery and rotor angle recovery of nearby generating units during extreme test conditions is evaluated and observed. Based on the detailed grid stability analysis, a critical series impedance value is identified for a defined grid condition. This critical series impedance value ensures the grid stability during extreme online test conditions.

The simulated results are cross checked with field results. Based on confidence gained from the simulation & field results, the safe rating of the power transformer for online testing has been decided during the commissioning of the laboratory. This online testing activity involves test laboratory team, grid operator and central transmission utility. Therefore, a coordinated online testing scheme has been proposed in this research article, which will monitor the state of the grid through local PMU installed at laboratory site. Depending on the required available short circuit capacity, the grid operator will allow test team to conduct the online testing in the laboratory.

The commission this unique test facility as outcome of this study and innovative approach is a direct contribution to Indian power sector and it will serve as benchmark for establishment of similar laboratories in India and aboard.

ACKNOWLEDGMENT

The work presented in this article is a part of the consultancy work carried out for impact of online testing on the grid, NHPTL. Author(s) are highly thankful to the *NHPTL* for their support for providing the actual network data.

REFERENCES

[1] www.cpri.in, 'Testing & certification'. [Online].Available: http://www.cpri.in/about-us/departmentsunits/high-power-laboratory-hpl.html.

[2] F. Wenli, L. Zhigang, H. Ping, and M. Shengwei, "Cascading failure model in power grids using the complex network theory," IET Generation, Transmission & Distribution, vol. 10, no. 15, pp. 3940–3949, Nov. 2016.

[3] www.cea.nic.in, 'Reports'. [Online]. Available: http://www.cea.nic.in/monthlyinstalledcapacity.html

[4] www.nhptl.com, [Online]. Available: http://www.nhptl.com/aboutus.html#abou1.

[5] "Power Transformers, Part-5-ability to withstand test". International Standard IEC 60076-5,

[6] ABB, "Testing of Power Transformers", Zurich, 2003.

[7] "Assessment of the impact of the High Power Laboratory into POWERGRID Network", CESI report, Feb 25 2010.

[8] D. Geißler and T. Leibfried, "Short-Circuit Strength of Power Transformer Windings-Verification of Tests by a Finite Element Analysis-Based Model," in IEEE Transactions on Power Delivery, vol. 32, no. 4, pp. 1705-1712, Aug. 2017.

[9] Prabha Kundur, Neal J. Balu, Mark G. Lauby "Power System Stability-Chapter 14 &15," Power System Control and Stability, 2009.

[10] G. Didier, J. Leveque, and A. Rezzoug, "A novel approach to determine the optimal location of SFCL in electric power grid to improve power system stability," IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 978–984, May 2013.

[11] Report by CEA, “Manual on Transmission planning criteria”, Central Electricity Authority, India, 2013.
[12] www.posoco.in, ‘Functions of NLDC’, [Online]. Available: https://posoco.in/about-us/functions-of-nldc.
[13] D. M. E. Ingram, P. Schaub, R. R. Taylor and D. A. Campbell, "System-Level Tests of Transformer Differential Protection Using an IEC 61850 Process Bus," in IEEE Transactions on Power Delivery, vol. 29, no. 3, pp. 1382-1389, June 2014.
[14] E. Dmitrova, M. L. Wittrock, H. Johannsson, and A. H. Nielsen, “Early Prevention Method for Power System Instability,” IEEE Transactions on Power Systems, vol. 30, no. 4, pp. 1784–1792, Jul. 2015.
[15] S. Zhao, H. Jia, and D. Fang, “Partition-composition method for online detection of interconnected power system transient stability”, IET Generation, Transmission & Distribution, vol. 10, no. 14, pp. 3529–3538, Nov. 2016.
[16] E. A. Mohamed, Y. Qudaih and Y. Mitani, "Power system stability improvement using STATCOM and RSFCL during grid faults," 2016 19th International Conference on Electrical Machines and Systems (ICEMS), Chiba, 2016, pp. 1-6.

Dr Manohar Singh, manoharsingh@cpri.in,9632940855

Vishnuvardhan. Telukunta, vishnu2459@gmail.com , 9550297373

K.S Meera, meera@cpri.in, 9972854950

Unmanned Aerial Vehicle (UAV) Enabled Stringing

Author	**Sandesh Mishra**
Contact No.	**09871116049**
Email	**m.sandesh@gmail.com**
Place	**New Delhi**

Index

Topic **Page No.**

Annexure

Bibliography

- http://www.circuitstoday.com
- UAS Safety and Risk Management by University of California

About the Author

Sandesh Mishra is an experienced power sector professional. He has worked in Power Generation, Transmission, Mining and Aviation Sectors in companies like Bharat Aluminium Company Limited, Vedanta Aluminium Ltd. & Sterlite Grid Ltd. He has successfully handled various profiles of sourcing, commercial, purchase, business development, business excellence and aviation in his career. He is currently associated with Arcturus Business Solutions where he is also a Consultant to Maharashtra Electricity Regulatory Commission.

His basic qualification includes Production Engineering from NIT Jamshedpur and MBA(Operations and Marketing) from Symbiosis, Pune . He has successfully completed EXIM Certification Course from IIFT- New Delhi, Contract Management & Public Procurement from World Bank (MooC). He can be reached at m.sandesh@gmail.com.

Executive Summary

With robust economy growth and Govt of India "power for all" policy initiative, installed capacity of generation across India has crossed 330 GW. In order to ensure reliable power from the generation hubs in the country to the demand centres, major augmentation schemes in transmission network is being planned and executed. Fast transmission project execution is the need of present time which always faces geographical constraints (hilly or inaccessible area) and Right of way problems. The pace of mechanisation in transmission project execution (specially stringing) is slow and the domain is still dominated by manual process which in turn raises safety challenges.

Transmission line stringing process, which is executed manually in India, consumes almost 45 % of the total project execution time. The project timelines are usually uncertain due to manual process, safety constraints and RoW encountered in the execution timeframe. Expensive helicopter stringing which increases safety and reliability of project execution is a dominant practice outside India. Indian exposure to helicopter stringing is less due to its high cost. The research is dedicated to find a reliable alternative to expensive helicopter stringing, which can potentially increase safety in the project execution.

Unmanned Aerial Vehicle (UAV) is one of disruptive technology which is explored in this paper for facilitating transmission tower stringing in different terrain. After finalisation of relevant technical specification of UAV and partnering with one of India's leading EPC , UAV enabled stringing were tested in three different geographical locations i.e Rajasthan, Sikkim and Himanchal Pradesh. Results were encouraging at all three location as usage of UAV saved time, resolved RoW problems and helped to cross live line crossing.

Though the current UAV regulations by Director General of Civil Aviation (DGCA) are not encouraging but still it is being felt that going forward UAV holds a promising future in executing transmission projects safely on time.

Need & Objective of the Research

India's GDP is growing fast, which is giving rise to increased industrial and commercial activities in the country. With the growth in economy, energy demand has also seen a healthy year on year growth. Demand of electricity in India has been continuously rising in the past and with Government of India's (GoI) initiative "Power for all", it is expected to rise further in coming years.

Currently the installed capacity in India's stands at more than 330 GW which is suitably matched on the transmission side. Indian national grid which consist of various transmission lines of 132/220/400/765 kV (3,80,402 ckm of transmission lines and 7,82,830 MVA of transformation capacity of Substations) is capable of transfer bulk power from the generation hubs in the country to the demand centres.

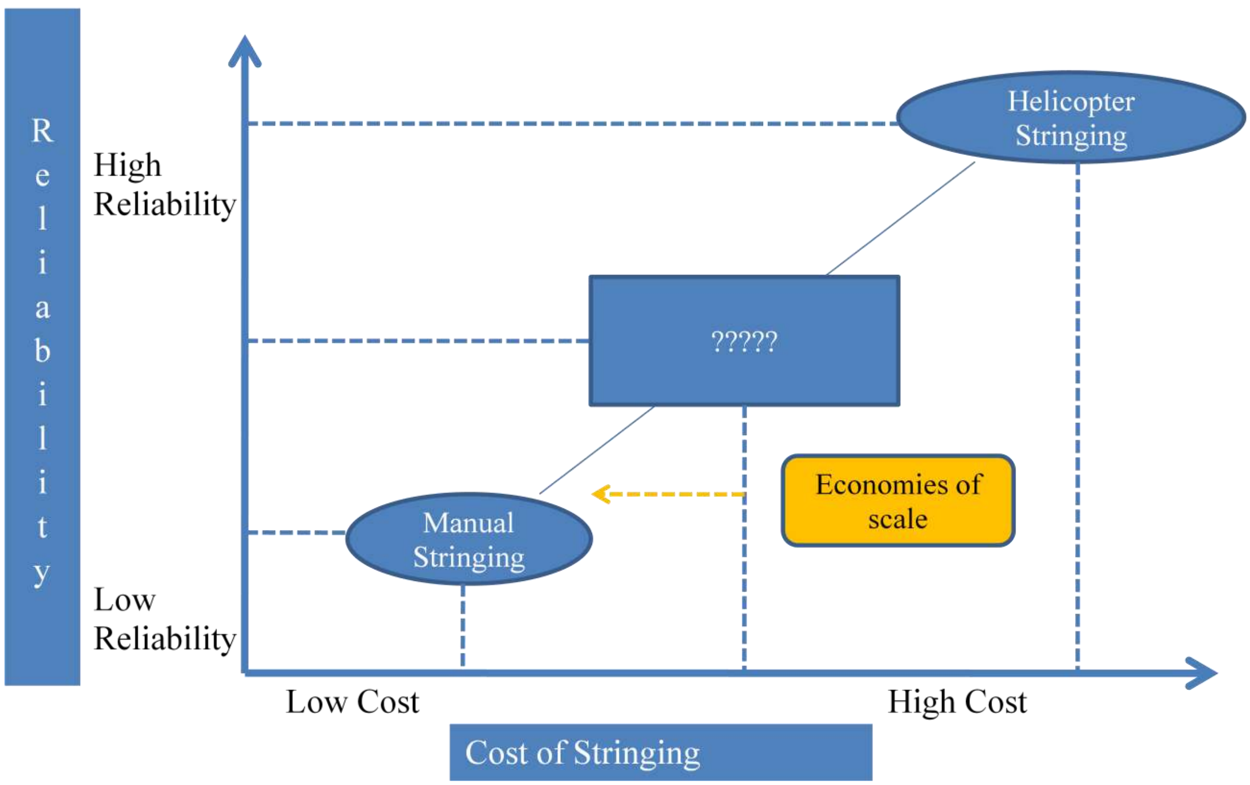
Ministry of Power (MoP) is now very aggressive, setting an ambitious plan of executing approx 14702 circuit km of new transmission lines project, during the period of April 2016 to Nov 2017. It is a pleasant fact that, with public and private developer's efforts, we have achieved nearly 95% of the target considering that more than 80% were EHV lines(400 kV and 765kV).

To cater the higher capacities, transmission lines are to be executed in a shorter time period. Traditional ways of execution (especially stringing) are still subjected to judgemental errors, time lag, land access and problem of RoW. Transmission Stringing traditionally is dominated by manual gang in India. Standard Operating procedure (SoPs) for stringing is fully documents by utilities. SoPs attached as Annexure -1 is given by UPPTCL as a reference.

Since this is a specialized manual skill set, there is always a scarcity of skilled gangs in absence of any systematic capacity building program. Stringing gang management is subject to supply demand game as capacity of such gang is not increasing but the number of project (demand) is always on the rise. Retention of manual gangs in event of RoW problems is also a bigger challenge. Manual gangs of stringing also are subjected to seasonal absenteeism (holidays of Durga Pooja, Chhat, pongal or extreme winter season etc) as most of gang members visits their home during various festivals. Moreover factor of safety for dare devil gang members of stringing is also worrisome. Above mentioned factors makes stringing activity "a task with high uncertainly".

Apart from manual stringing, helicopter is also employed for the stringing. Helicopter stringing, though expensive, is normally practiced in Europe and America where human resources are in shortage. Helicopter stringing becomes feasible in case of extreme terrain (hills, valley, snow clad mountains, rivers), heavy Right of Way(RoW) and inaccessible area like marshy land etc. It is also clubbed by heavy level of planning as every hour of helicopter flying cost irrespective of productive usage. Although pulling conductors directly from conductors is possible, maximum efficiency is achieved when pilot lines are pulled with the helicopter and conductor stringing is done in a conventional manner.

Manual and helicopter stringing does have its own merits and disadvantages. Major advantage for manual stringing is cost competitiveness and major advantage of helicopter stringing is reliability. The table below gives the clear idea where the both the methods varies on cost & reliability graph. The whole objective of the research is to find a third alternative which have both the advantages of cost and reliability. The most significant factor is checking the reliability parameter as cost shall come down in future with economies of scale in India.



Since it has been observed that when helicopters are used to connect the tower tops by pilot wire and rest process is completed conventionally, the hybrid process gives the maximum productivity in comparison to pulling conductor directly. The challenge is to find some cost effective aerial technology in the similar hybrid model which will retain high reliability without compromising safety in the process.

So the objective of this research is to find cost effective aerial technology which is reliable, safe and has less mobilization time as compared to helicopter. It would be better that the said technology should be non polluting and environmental friendly.

Introduction to Unmanned Aerial Vehicle (UAV) Technology

Unmanned Aerial Vehicle (UAV) Technology is one of the disruptive technologies which have huge potential to transform the way of working in various sectors. This technology helps us to collect precise data (which can be instrumental in decision making) , even in difficult terrain, with minimal human involvement virtually eliminating risk of injury to humans.

UAV also known as drones can be treated as "eyes and ears" in the sky to effectively and efficiently execute various tasks. Their capabilities allow them to:

- Quickly and easily capture images and videos that are typically difficult to obtain
- Perform well under challenging conditions such as inclement weather
- Enable organizations and people to share and analyze information in real time to make faster, more knowledgeable decisions.

Since UAV can be used to perform various niche functions faster and safely and it can be customized against each and every niche requirement, it is predicted that its usage shall increase in coming years.
Currently UAV are being used in the following sectors :-

- Thermal Power Plants, Transmission lines and Wind & Solar Power farms
- Oil & Gas, Gas pipelines
- Railways, Building & Bridges
- Precision Agriculture & Mining

In this paper , we intend to discuss the UAV usage in Power Transmission Sector.

UAV or Remotely Piloted Automated Vehicle (RPAS) can be classified on a different basis of application like Aerial Mapping, Surveillance & Photography etc. However, the common classification of UAV/RPAS(drones) can be made on the basis of aerial platforms. Based on the type of aerial platform used, we can broadly classify them under three categories:

1. **Multi Rotor UAV**
2. **Fixed Wing UAV**
3. **Hybrid VTOL UAV**

1. **Multi Rotor UAV -**Multi Rotor UAV are the most common types of drones which are used by professionals and hobbyists alike. They are used for most common applications like aerial photography, aerial video surveillance etc. Different types of products are

available in this segment in the market – say multi-rotor drones for professional uses like aerial photography .These are the easiest to manufacture and they are the cheapest option available as well. Multi-rotor UAV can be further classified based on the number of rotors on the platform. They are mainly **Quadcopter** (4 rotors), **Hexacopter** (6 rotors) and **Octocopter** (8 rotors).

Quad copter Hexa copter Octo-copter

They are easy to manufacture and relatively cheap. The prominent downsides being it's limited flying time, limited endurance and speed. They are not suitable for large-scale projects like long distance aerial mapping or surveillance. The fundamental problem with the multicopters is they have to spend a huge portion of their energy (possibly from a battery source) just to fight gravity and stabilize themselves in the air. At present, most of the multi-rotor drones out there are capable of only a 20 to 30 minutes flying time.

2. **Fixed Wing UAV** -Fixed Wing UAV are entirely different in design and build. They use a 'wing' like the normal airplanes out there. Unlike multi-rotor drones, fixed wing type models never utilize energy to stay afloat on air (fixed wing types can't stand still on the air) fighting gravity. Instead, they move forward on their set course or as set by the guide control (possibly a remote unit operated by a human) as long as their energy source permits.

Fixed Wing UAV

Most fixed wing drones have an average flying time of a couple of hours. Gas engine powered drones can fly up to 16 hours or higher. Owing to their higher flying time and fuel efficiency, fixed wing drones are ideal for long distance operations (be it mapping or surveillance). But they cannot be used for aerial photography where the drone needs to be kept still on the air for a period of time.

The other downsides of fixed-wing drones are higher costs & skill training required in flying. It's not easy to put a fixed wing drone in the air. It requires a 'runway' or a catapult launcher to set a fixed wing drone on its course in the air. A runway or a parachute or a net is again necessary to land them back in ground safely. On the other side, multi-rotor drones are cheap as compared to fixed wing. Flying a quadcopter doesn't require special training. Guiding and controlling a quadcopter can be learned on the go.

3. **Hybrid VTOL UAV-** These are hybrid versions combining the benefits of Fixed wing models (higher flying time) with that of rotor based models (hover). This concept has been tested from around 1960's without much success. However, with the advent of new generation sensors (gyros and accelerometers), this concept has got some new life and direction.


Hybrid VTOL UAV

Hybrid VTOL's are a play of automation and manual gliding. A vertical lift is used to lift the drone up into the air from the ground. Gyros and accelerometers work in automated mode (autopilot concept) to keep the UAV stabilized in the air. Remote based (or even programmed) manual control is used to guide the drone on the desired course.

Based on the complexity and usage UAV platforms can be chosen and it can also be customized on the following parameters :-

- Weight of UAV- Weight of UAV plays an important part in selection. As weight of the UAV is directly proportional to the complexity and features. As per DGCA's latest draft guideline in India, UAV or RPAS is classified under following weight categories:-

    - Nano : Less than or equal to 250 grams.
    - Micro : Greater than 250 grams and less than or equal to 2 kg.
    - Mini : Greater than 2 Kg and less than or equal to 25 kg
    - Small : Greater than 25Kg and less than or equal to 150 kg.
    - Large : Greater than 150 Kg.

  Less weights UAV are exempted from the taking flying approval but flying heavier UAV/RPAS requires complex set of procedure which is cumbersome and not Industry friendly.

- Payload :- It the cumulative weight of sensors/objects which a UAV can carry onboard.
- Max flight time :- Flight duration of multirotor UAV/RPAS is dependent on batteries so they can fly up to short duration of 30 min (average time). Fixed wing UAV uses gasoline or combustible fuel which increases flying time.
- Obstacle sensing sensors:- These sensors are quite helpful as they prevent UAV collision with an obstruction like over head line, asset etc
- Operating Frequency:- Normally operating frequency used in the UAV operation is the free frequency nominated by Dept. of Telecommunication (GoI).
- Visual Line of Sight- UAV though capable of operating on automated mode well beyond visual line of sight but DGCA in its current draft regulation allowed only visual line of sight flights only. In simpler terms, UAV operators can operate UAV/RPAS up to a distance where he/she can actually see the UAV. Typically it is 3-5 km.

Research Approach

- Identification of Cost Effective Aerial Technology: Scouting cost effective aerial technology which has a potential to enable faster project execution (especially stringing) was the major challenge. Unmanned Aerial Vehicle (UAV) Technology being one of the disruptive technologies, which have huge potential to transform the way of working, was chosen to check the suitability of application on the stringing landscape. This technology helps us to perform various niche functions faster and safely, even in difficult terrain, with minimal human involvement virtually eliminating risk of injury to humans. UAV technology was the solution which seems to be cost effective (as compared to helicopter) stringing) and reliable (as compared to manual stringing).

- Selection of UAV Many multi-rotor UAV having suitable payload were evaluated and finally UAV was customized along with sourcing of suitable guide wire. UAV for the stringing was customized on the consideration of mainly following parameters :-

    - Type of UAV – Multirotor (Hexa or octocopter)
    - Structure of UAV – foldable
    - Max Tax off weight - 12kg
    - Max payload – 3kg
    - Max flight duration – 25 min
    - Cruising speed – 0-10 m/s
    - Operating Temperature—0 to 50 degree C
    - Max Wind resitance – 12m/s
    - Maximum operating altitude – 3000 m
    - Hovering accuracy:-_Max 1.5 meter in the air and ability to re align itself on the same co-ordinates in the event of deviation from external factors(wind etc)

    Customized UAV was made ready along with commercial and non-disclosure agreement(NDA). A picture of UAV used for stringing is shown below

- Tie up with EPC contractor for live project: Many reputed EPC Contractors were approached for the live application. One of the EPC Contractors (name withheld due to confidentiality) agreed for the application of UAV in its live project. We did three trial projects in three different terrains to check the reliability and its potential usage in stringing.

- Work Methodology adopted

i. Preparation

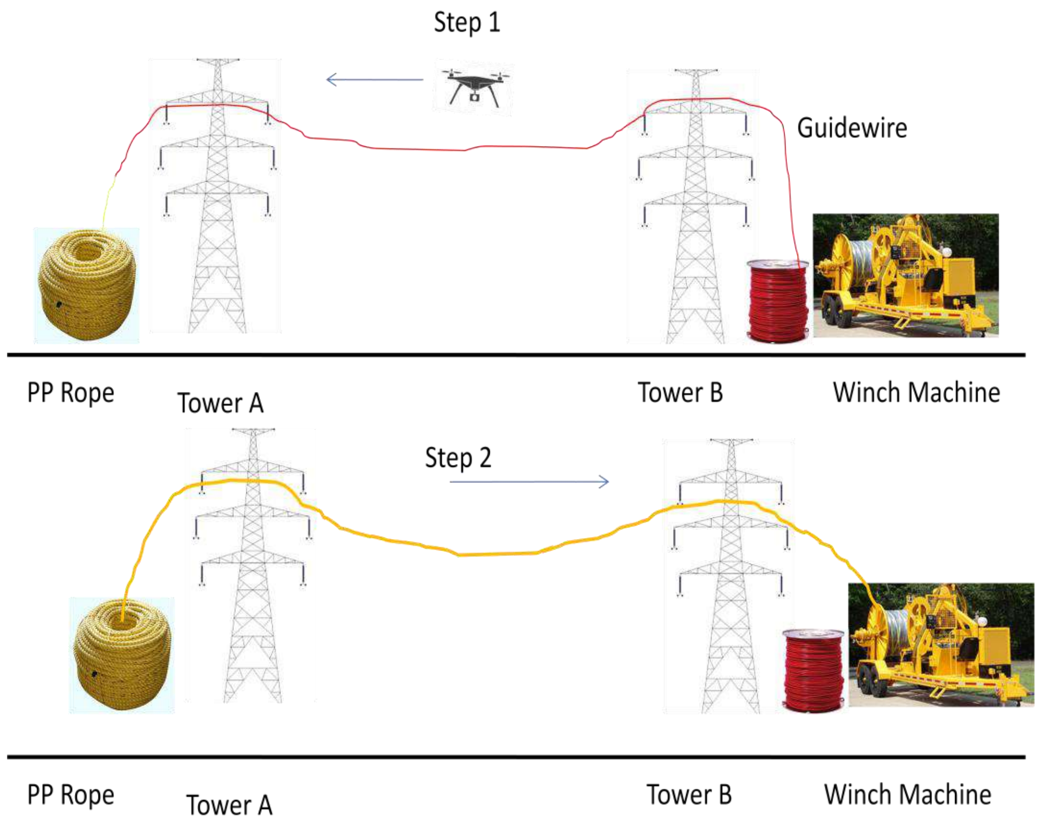
Construction material list arranged by EPC Contractor is :-

a. Winch (output power depends on the transmission line weight)
b. Pulleys
c. 12 mm of PP rope (min 2 bundles of 220 mtrs) for 1 span
d. Two-way radios (Min.1 set)
e. Preliminary data sheet for flight planning (Height of the towers, distance between towers, voltage of the transmission line, wind speed)
f. Plummet that could be tight up to the guide line (can be screw cap)

ii. Pre-flight checking

UAV Procedural Checking as per standard operating procedure and safety protocol. Safety matrix for the UAV is attached as Annexure – 2

iii. Work procedure



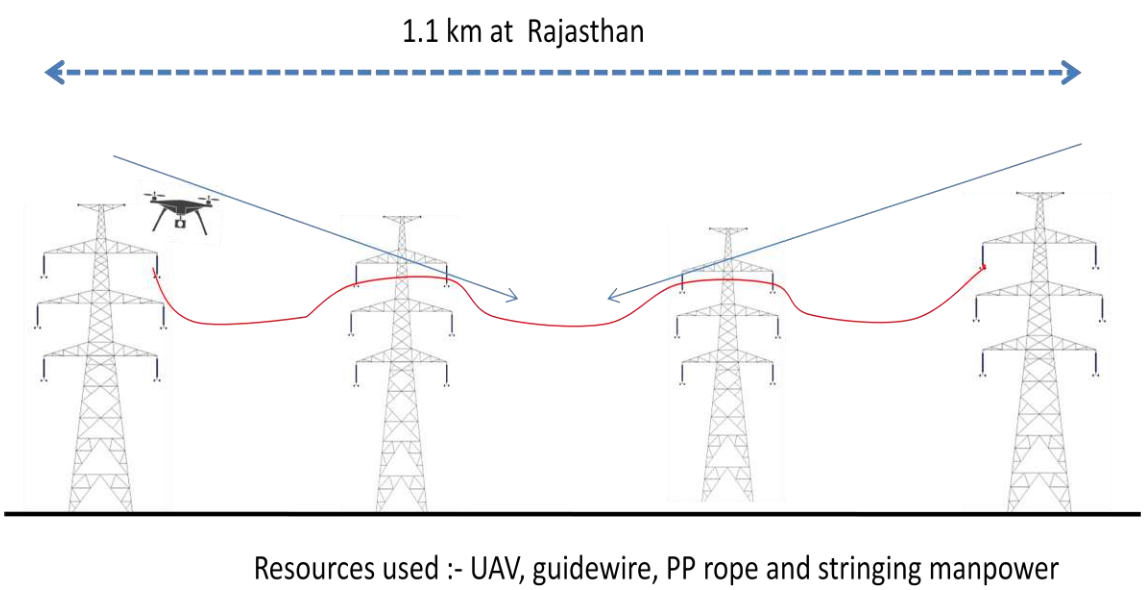
a) First plummet to be attached to the guideline.
b) Guideline was attached to the UAV
c) UAV flying over tower B to Tower A as shown in Step 1
d) UAV drops the guide wire on the Tower A and guide wire is tied to 12mm PP rope at Tower A end.
e) One end of guide wire ,near tower B, is fed to winch machine.
f) Winch machines pulls guide wire in Step 2 and strings PP rope between Tower A & tower B
g) Guide wire which is free, can be re-used in another span.
h) Pilot wire and Conductor can be pulled after the PP rope.

Field Testing – Proof of concept of ground

Three different terrains were chosen to check the applicability of UAV in the stringing process. Demonstration projects were done in

- ✓ Rajasthan (plain terrain) – It was a plain terrain and reliability of UAV enabled stringing were checked in the demonstration. Total span was 1.1 km. As per plan we were able to lay guide-wire rope on both phases of the section of 1100 meter consisting of 2 tension and 2 suspension towers.

  Total span was operated into two halves. UAV lifted off in between the suspension towers and went left to the last tension tower and transported the guide wire on the tower within minutes. Guide wire was passed from pulley and PP rope was attached to string the guideline back to original point of liftoff. Same process was repeated on the right side.



UAV lifted off from ground with guide wire:-

UAV dropping the guide wire on the tower.

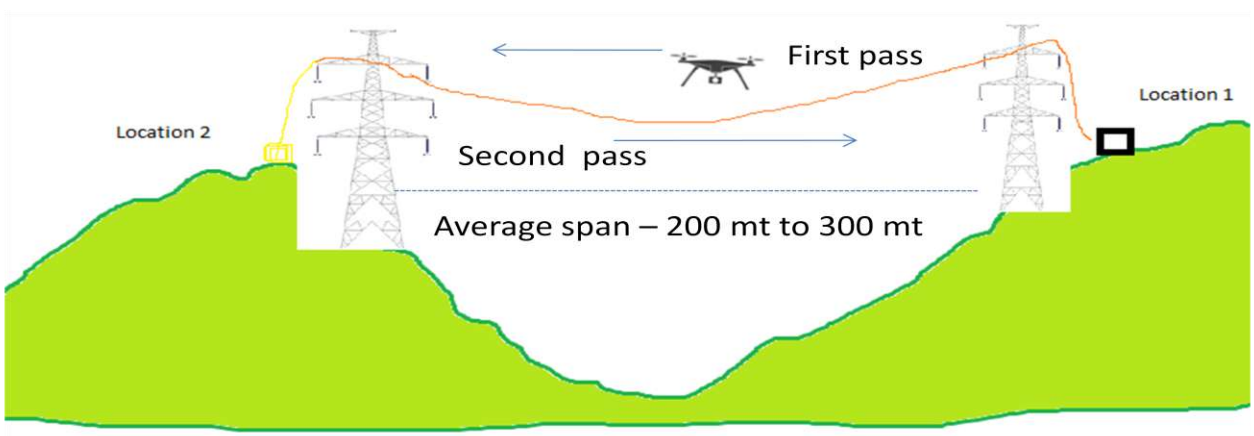
✓ Sikkim & Himanchal Pradesh (Hilly terrain)

Both sites have following issues

- Tedious terrain for manual gang

- Safety hazard and damage to the tools
- RoW issues due to damage to Crops (Apple orchard in H.P)
- Tree cutting and pruning requirement with conventional stringing

UAV carried guide wire from Location 1 to Location 2 in first pass and transported the guide wire on location 2. Guide wire was attached to PP rope at location 2 and winch was used at location 1 to string the guide wire and PP rope. PP rope was followed by pilot wire and conductor.



Hilly Terrain & valley at North East & HP

UAV in action in Himanchal Pradesh

Team which executed the demonstration successfully….

Observations & Learning

Following are the observations and learning from the UAV enabled stringing demonstration:-

- Crossing the span in minimum time - UAV has crossed the span within 2 min in plains and 5 min in the hilly terrain with guide wire. Manual paying out at hills, is a time consuming and unsafe procedure. Hours of manpower is saved and the task is performed within minutes.
- Normal pulley was a big constraint which limited the area of operation in spite of longer flying capacity of UAV in the plains.
- UAV with guide wire took 5 minutes to cross valley and hillocks in the hilly terrain and a connection was established between two towers by pulling PP rope with help of wench machine which eliminated human exposure with regards to safety.
- UAV enabled stringing is independent of tower erection as it can done in parallel with tower erection.
- UAV enabled stringing facilitated RoW resolution in Himanchal Pradesh as operation happened in air and apple orchards were not disturbed. Even the farmers were happy to see this technique which saved damages to their crops.
- Low LT lines were also crossed as the operation happened high in the air. Taking scheduled outages is becoming difficult so it can serve as a safe alternative. Due to insulation on guide wire it can be easily be used in various crossing like railway, river, power line etc.
- Tree pruning and tree cutting (damage to the environment) is also saved with using UAV based stringing as conventional stringing requires tree cutting and tree pruning as to save conductor damage during sagging.
- Guide wire is to be protected from rain (water) as it is extremely sensitive to the moisture and humidity. It losses strength when exposed to rain.

Based on various observation and learning from the field demonstration, a simple analysis is done for all three types of stringing on various parameters like cost, mobilization, statutory compliances, safety etc. Compilation of various parameters against all 3 type of stringing is given below:-

	Cost	RoW issues	Timeline (Reliability)	Mobilization	Tree cutting	Regulatory compliances	Safety
Helicopter Stringing	Very High	No	Certain	Long	Not required	Difficult	High
UAV enabled Stringing	Intermediate	No	Certain	Fast	Not required	Moderate	High
Conventional Stringing	Low	Yes	Uncertain	Fast	Required	Easy	Low

Conclusion

We have found that UAV enabled stringing can be very easily deployed and can be used in all project of hilly area as

- it reduces time,
- it increases mechanization,
- it increases safety & certainty
- it facilitate RoW resolution issues
- it can be used for crossings-like rivers, mountains, LT lines, railway lines etc.
- Initially commercial aspects of UAV enabled stringing seems to be a bit higher but cost will come down with economies of scale. Moreover gains coming out of using UAV are very high as it increases safety and certainty of project completion.

It is easily deployable in the plains with making some minor modification in pulley. With some more adjustment in the procedure, UAV can be potentially used to string a whole section rather than span. This will certainly increase the productivity and safety in stringing.

We have also found a project in SAARC country where UAV enabled stringing was used in a project and following were the result* :-

- Productivity Increase : 3 days work cut to 2 hours
- Projected Timeline Crashed : **2 months**
- ROW Challenge : Not encountered
- Cost Saving in Stringing : Almost **15%**
- Safety Hazards : Eliminated
- Protected Environment : Almost **50000 trees saved**

*This data is from the EPC Company which has worked in SAARC country (hilly terrain) also for the project. The concluding data also verifies the conclusion from the field demonstration and research.

Way Forward

Currently UAV are already used in various power sector's applications like UAV based coal volumetric estimation, UAV based power line inspection for defects & UAV based land survey etc. We expect that UAV utilization shall rise in near future as more and more niche areas of power sector like UAV enabled stringing.

Though the Director General of Civil Aviation's (DGCA) recent draft guideline on Remotely Piloted Aerial System (RPAS or UAV) released on 1st Nov 2017 was not favourable to the power sector, we expect that things will change when the companies in power sector will realise full potential of unmanned technologies. Ministry of Power and other institution in power sectors like CEA,CBIP, CPRI should write to DGCA for treating power as essential sector and frame easy regulations for the UAV application in power sector.

In spite of the complex regulations for flying UAV, we are hopeful that power sector will continue to utilize this UAV technology as the advantages coming out of this new technology outweighs many odds.

At the last, we can sum it up that UAV's are enablers and a futuristic strategic tool in power sector and UAV enabled stringing is the future of transmission sector.

Annexure – 1

Standard Operating Procedure for Stringing

Stringing of transmission lines

5.1 HANDLING OF CONDUCTOR AND EARTHWIRE

i. Handling and transporting of the conductor and accessories shall be carried out in such a manner as to minimize the possibility of damages from abrasion through rough handling or dirt and grit and getting into the reel of the conductor by touching or rubbing against ground or objects, causing injury to the conductor etc. Particular care shall be taken at all tines to ensure that the conductor do not become kinked twisted or abraded in any manner. If the conductor is damaged, the section affected shall be replaced or repaired by putting joint or using repair sleeves or polishing with emery cloth, so as to give satisfactory performance.

ii. At all stage of construction proper care shall be taken so that the conductor surface is smooth enough to be given satisfactory corona and radio interference performance. All equipment used in handling or transporting the conductor such as grips, pulleys slings, cable care etc. shall be so designed and maintained that the surface which may contact the conductor, are kept free of foreign or defects.

iii. Care shall be taken while running out the conductors such that the conductors do not touch or rub against the ground or objects which could scratches or damage to the strands. The conductor shall not be over strained during erection. The conductor shall be run out of the drums from the top in order to avoid damage due to chaffing. Drum battens shall not be removed until conductor drums are properly mounted at the drum station on the line, and battens shall be immediately refitted on the drum if any surplus conductor is left thereon. Drums will be transported and positioned on station with the least possible amount of rolling, immediately after running out, the conductor shall be raised at the supports to the level of the clamps and placed into the running blocks. The grooves of the running blocks shall be of a design that the seat is semi-circular and larger that the diameter of conductor/earth wire and it does not slip over or rubs against the sides. The grooves shall be lined with hard rubber or neoprene to avoid damage to conductor and shall be lined with hard rubber or neoprene to avoid damage to conductor and shall be mounted on well oiled bearings. At all stages of construction proper care shall be taken so that the conductor surface is smooth enough to give satisfactory corona and radio interference performance.

iv. The running blocks shall be suspended in a manner to suit design of the cross-arm. All running blocks specially those at the tensioning end, will be fitted on the cross arms with jute cloth wrapped over the steel works and under the sling to avoid damage to the slings as well as the protective surface finish of the steel work. In case, section towers are used even for temporary terminations, if this be unavoidable, they shall be well guyed and steps shall be taken to avoid damage. The drums shall be provided with a suitable breaking device to avoid damage, loose running out and kinking of the conductor. The conductor shall be continuously observed for loose or broken strands or any other damage. When approaching end of a drum length at least three coils shall be left when the stringing operations are stopped. These coils shall be removed carefully and if another and if another length is required to be run out a joint shall be made as per the recommendations of the conductor manufacturers. normally, the joints shall be so made that these are not required to pass through running out of blocks, the joints will be protected with suitable joint protector sleeves.

v. The conductors, joint and clamps shall be erected in such a manner that no bird-caging over-tensioning of individual wires or layers or other deformation or damage to the conductors shall occur. Clamps or hauling devices shall, under erection conditions, allow no relative movement of strands or layers of the conductors.

vi. Repairs to conductors, in the event of damage being caused to isolated strands of a conductor during the course of erection, if necessary, shall be carried out during the running out operations with repair sleeves. Repairing of conductor surface shall be done only in case of minor damage, scuff marks etc, keeping in view both electrical and mechanical safety requirements. The final conductor surface shall be clean, smooth and shall be without any projections, sharp points, cuts, abrasions etc.

vii. Repair sleeves may be used when the damage is limited to the outermost layers of the conductor and is equivalent to the severance of not more than one third of the strands of the outermost layer. No repair sleeves shall be fitted within 30 m of tension or suspension clamp or fittings, nor shall more than one repair sleeve per conductor be normally used in any single span.

viii. Conductor splices shall be so made that they do not crack or get damaged in the stringing operation. Only such equipment/methods during conductor stringing which ensure complete compliance in this regard shall be used.

ix. Derricks shall be used where roads, rivers, channels, telecommunication or overhead power lines, railways, fences or walls have to be crossed during stringing operation. it shall be seen that normal services are not interrupted or damage caused to property. Shut down shall be obtained when working at crossing of overhead power lines.

x. The proposed transmission lines may run parallel for certain distance with the existing 400 KV, 220 KV & 132 KV lines which will remain energised during the stringing period. As a result, there is a possibility of dangerous voltage build up due to electromagnetic and electrostatic coupling in the pulling cables, conductors and earthwires which though comparatively small during normal operations can be severe during switching and ground fault conditions on the energised lines.

xi. The sequence of running out shall be from to down-wards i.e. the earth wire shall be run first followed by power conductors. After running out the top conductor the conductor at the opposite side at the bottom level should be run out. After wards the remaining phase conductor shall be run out. imbalance of loads or tower shall be avoidable as far as possible.

xii. Adequate steps to prevent clashing of sub conductors after paying out of conductor before spacers/spacer dampers are installed. Care shall be taken that all the two sub conductors of the bundle are taken from same conductor supplier and preferable from the same batch so that creep behavior of these remains identical during sagging, care shall be taken to eliminate differential sag as far as possible.

5.2 TREE CUTTING

During paying out of conductor and earthwire and also during stringing in forest area, it shall be ensured that minimum trees are cut and that too to the extent permitted by the forest authorities.

5.3 PULLING IN OPERATION

Before the commencement of the stringing, initial and final stringing charts for the conductor and earth wire showing the sags and tension for various temperatures and spans along with equivalent spans in the lines should be available. The stringing shall be done as per approved stringing charts.

The earth wire shall be strung and securely clamped to the towers before the conductors are drawn up in the order of the top conductors first, then the conductor on the opposite side and in the end the lower conductor at the same side. it shall be ensured that all the conductors of one section should have identical tension time history.

The pulling of the conductor into the travellers comprising of serial and ground rollers shall be carried out in such a manner that the conductor is not damaged or contaminated with any foreign substance and that it may not be rubbed with the rough ground surface, or it damages the standing crops. For this the height of ground rollers shall be fixed in such a manner that the conductor/earthwire does by douching. The travellers shall have size and shops most suitable for the type of stringing and size of conductor involved and as recommended by the conductor manufacturer. These shall be approved by the supervision Engineer before use. The travellers surface in contact with aluminum surface of conductor shall be of such a material that conductor is not damaged, e.g. neoprene rubber or stainless steel. These shall be equipped with high quality ball or roller bearings for minimum friction. They should be inspected daily for free and easy movement in blocks during stinging and sagging.

During pulling out operation the tension in each conductor and earthwire shall not exceed the design working tension of the conductor at the actual prevailing temperature. After being pulled the conductor and earthwire shall not be allowed to hang in the stringing blocks for more than 96 hours before being pulled to the specified sag. During the time the conductors and earthwire are on the stringing block before sagging in, It shall be ensured that the conductors and earthwire are not damaged due to clashing vibration or other causes.

The tensioning and sagging shall be done in accordance with the approved stringing charts before the conductor and earthwire are finally attached to the towers through the earthwire clamps for the earthwire and insulator stings for the conductor. Dynamometer shall be employed for measuring tension in the conductor and earthwire. The dynamometers employed shall be periodically checked and calibrated with a standard dynamometer. For 400 KV lines the following additional precautions shall be taken

The stringing of the conductor shall be done by controlled tension method by means of tension stringing equipments. The earthwire may also be strung by the same method. The equipment shall be capable of maintaining a continuous tension of not less than 10,000 kg per bundle which shall be such that the sag for each sub conductor is maintained about 20% greater than the sags specified in the stringing sag tables.

Controlled stringing method suitable for simultaneous stringing of the sub conductors shall be used. All the power conductors making one phase bundle shall be pulled in and paid out simultaneously. The two power conductors of the bundle shall be of matched length and of the same manufacturer and batch to ensure that the two conductor making one phase have identical tension characteristics. After being pulled the conductor/earthwire shall not be allowed to hang in the stringing blocks for more than 96 hours before being pulled to the specified sag.

Necessary arrangements should also be made for paying out the pilot wire for stringing of conductors and earthwire by helicopter in line route where dense forests are involved and paying out of pilot wire by conventional method is not possible.

The complete details of the stringing method which are proposed to be followed should be planned and decided. Before the commencement of the stringing the stringing charts for the conductor and earthwire showing the initial and final sags and tension for various temperatures and spans along with equivalent spans in the lines should be got prepared, checked and approved.

During paying out of conductor and earthwire and also during stringing in forest area, it shall be ensured that minimum trees are cut. If required 4 meters extension to towers may be used to obtain proper clearance. If necessary, earthwire shall also be strung by tension stringing equipment to avoid cutting of trees. When paying out of conductor & earthwire by conventional method is not possible without cutting of large number of trees, paying out may be done through helicopter as detailed.

The conductor and earth wire shall be sagged in accordance with the approved stringing charts before they are finally attached to the towers through the earth wire clamps for earthwire and insulator strings for the conductors.

The conductors shall be pulled up to desired sag and left in travellers for at least one hour after which the sag shall be rechecked and adjusted, if necessary, before transferring the conductors from the travellers to the suspension clamps. The conductors shall be clamped within 36 hours of sagging in. The adjustment in sag for creep age of conductor should also be made before finally clamping,

The sag will be checked in the first and last span of the section in case of sections upto eight spans and in one intermediate span also for section with more than eight spans. Any damage to the towers or the conductors through over stressing during stringing shall be awaited. Dynamometers shall be used in checking the tension in the conductors and earthwire and these instruments shall be periodically checked with a standard dynamometer. The sags shall also be checked when the conductors have been drawn up and transferred from aerial blocks to the insulator clamps.

The stringing blocks, when suspended on the transmission structure for sagging, shall be so adjusted that the conductor on the travellers will be at the same height as the suspension clamp to which it is secured.

At sharp vertical angles the sags and tension shall be checked on both sides of the angle. The conductor and earthwire shall be checked on the travellers for equality of tension on both sides. The suspension insulator assemblies will normally assume vertical positions, when the conductor is clamped. Sagging operations shall not be carried out under wind, extremely low temperature or other adverse weather conditions which prevent satisfactory sagging.

5.5 CONDUCTOR DAMAGE AND REPAIR

If the conductor is damaged for whatever reason and the damage is not repaired by repair sleeves or emery cloth, the same shall not be used. Repairing of conductor surface shall be done only in case of minor damages, scuff marks etc. which are safe from both electrical and mechanical points of view. The final conductor surface shall be clean, smooth, without any projections, sharp points, cuts or abrasions etc. for giving satisfactory corone and R.I. performance.

5.6 JOINTING

All the joints on the conductor or the earthwire shall be of compression type in accordance with the recommendations of the manufacturers, for which the necessary tools and equipments like, compressors and dies, grease gums presses etc, shall have to be arranged by the contractor. These joint will be made in the best workman like manner, shall be perfectly straight and having maximum strength. Each part of the joints shall be cleaned by wire brush to make it free of rust or dirt etc, and properly greased before the final compression is done with the compressors.

All joints or splices shall be made at least 30 meters away from the structures. No joints or splices shall be made in spans crossing over main roads, railways, small rivers or in tension spans. Not more than one joint shall be allowed in one span. The compression type fittings used shall be of the self centering type or care shall be taken to mark the conductors to indicate when the fitting is centered properly. During compression or splicing operation the conductor shall be handled in such a manner as to prevent lateral or vertical bearing against dies. Care shall be taken to protect the conductor from scratches, abrasions or other damages. After pressing the joint the aluminum sleeve shall have all corners rounded, butts and sharp edges removed and smoothened.

5.7 CUPPING-IN

Clapping of the conductors in position shall be done in accordance with the recommendations of the manufacturer. Conductor shall be fitted with arm our rods where it is made to pass through suspension clamps and with vibration dampers at all the suspension and tension points, as recommended by the manufacturer.

The jumper at the section and angle towers shall be formed to parabolic shape to ensure maximum clearance requirements. Clearance between the conductors and ground and between jumpers and the tower steel works shall be checked during erection and before handing over the line. If pilot suspension string is used with jumpers, the same shall be clamped with jumper.

Fasteners in all fittings and accessories shall be secured in position. The security clip shall be properly opened and sprung into position.

5.8 FIXING OF CONDUCTOR & EARTHWIRE ACCESSORIES

Vibration dampers, arm our rods and other conductor and earth wire accessories shall be installed as per the design requirement and as per the respective manufacturer's instructions. The Vibration dampers, spacers and spacer dampers shall be provided at both ends of each span at suitable distance from the supporting points for each conductor/earthwire as per recommended practice and placement charts of manufacturer. Spacers/Spacer damper shall be fitted within 24 hours of conductor clamping while installing the conductor and earth wire accessories proper care shall be taken to ensure that surface are clean and smooth and no damage shall occur to any part of the accessories.

5.9 FINAL CHECKING, TESTING & COMMISSIONING

i. After completion of the works, final checking of the line shall be done to ensure that all the foundation works, tower erection and stringing have been done strictly according to the specifications and approved by the supervising Engineer. All the works shall be thoroughly inspected keeping in view the following main points

   -

   a) Sufficient backfilled earth is lying over each foundation pit and it is adequately compacted.

b) Concrete chimneys and their coping are in good finely shaped conditions.

c) All the tower members are correctly used, strictly according to final approved drawing and free of any defect or damage whatsoever

.

d) All bolts are properly tightened and punched.

(e) The stringing of the conductors and earthwire has been done as per the approved sag and tension charts and desired clearances are clearly available.

(f) No damage minor or major to the conductors, earthwire accessories and insulator strings still unattended are noticed and rectified.

ii. After final checking the line shall be tested for insulation in accordance with tests prescribed. All arrangements for such testing or any other test desired shall be done. Any defect found out as a result of such tests, shall be rectified.

iii. In addition to the above it shall be ensured that the total and relative sags of the conductors and earthwire are within the specified tolerances. Such tests shall be carried out at selected points along the route as deemed necessary.

iv. After satisfactory tests on line, the line shall be energised at full operating voltage.

Courtesy UPPTCL - http://upptcl.org/tech_info/stringing_of_transmission.htm

Annexure-2

HAZARD IDENTIFICATION & RISK ASSESSMENT FOR UAV

The drone flight safety is the desired optimum state in which drone operations executed in certain circumstances can be controlled with an acceptable operational risk. By performing a safety risk assessment, we could help in advance to identify drone operation safety hazards. The UAV safety risk assessment, based on a systematic approach from safety hazard identification to risk management, ensures the maintenance of the required safety standards for drone operations. This approach is an appropriate solution, which fits according to the effort and usability. Not only the results but also the whole UAV safety risk assessment process should be documented to ensure a continuous safety assurance.

The UAV safety risk assessment is an instrument used to identify and assess active and latent safety hazards for drone operation. This safety risk assessment includes actions for mitigating the predicted probability and severity of the consequences or outcomes of each operational risk.

An UAV safety risk assessment makes safety risks measurable so that risks can be better controlled. Phases of UAV safety risk assessment We recommends to separate the UAS safety risk assessment into the following four phases

Part I – <u>Safety Hazard Identification</u>: Occurrences such as near misses or latent conditions, which led or could have led to drone operational flight safety harm, will be identified.

Part II – <u>Safety Risk Assessment</u>: All identified hazards will be assessed, according to the operational risks severity and operational risk probability.

Part III – <u>Safety Risk Mitigation</u>: According to the operational risk acceptance level, risk mitigation action will be defined.

Part IV – <u>Safety Documentation</u>: Not only the results but also the whole UAS safety risk assessment process should be documented to ensure a continuous safety assurance.

Likelihood	Meaning	Value
Frequent	Likely to occur many times	5
Occasional	Likely to occur sometimes	4
Remote	Unlikely to occur, but possible	3
Improbable	Very unlikely to occur	2
Extremely Improbable	Almost inconceivable to occur	1

Severity	Meaning	Value
Catastrophic	Equipment destroyed, deaths	5
Hazardous	A large reduction in safety margins, serious injury, major equipment damage	4
Major	A significant reduction in safety margins, serious incident, injury	3
Minor	Nuisance, use of emergency procedures, minor incident	2
Negligible	Few consequences	1

Risk Probability Table **Severity Table**

Risk	Catastrophic(I)	Hazardous(II)	Major(III)	Minor(IV)	Negligible(V)
Frequent(A)	25	20	15	10	5
Occasional (B)	20	16	12	8	4
Remote (C)	15	12	9	6	3
Improbable(D)	10	8	6	4	2
Extremely Improbable (E)	5	4	3	2	1

Unacceptable (Red) - The probability and/or severity of the consequence is intolerable. Major mitigation or redesign of the system is necessary to reduce the probability or the severity of the consequences of the safety hazard to an acceptable level.

Tolerable level (Yellow)- the consequence and/or likelihood is of concern; measures to mitigate the risk to a reasonably low level should be sought for. This risk can be tolerated if the risk is understood and if it has an endorsement within the organization.

Acceptable level (Green)- the consequence is very unlikely or not severe enough to be of concern. The risk is tolerable and the safety objective has been met. However, consideration should be given to reduce the risk further to a reasonably practical level.

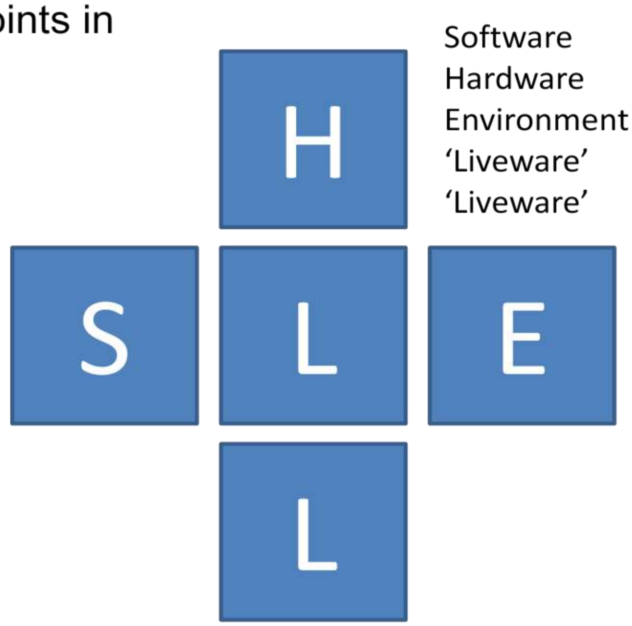
Control Strategy

Hierarch of Controls

1. Eliminate the hazard
2. Reduce the hazard level
3. Provide safety devices
4. Provide safety warnings
5. Provide safety procedures

Effective Control Strategies

- Address the weak points in the SHELL Model



A safety risk assessment is the fundamental of safe drone operation and an instrument for continuous improvement, Risk Analysis is a continuous and dynamic process. Our control strategy should account for that.

Components of the SHELL Model

Software

- Non-physical, intangible aspects of the aviation system that govern how the aviation system operates and how information within the system is organised
- Software may be likened to the software that controls the operations of computer hardware
- Software includes rules, instructions, regulations, policies, norms, laws, orders, safety procedures, standard operating procedures, customs, practices, conventions, habits, symbology, supervisor commands and computer programmes.
- Software can be included in a collection of documents such as the contents of charts, maps, publications, emergency operating manuals and procedural checklists

Hardware

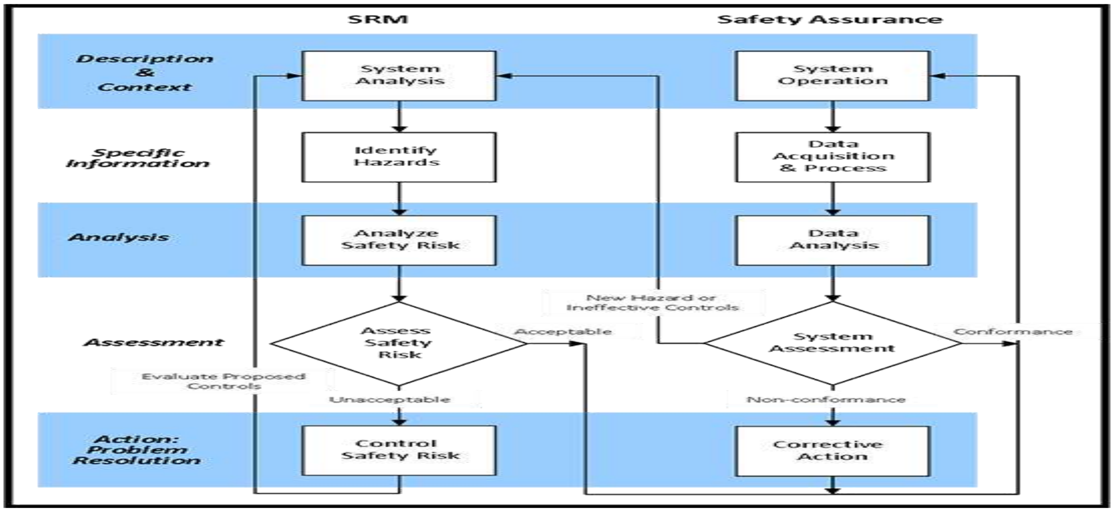
- Physical elements of the aviation system such as aircraft (including controls, surfaces, displays, functional systems and seating), operator equipment, tools, materials, buildings, vehicles, computers, conveyor belts etc

Environment

- The context in which aircraft and aviation system resources (software, hardware, liveware) operate, made up of physical, organisational, economic, regulatory, political and social variables that may impact on the worker/operator
- Internal air transport environment relates to immediate work area and includes physical factors such as cabin/cockpit temperature, air pressure, humidity, noise, vibration and ambient light levels.
- External air transport environment includes the physical environment outside the immediate work area such as weather (visibility/turbulence), terrain, congested airspace and physical facilities and infrastructure including airports as well as broad organisational, economic, regulatory, political and social factors (International Civil Aviation Organisation, 1993 5).

Liveware

- Human element or people in the aviation system. For example, flight crew personnel who operate aircraft, cabin crew, ground crew, management and administration personnel.
- The liveware component considers human performance, capabilities and limitations (International Civil Aviation Organisation, 1993 5).



Safety Risk Management and Safety Assurance are two separate processes but they must be able to share information

Formats

Sr.no	Hazard	Element	Root Cause	Worst Consequences	Type of Finding	Severity	Probability	Risk Level	Corrective Action	Preventive action (PA)	Responsible	Due Date
1	Lack of Power	Hardware	Battery	Affect airworthiness	Minor	Major	Occasional	Tolerable	Change Battery	Review Power system	XX XX	XX. XX. XX
2	Over running during take off	Liveware	GPS	Harm to people	Major	Catastropical	Occasional	Unacceptable	Keep people away from area	System Calibration	XX XX	XX. XX. XX

A risk assessment needs to include factors such as:

- Bird Strikes
- Pilot and spotter / cameraman looses sight of the UAV / RPA
- The pilot has a medical emergency
- Adverse weather conditions
- Take-off and Landing operations
- Incorrect assembly of aircraft parts
- Radio interference

Data Groups

Any hazard which is observed under the following categories should also be included after the site execution :-

Flight info /UAV information/Flying over people/Pilot & Ground Crew/Incidents/accidents/near misses/Environment/safety stats of UAV/ UAV Telemetry etc

Fault Current Limiter Selection Considerations for Utility Engineers

K. Tekletsadik, P. Lubicki, S. Nickerson, J. Ludlum, P. Murphy, V. Dabeer
Applied Materials, Inc. U.S.A

SUMMARY

Several Fault Current Limiter (FCL) technologies have matured from R&D and demonstration projects into commercially available systems. So far, the technical knowledge about FCL systems, design parameters and impact analysis on utility equipment is primarily contained within the FCL manufacturer’s technical expertise. The time has come to further disseminate the technical knowledge to utility engineers so that they can design fault current management systems with the technical expertise that enables them to specify FCLs for their applications. Applied Materials is developing Superconducting Fault Current Limiters (SCFCL) and Solid State Fault Current Limiters (SSFCL) for transmission and distribution voltage levels. Both FCL technologies are being subjected to in-grid demonstrations and commercialization. This paper is aimed at describing how utility engineers may consider selecting a FCL for a specific location and application, based on the authors’ experience. It is not intended as a manual or guide to be used or relied upon without independent testing or verification. It also discusses three FCL demonstration projects including SCFCLs in California and New York, and a SSFCL shipped to a utility site for installation.

KEYWORDS
Fault Current Limiter, Superconducting, Solid State, FCL, SCFCL, SSFCL.

1. Introduction

As FCL technology transforms into a market-ready system, the design and specification of the system transitions from the manufacturer to the utility engineers. Applied Materials is taking a lead in this transformation and is developing an FCL family of systems based on SCFCL and SSFCL technologies. The main objective of this publication is to provide considerations for utility engineers in selecting the right FCL solution for a specific location and application. The FCL component has been developed for PSCAD, DigSilent, PSS/E, EMTP, and PSpice circuit simulation software packages. In general, any of the available software packages can be used with no or minimal loss of accuracy.

This paper will also discuss three FCL demonstration projects including SCFCLs in California and New York, and a SSFCL scheduled to be installed at a utility substation. Sharing our experiences in the design, manufacturing and installation of FCL demonstration systems is one of the main goals of this article. These demonstration units are installed and being evaluated over a period of one-to-two years in order to demonstrate the systems' reliability over longer-term operating conditions.

2. Benefits of Fault Current Limiters

The benefits of FCLs can be categorized based on two system types. The first one is related to existing systems where the main expected benefits of FCLs are increased asset utilization, equipment upgrade deferral, life extension, improved safety, improved reliability and operational flexibility, enabling interconnection of grids and avoiding major projects like splitting buses and building new substations.

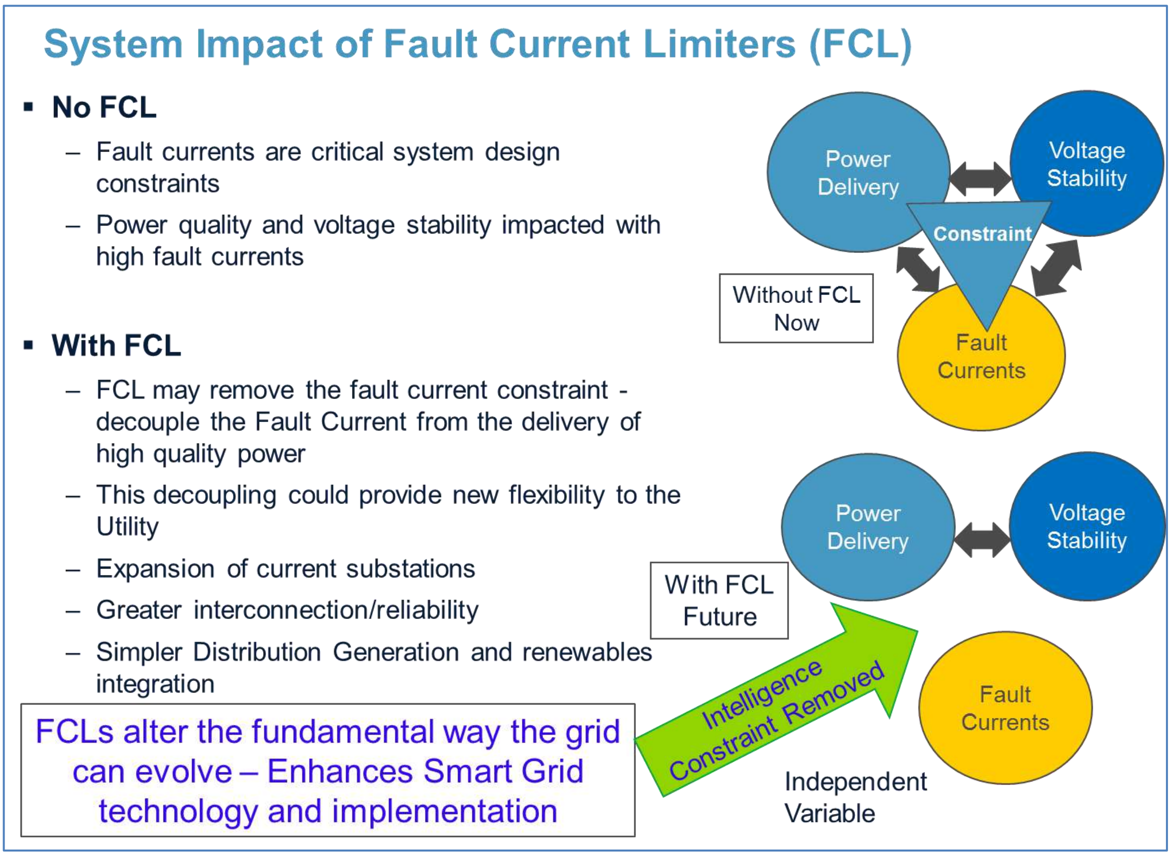


Figure 1 Impact of FCL on future Power System design

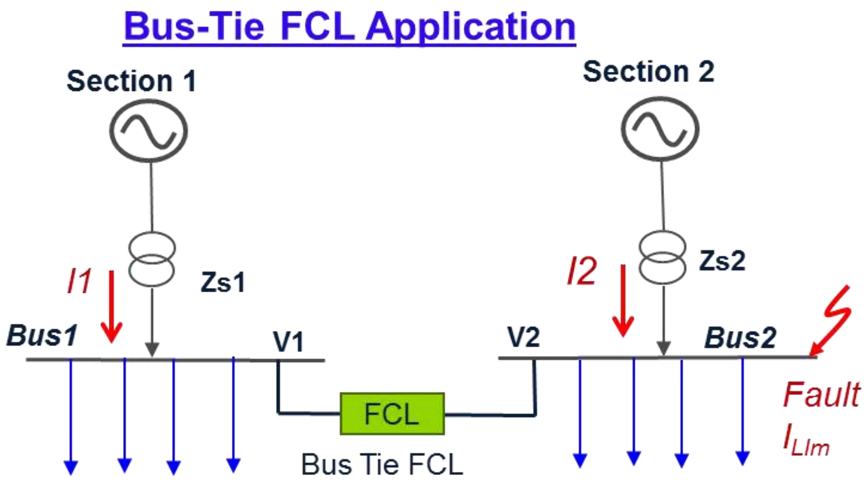
The second type of benefit is for new systems design where a fault current constraint is removed from the critical system design equation and all equipment is designed with low fault currents. As an example, a new system that uses FCLs could be designed for a maximum fault current of 50% or less than its equivalent old system. It can also mean power system equipment manufacturers build cost-effective and low-fault current rating equipment such as breakers, low impedance transformers, compact reactors, etc. With the FCL's new approach, a higher quality of power with stable systems can be designed. New systems can be designed for low fault current rating results with benefits of improved transient stability and voltage stability that improves the system resilience to power outages. Figure 1 shows how the FCL impacts the future generation, transmission and distribution systems by decoupling the fault current constraint from the system design. As the cost of FCLs continues to decrease and pilot projects move into deployment, FCLs have the potential to alter the way we design and plan the electrical grid.

3. FCL Technologies and Applications

Applied Materials is developing two types of FCL technologies, Superconducting (SCFCL) and Solid State (SSFCL). The FCL systems are based on a modular design platform that can be easily configured to meet various customer needs based on location, space availability and applications. The SCFCL is primarily for transmission voltage levels from 66 kV to 400 kV, whereas the SSFCL is targeting distribution voltage levels of up to 66 kV.

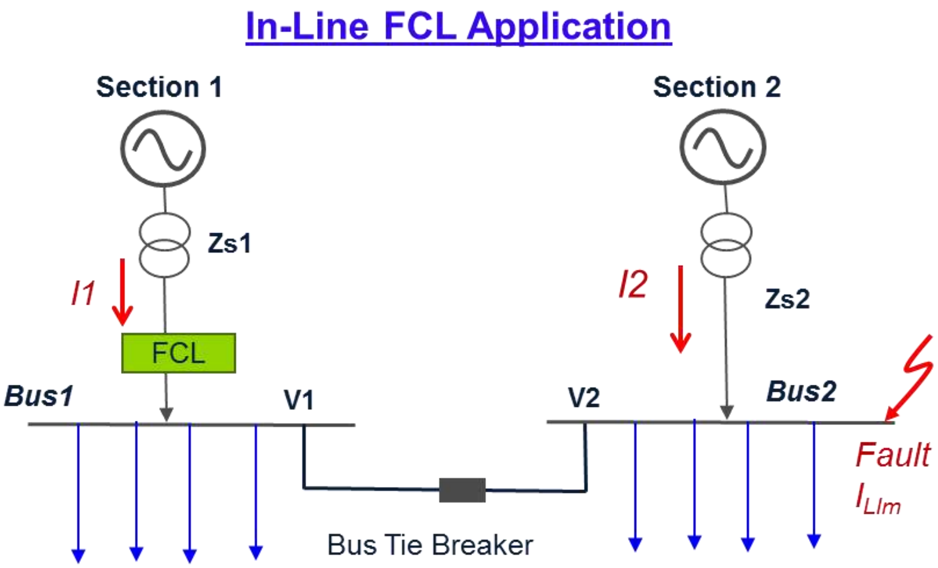
The application of FCLs may cover all sizes of utilities in their generation, transmission and distribution systems. Independent power producers and industrial customers also could benefit from FCLs. Based on the installation and configuration types, FCLs could be installed in-line with a feeder, in a bus-tie application or transformer neutral-to-ground connections. Generally, where there is a fault current problem that causes excessive electromagnetic forces and mechanical stress, thermal stress and high arc energy, FCLs could be used to eliminate or reduce the impact of excessive stress on equipment.

Figure 2 shows a typical bus-tie FCL application, where it is primarily used to interconnect buses. This application can also be extended to system interconnections of larger grids or substations to increase power availability and system reliability. The bus-tie application is also very useful for voltage sag improvement, where the voltage drop at the un-faulted (healthy) section can be maintained to a value that does not affect the customers connected to that section. This application improves grid interconnection and enables the addition of renewable energy generation with minimal impact on the existing system. The other type of FCL connection is in-line (shown in Figure 3) with a feeder or transformer to limit the fault current contribution from that line and protect it from fault currents from the rest of the system.



- Fault Current Limitation
  - FCL Fault Current Reduction, $cr = \frac{I_P - I_{Lim}}{I_P}$, where I_P = prospective fault current and I_{Lim} = limited fault current
  - Limited Fault Current , I_{Lim} = (1 - cr).I1 + I2
- Voltage Sag Improvement
  - V1 = cr.Vs, for example a system with an FCL of cr = 0.8, the voltage at the un-faulted Bus1 can be kept to 80% of the system voltage (Vs)

Figure 2 Typical Bus-tie FCL Application



- Fault Current Limitation
  - FCL Fault Current Reduction, $cr = \frac{I_P - I_{Lim}}{I_P}$, where I_P = prospective fault current and I_{Lim} = limited fault current
  - Limited Fault Current , I_{Lim} = (1 - cr).I1 + I2

Figure 3 Typical in-Line FCL Application

4. Installations

Figure 4 shows a distribution SCFCL installed in Santa Clara, CA. It is a 15 kV class, 1000 A 3 phase SCFCL and uses an active Liquid Nitrogen Supply. This system has been installed and running in the system for the last 12 months and has operated as designed to date. This technology could also be supplied with an optional bulk Liquid Nitrogen system which reduces the overall system complexity and cost.

Figure 4 Silicon Valley Power, Santa Clara, California

Figure 5 shows a recent installation at Central Hudson Knapps Corner Substation in Poughkeepsie, New York. It is a 15 kV class neutral-to-ground SCFCL. This SCFCL has already experienced 2 faults and performed as expected.

A neutral–to-ground FCL is used where more than 80% of faults are phase-to-ground faults. In such applications, using a neutral-to-ground FCL seems to be a reasonable solution. It is understandable that 20% of faults that are phase-to-phase or balanced three phase faults are not limited with the neutral-to-ground FCL. The other concern with the application of neutral-to-ground FCL system, especially at higher voltage applications, is the overvoltage in the healthy phases.

$$Overvoltage = V_P . \sqrt{1 + \frac{V_{FCL}}{V_P} + \left(\frac{V_{FCL}}{V_P}\right)^2}$$

For example: for neutral-to-ground FCL with a 50% current reduction, the overvoltage on the healthy phases could go up to $1.32V_P$ (32% overvoltage). This may be acceptable at distribution systems but needs to be checked for insulation coordination purposes at transmission voltage levels.

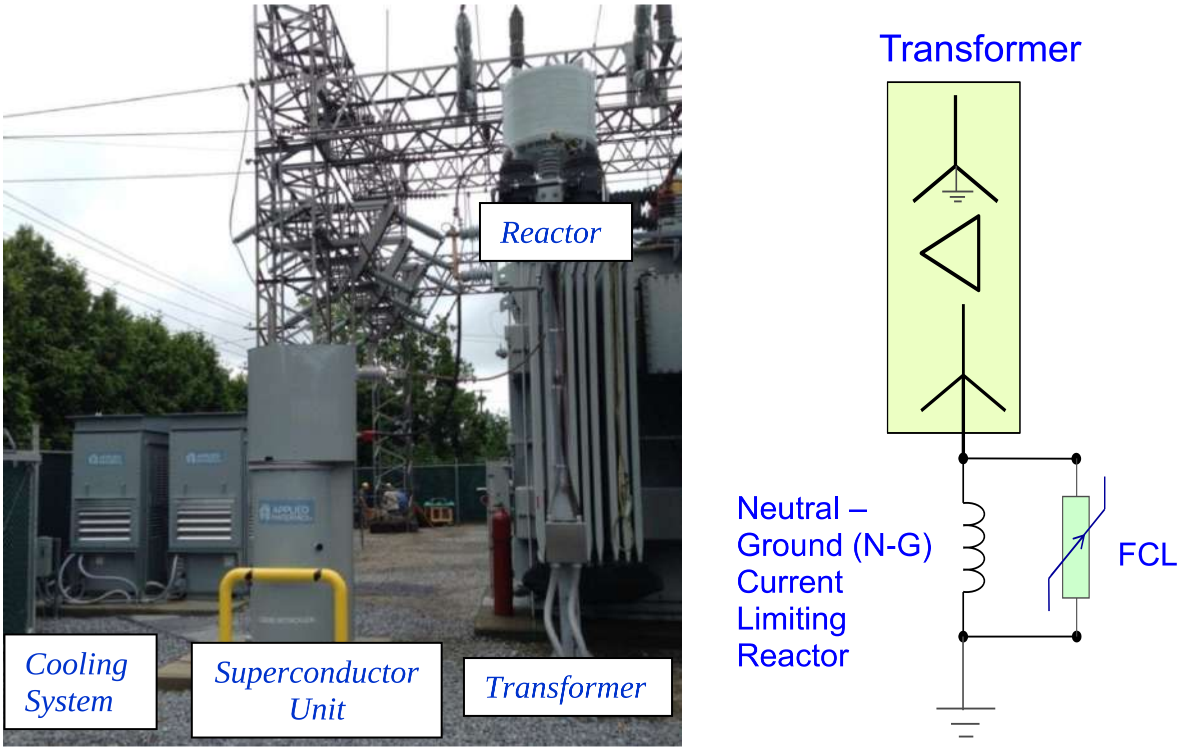


Figure 5 Central Hudson, Poughkeepsie, New York

Figure 6 shows a SSFCL being tested at a KEMA power test lab. This system is a 23 kV SSFCL built to limit fault currents from up to 26 kA symmetrical rms (65 kA peak) to as low as less than 6 A peak. We believe that one of the key benefits of the SSFCL is its flexibility in current-limiting performance where its application can cover a wide range of fault currents. For instance this SSFCL is designed to work for an application where the required limited fault current varies between 6 A peak (99.99% current reduction) to 40 kA peak (23% current reduction). SSFCL also has an added advantage of instant recovery for applications where instant recovery is critical, such as systems that are sensitive to voltage drops during recovery time.

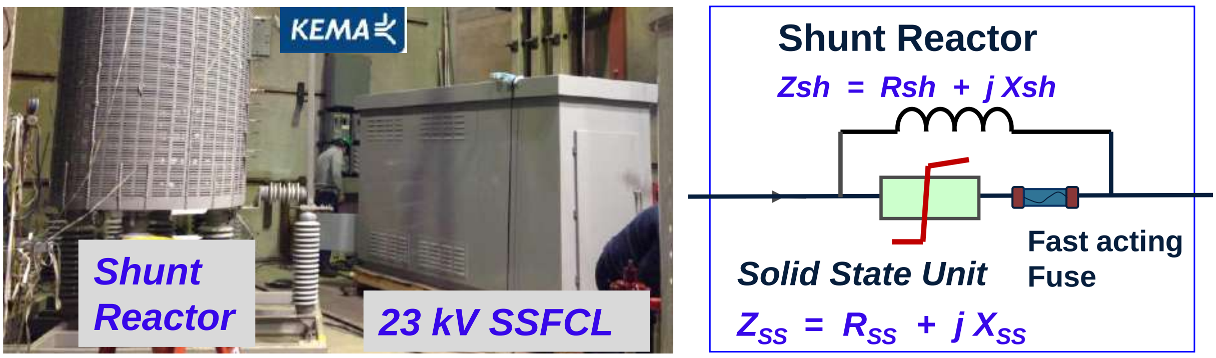


Figure 6 23 kV SSFCL tested at KEMA

Figure 7 shows a typical current-limiting performance of SSFCL tested at KEMA. The waveforms show a test set up at 23 kV system voltage (13.28 kV phase-to-ground) limiting 11.1 kA rms (30 kA peak) to 7.73 kA rms (21 kA peak), that is a 31.2% current reduction. This SSFCL has been tested to its design limits of up to 26 kA rms prospective fault currents and performed as expected.

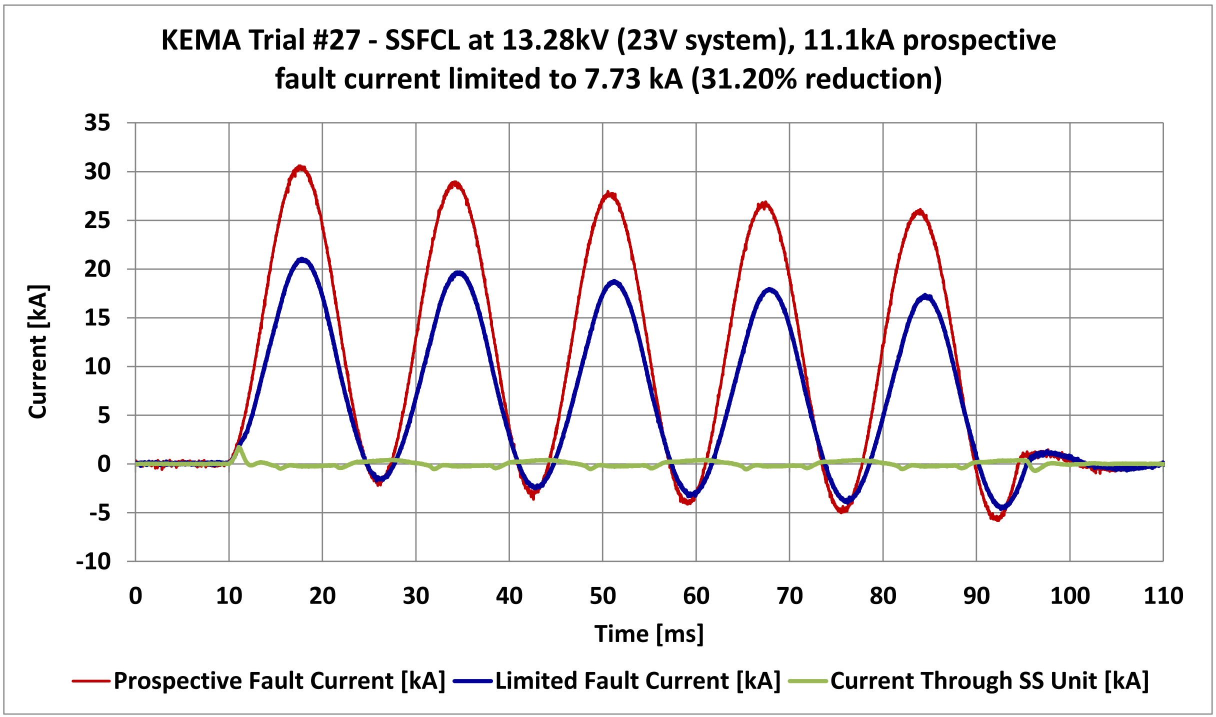


Figure 7 KEMA test results for a SSFCL fault current limitation test.

5. Cost Drivers

When looking for a FCL, engineers should be aware of the cost drivers for the FCL system they are planning to buy. The major cost drivers are the load current (I_L) and the fault current reduction required which is directly proportional to the voltage drop across the FCL during fault (V_{FCL}). It is therefore possible to get a cost factor (CF) related to the rating of the FCL as;

$$CF = k1.I_L.CR = k2.I_L.V_{FCL} = k2.I_L.I_{Lim}.Xsh$$

The cost factor constants k1 and k2 are FCL-type dependence and are expected to decrease as the FCL technology matures and the cost of the FCL decreases through materials performance improvements and as the cost of volume manufacturing decreases.

This equation shows that a higher the load current and current reduction results in higher cost of the FCL. The size and weight of the FCL is also linearly proportional to the cost factor. Understanding these factors helps the utility engineers to optimize the FCL location and application to get a cost-effective solution.

6. System Requirements

Table 1 below shows an FCL systems requirement table, where the most important system parameters required for selecting a FCL are listed. This table is intended as an example of how to calculate the FCL design parameters and provides a means to write a specification or rating of the selected FCL.

Table 1 FCL System Requirement Table

System Parameters - Provided by Utility		
System Voltage - Line-to-Line, *Vs*	220	KV rms
Maximum Load Current, I_L	1500	A rms
Prospective Fault Current, *Ip*	25	kA rms
Limited Fault Current, I_{Lim}	12.5	kA rms
Calculated System Parameters		
System Short Circuit Impedance, $Zs = \frac{Vs}{Ip.\sqrt{3}}$	5.08	Ω
Current Reduction, $CR = \frac{Ip - I_{Lim}}{Ip}$	50	%
Shunt Reactor Impedance, $Zsh = Zs\frac{CR}{1-CR}$	5.08	Ω
Voltage Drop Across FCL, $V_{FCL} = Zsh.I_{Lim}$	63.5	kV rms
Recovery time after Fault is cleared	2.0 - 3.5	Sec
Fault Current Limiter Rating		
220 kV System Voltage, with 63.5 kV Voltage drop, 1500A, 5.08 Ω Shunt Reactor, Limits 25 kA to 12.5 kA (50% fault Current Reduction) and recovers to its normal operating mode within 3.5 seconds		

As shown in Table 1, a utility engineer can calculate the key system parameters for short circuit analysis. Based on these calculated parameters one could estimate the specifications or ratings for an FCL for that application. The example above describes this process for a 220 kV system. Since most short -circuit analysis is done with power system software packages; the next section describes the best approach a utility engineer could take to design an FCL of his or her choice.

7. FCL Simulation Models

This section addresses a key skill set for a utility engineer in how to incorporate FCLs into their short-circuit analysis. Applied Materials has developed several simulation models for both SCFCL and SSFCL systems. These models went through extensive revisions and were experimentally verified through extensive testing at component and system levels. In addition to the in-house test lab for component and module level testing, KEMA power test labs has been used extensively to characterize the performance properties of the FCL systems. FCLs have undergone over seven weeks of KEMA testing, exposing the system to thousands of high power faults, and have performed per design specifications and simulation results.

Figure 8 shows some of the basic simulation models developed for FCL systems. These models start from physics-based models that include transient electrical and thermal analysis and progress to simplified models with minimal or no loss of accuracy. Our in-house design software and PSCAD use the physics-based model. For some commercial software packages, like DIgSilent, ramped and step approximation functions are used to model the transition resistance of the Superconductor and Solid state units. Further simplification shows that the Superconductor unit can be represented by a fixed resistor with a value around 3 to 5 times the parallel shunt reactor. Even further simplification shows that a current limiting reactor model is accurate enough that the simulation has no loss of accuracy. Utilities that use frequency-based software, like PSS/E may be able to use the simplest model.

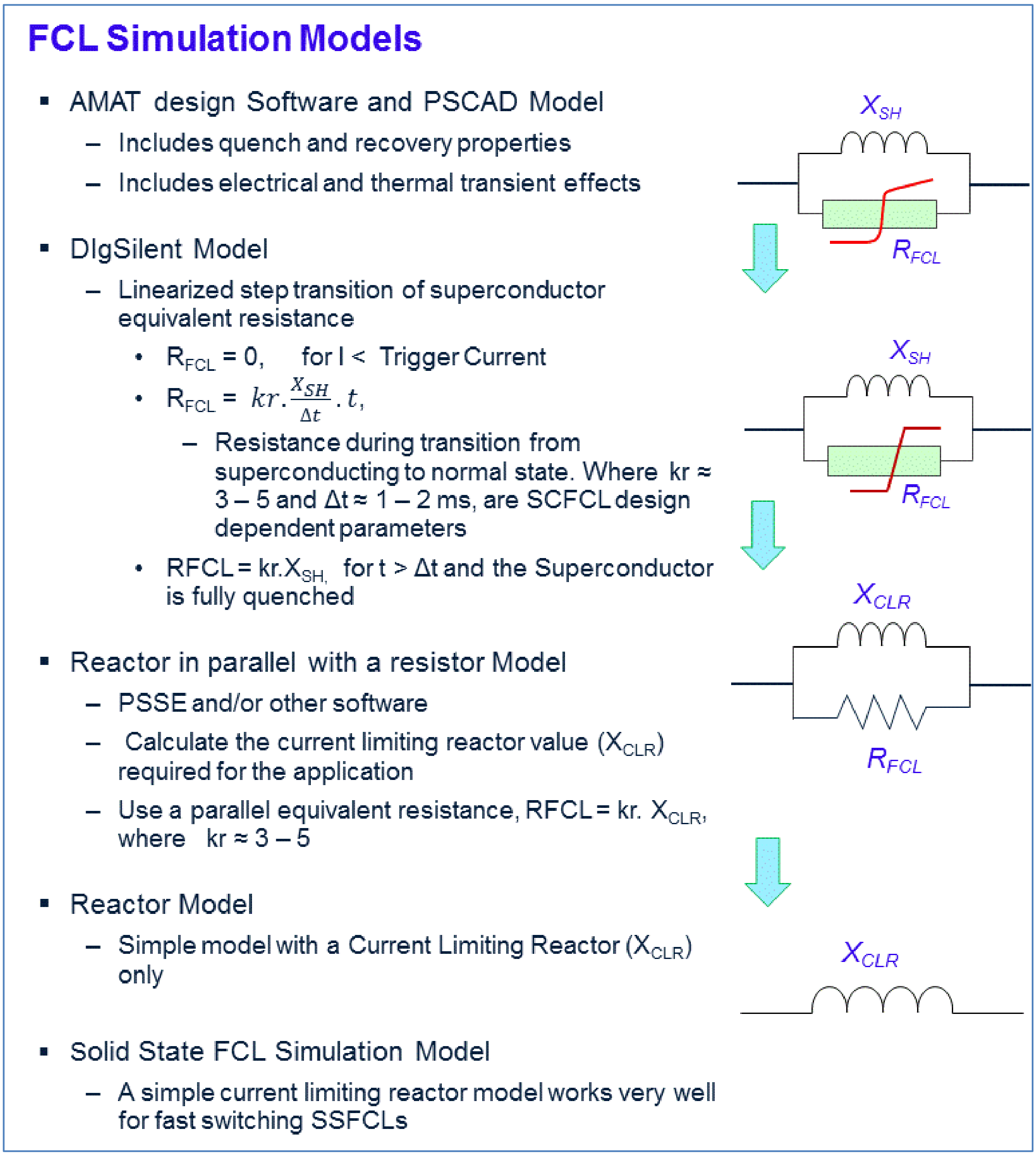


Figure 8 FCL Simulation Models

Figures 9 to 13 show simulation results for different types of FCL models. In general, since the fault current is much greater than the trigger current for the FCL, the FCL circuit in either the SCFCL or SSFCL introduces sufficient impedance within 1- 2 ms. Meanwhile, most of the current transfers to the current limiting shunt reactor. The difference between the physics-based simulation model and those approximations is negligible.

It is important to note that the way both SCFCLs and SSFCLs are designed, the transient overvoltage across the parallel connection of the shunt reactor and the Superconductor or Solid State unit is controlled with voltage control circuits and the simulation models should be used with no concern about the transient overvoltage. The impact of the FCL on Transient Recovery Voltage for breakers is therefore negligible.

Figure 9 shows how the Superconductor senses fault current, quenches, introduces high resistance and current transfers to the parallel shunt reactor and hence fault current is limited by the reactor. This simulation model is based on a 220 kV transmission SCFCL with a prospective fault current of 25 kA (symmetrical rms) and designed to limit the fault current to 12.5 kA, a 50% current reduction including the first peak.

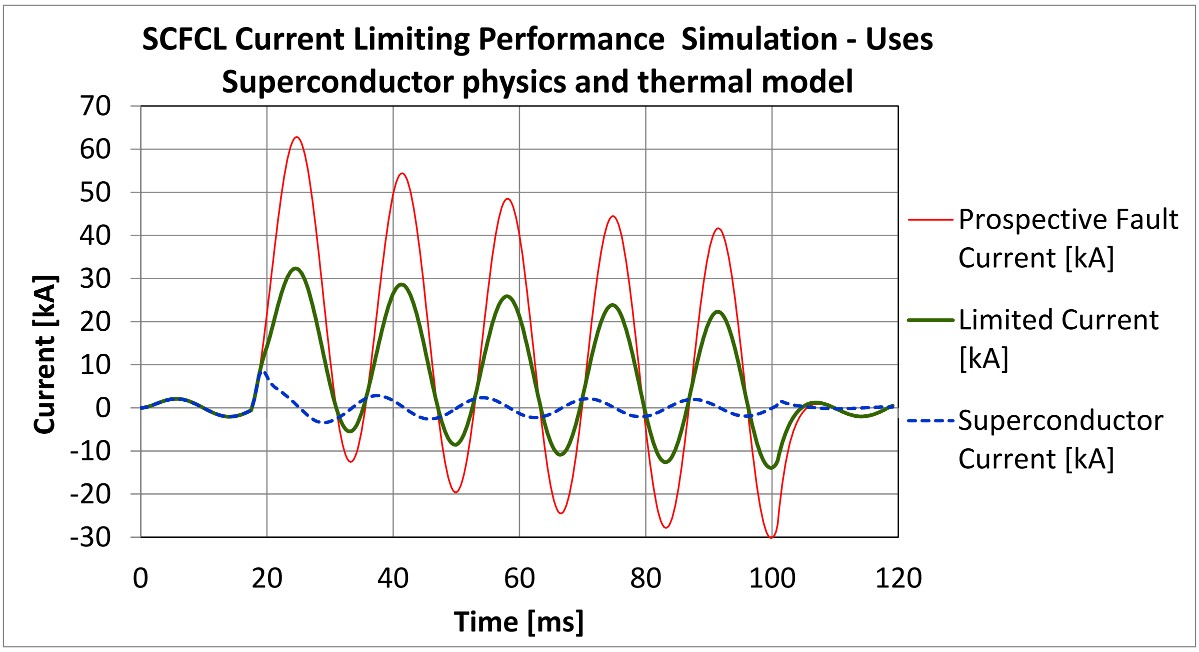


Figure 9 SCFCL current limiting performance simulation using superconductor physics and thermal model

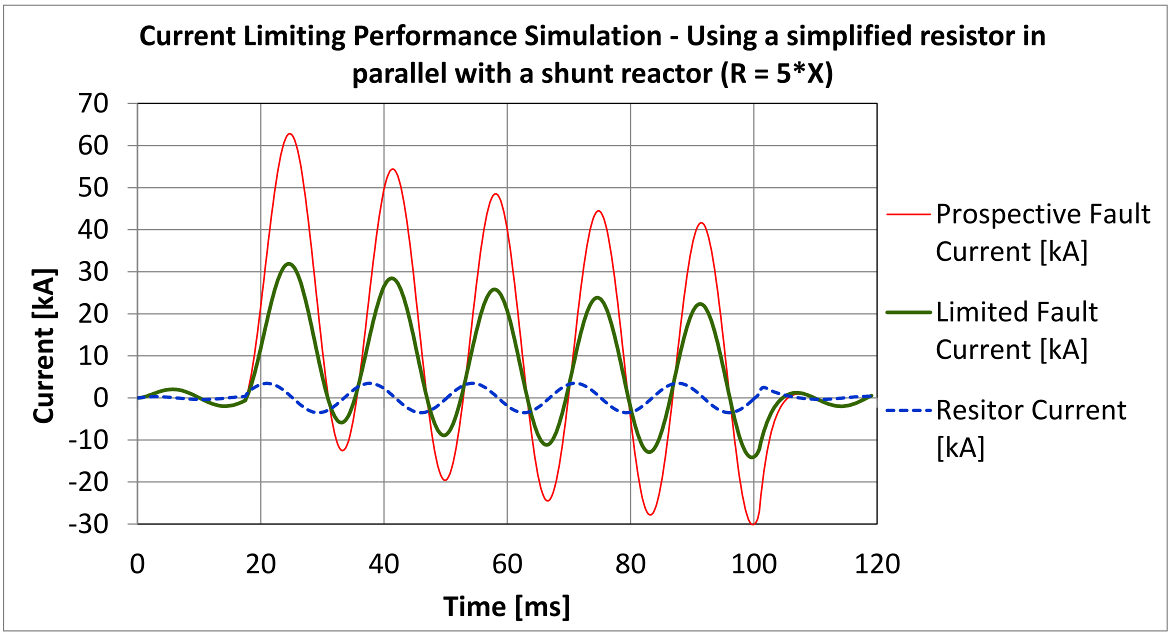


Figure 10 SCFCL model using a reactor in parallel with a fixed resistor

As seen on Figure 10, using a simplified parallel reactor and resistor model misses the transient effects of the Superconductor heating at the start of the fault for around 1 to 2 ms. Neglecting this effect did not affect the overall limited fault current waveform shape of amplitude.

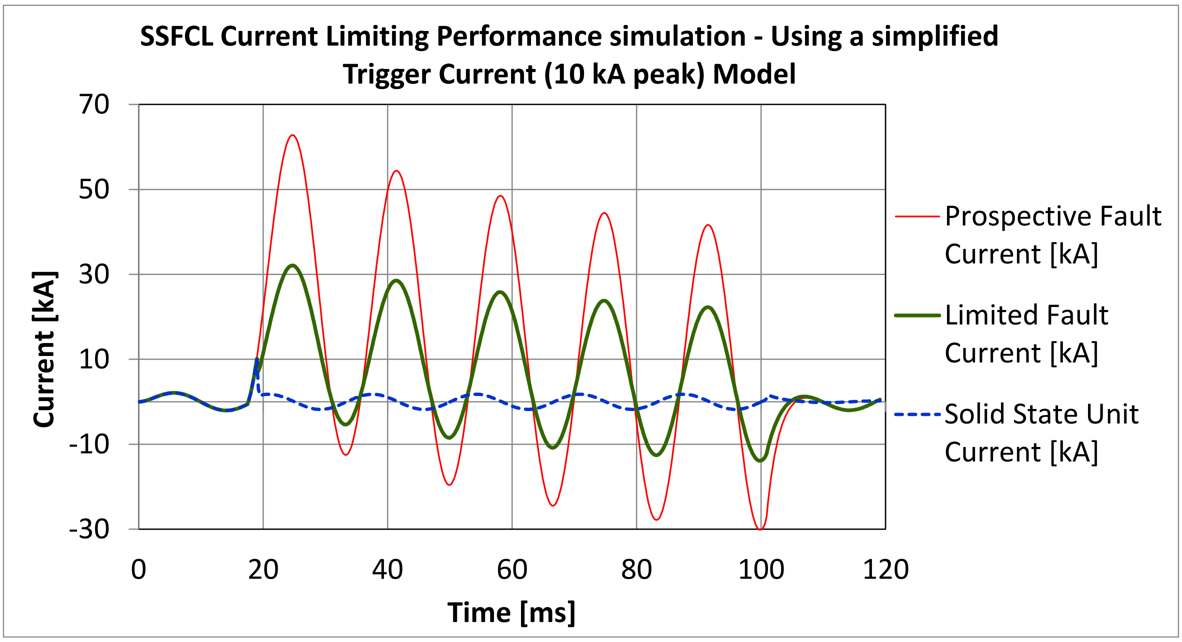


Figure 11 SSFCL Current limiting simulation

Figure 11 shows a simulation of a SSFCL using a pre-set trigger current. This simulation model is based on a SSFCL with a prospective fault current of 25 kA (symmetrical rms) and is designed to limit the fault current to 12.5 kA, a 50% current reduction including the first peak. Compared with the SCFCL, SSFCL simulation is even more suitable for further simplification because of negligible or extremely low current flowing through the SS unit after it triggers the unit and almost all the fault current transfers to the parallel shunt reactor.

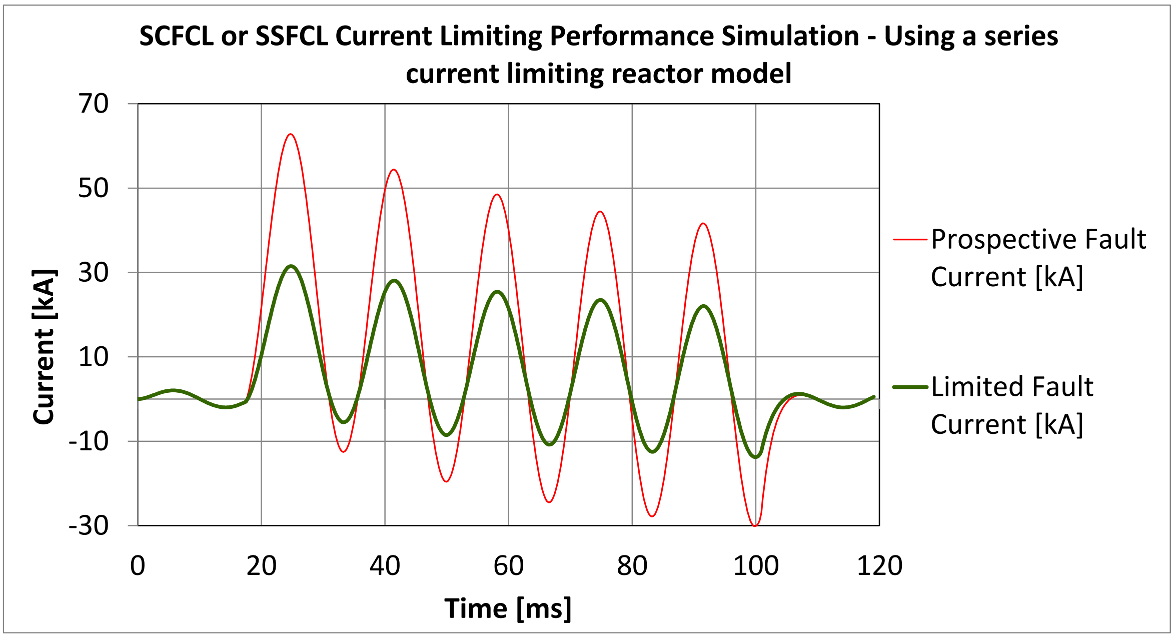


Figure 12 FCL Simulation using a series current limiting reactor

Even with further simplification using a series current limiting reactor, as shown in Figure 12, there is no loss of accuracy on the limited fault current waveform or amplitude.
Figure 13 shows a comparison of four different models described above. For the purpose of short-circuit analysis, utility engineers can use even the simplest model with negligible or no loss of accuracy. The key takeaway here is the FCL knowledge is now available to utility engineers in the form of a simplified simulation model. Utility engineers can design their own FCL and ask the manufactures to make their selected system. It is as simple as selecting the value of a series current limiting reactor.

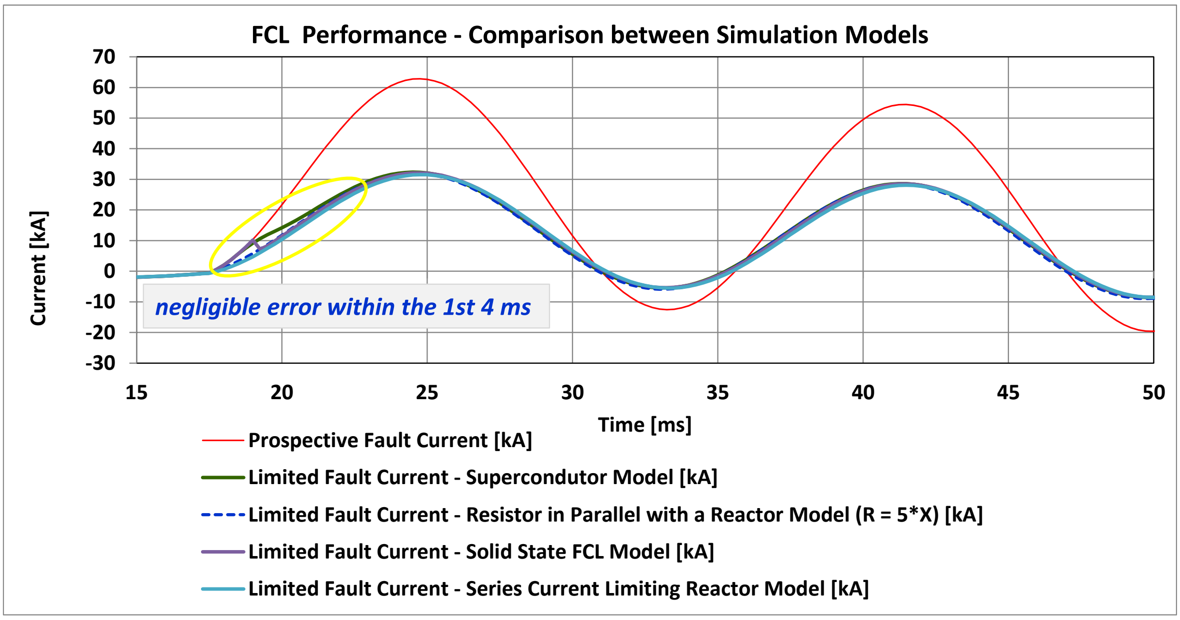


Figure 13 A comparison of four different models described above

One additional FCL performance parameter is the recovery time after the fault clears. Recovery time is mostly associated with SCFCL for obvious reasons, as the superconductor heated and transitioned to non-superconducting state by the fault requires time to cool and return to the superconducting state. The Applied Materials SCFCL is designed to recover within 2 to 3.5 seconds after the fault is cleared. Figure14 shows the typical recovery time is takes a superconductor unit to recover at around 2.2 seconds.

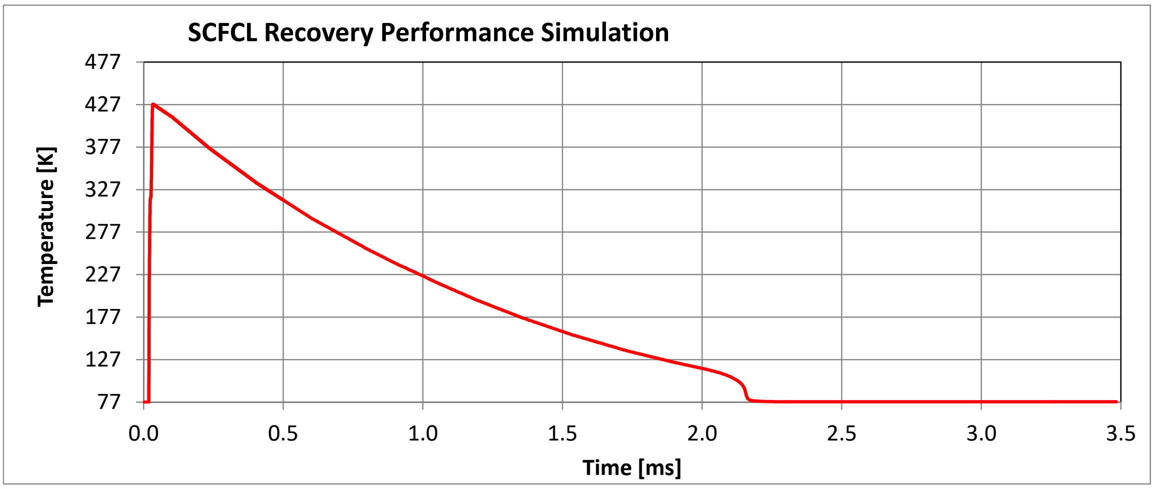


Figure 14 SCFCL Recovery Performance Simulation result

SSFCL can be designed to recover instantly, since there is no component that changes temperature as quickly during the fault. For applications where the recovery time has high impact on the system performance, such as transient stability, voltage stability and protection issues, SSFCL appears to give a clear advantage over SCFCL.

8. Conclusion

As the cost of FCLs continues to decrease and pilot projects move into deployment, FCLs have the potential to alter the way we design and plan the electrical grid. This smart technology can improve safety and reliability, defer capital and offer operational flexibility. Utility engineers may wish to consider adding FCL technologies and systems to the utility toolbox and using them to design a cost-effective fault current management system for existing or future systems.

BIBLIOGRAPHY

[1] Kasegn Tekletsadik, Paul Murphy, Scott Nickerson, Charles Stanley and Semaan Fersan “Progress in Transmission Level Fault Current Limiters” 2013 IEEE PES General Meeting, Vancouver, BC, Canada, July 21-25, 2013

Sizing and Performance Analysis of Grid Connected Battery Energy Storage Systems in Frequency Regulation Application

I.S. Jha[1], Subir Sen[2], Manish Kumar Tiwari[3], Ankur Chakraborty[4]

Power Grid Corporation of India Limited

a.chakraborty@powergridindia.com[4]

Abstract—**Battery Energy Storage Systems are becoming potentially viable solutions for integration of Renewables into the grid. They are being used in various renewable related applications like renewable power smoothing, renewable firming, energy time shift etc. Large scale BESS can also act as a grid connected balancing reserve for frequency regulation application. To earn experience and analyze suitability, Power Grid Corporation of India Limited is implementing a pilot project in Puducherry with three different Battery Energy Storage System (BESS) technologies. Among these technologies Lithium Iron Phosphate and Advanced Lead Acid have already been commissioned. Both the systems are designed for same useful capacity and are being operated under same grid conditions. Therefore their performance is comparable.**

In this effort, comparison has been drawn between advanced lead acid and lithium iron phosphate battery energy storage systems in terms of sizing and performance parameters related to losses and response characteristics.

Keywords—Battery Energy Storage System (BESS); State of Charge (SOC); Frequency Regulation; Energy Time Shift; Depth of Discharge (DOD); Battery Management System (BMS); Power Management System (PMS); Power Conditioning System; Normalized Root Mean Square Error (NRMSE)

I. Introduction

Renewable Energy is becoming increasingly important in the energy mix across the globe owing to various drivers like fossil fuel depletion, energy security, global warming etc. Renewable Energy offers significant benefit in terms of zero carbon emission and low gestation period. However, Renewable Energy resources such as Solar and Wind pose challenges in terms of Grid Integration due to their inherent characteristics of variability, uncertainty and intermittency. Therefore for higher penetration they require mitigating measures in the form of balancing reserves which work as shock absorbers to maintain grid stability.

Due to fast response, flexibility in operation, modular construction and recent decline in prices have made Battery Energy Storage System (BESS) obvious option for renewable integration. BESS are being implemented at source side for renewable output smoothing [1]-[2] and renewable firming applications. On the other hand, large scale battery energy storage system at grid level can help in frequency regulation [3], energy time shift [4], peak shaving and T&D investment deferral applications also.

Power Grid Corporation of India Limited, Central Transmission Utility of India, has established a Battery Energy Storage System pilot project in Puducherry for Frequency Regulation and Energy Time Shift Applications.

In this pilot project, three different technologies: Advanced Lead Acid, Lithium Iron Phosphate and Zinc Iron Flow Battery technologies are being implemented in Puducherry. Among them advanced lead acid and lithium iron phosphate have already been commissioned. Both the systems are having same useful capacity and are installed at same location connected with same feeder thus experiencing same grid conditions. In this paper a comparison has been drawn between them through detailed analysis with respect to sizing and performance related to losses and response characteristics during Frequency Regulation application.

II. CHOICE OF TECHNOLOGY

Today Energy Storage Systems are commercially deployed in different forms such as Mechanical (Flywheel, Pumped Hydro, Compressed Air), Chemical (Hydrogen, Synthetic Natural Gas), Thermal (Molten Salt, Heat), Electrochemical (Different chemistries of batteries like Lead Acid, Li-Ion, NaS, NiMH) etc. Pilot project on Battery Energy Storage Systems was envisaged due to recent advancements in this category as well as their advantages of modularity, scalability and most importantly their fast response.

For BESS pilot project three technologies as mentioned below were chosen:

A. Advanced Lead Acid

Lead-based batteries are being used in various applications for over 100 years. Lead acid cells are robust and less sensitive to application conditions. They can be connected in large battery arrangements without sophisticated management systems. As commercial viability of Lead Acid Battery is already established, it is the most economical grid-connected battery energy storage option [5]. In advanced lead acid batteries, addition of carbon in electrodes increases energy density, power rating, and cycle life considerably.

B. Lithium Iron Phosphate

Lithium Iron Phosphate batteries have the advantages of high energy density, higher efficiency and a maintenance free design [6]. Another major advantage of them is versatility in design and scalability. These batteries can be adapted to any voltage level and power-energy requirement, ranging from high power intensive to high energy intensive applications.

This is also a fast maturing technology with a number of pilot and large scale projects being implemented world-wide.

C. Flow Battery

Flow Battery is an upcoming technology and world-wide many research projects going on in this domain. Vanadium Redox, Ni-Fe, Zinc Iron, Zinc Air etc. are some of the technologies which are increasing their footprints. Flow Batteries offer a higher depth of discharge, longer calendar life and higher cycle life than other conventional battery energy storage options. For the BESS pilot project Zinc Iron technology has been selected.

III. ARCHITECTURE OF BESS

Different Battery Energy Storage Systems are designed independently and hence the DC bus voltage (an integral multiple of cell voltage) is different for each of them. Each BESS comprises of its own Power Management System (PMS) and Power Conditioning System (PCS). PMS and PCS is collectively known as the Battery Energy Management System (BEMS). Functionalities of PMS and PCS is described briefly as follows:

A. Power Management System (PMS)

Power Management System (PMS) comprises of necessary software and hardware to perform pre-programmed applications such as Frequency Regulation and Energy Time Shift.

B. Power Conditioning System (PCS)

The primary function of PCS is to invert DC bus voltage to a pre-defined AC voltage and synchronization with the Grid. The AC bus voltage of 433 V is fixed for all the battery technologies and is defined as the Point of Common Coupling. Apart from grid synchronization PCS also houses the control and protection system of the BESS. PCS is equipped with suitable filter circuits to ensure power quality.

Keeping the overall size of the project and tolerance margin in consideration a 2 MVA transformer is considered for stepping up the 433 V of point of common coupling to local grid voltage of 22 kV.

The Single Line diagram for system connectivity is presented as follows:

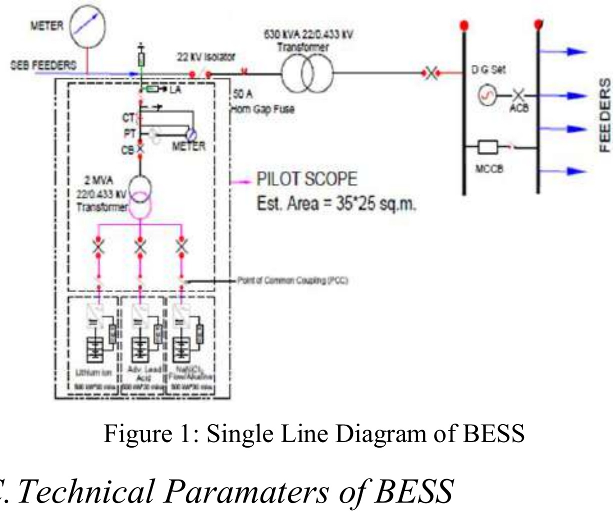


Figure 1: Single Line Diagram of BESS

C. Technical Paramaters of BESS

Advanced Lead Acid and Lithium Iron Phosphate BESS are established with following parameters:

Parameters	Advanced Lead Acid	Lithium Iron Phosphate
Capacity	500 kW, 250 kWh	500 kW, 250 kWh
Charging Rate	3hrs from rated DOD to 100% SOC	3hrs from rated DOD to 100% SOC
DC-DC Round Trip Efficiency	>90%	>80%
Service Life	10 years	10 years
Life Cycle	4000 cycles (900 MWh)	3000 cycles (675 MWh)

Since Flow battery is not being analyzed in this paper hence details of the same are not being explained.

IV. SIZING

Different technologies have different depth of discharge, which affect overall sizing and affect pricing as well. Hence to get economic solution and to keep competition among different technologies BESS capacity was defined in terms of useful capacity at output bus. Technology with higher depth of discharge would require smaller size to achieve useful capacity criteria. For both the technologies under comparison useful capacity is 500 kW, 250 kWh.

As defined by manufacturer of Advanced Lead Acid BESS, rated DOD is 65% (for 3000 cycles), however to keep power rating of 500 kW for 30 minutes with 2C discharge, overall sizing is kept 691.2 kWh constituted by 600 cells. To accommodate the batteries one 40 ft. container is installed, whereas PCS is installed in another 20 ft. container.

For lithium iron phosphate rated DOD is 70% (for 4000 cycles). Since these batteries are suitable for higher power ratings, to match the requirement of useful capacity with 2C discharge, overall sizing is limited to 398 kWh only formed through 1728 Nos. cells. Within one 40 ft. container all batteries and PCS are accommodated.

Footprint of advanced lead acid BESS is 1.5 times higher than lithium iron phosphate, however if we consider clearances in the surroundings of container the area utilized by advanced lead acid BESS is almost double in comparison to lithium iron phosphate BESS.

V. FREQUENCY REGULATION APPLICATION

The design of frequency regulation algorithm is done from this intuitive stage:

i. BESS should charge when grid frequency is higher

ii. BESS should discharge when grid frequency is lower

iii. BESS should remain in idle mode when frequency is within a stable band.

However, another important consideration for frequency regulation application is the State of Charge (SOC) of the Battery. The battery should discharge at a slower rate if the SOC of the battery is lower. Similarly, charging of the BESS should be at lower rate when SOC is higher. Hence, the power charge or discharge algorithm becomes a combined function of grid frequency and SOC of the battery.

Further, it is imperative, to maintain a desired level of SOC in the battery so that the BESS can effectively support the grid in low and high frequency scenarios. To achieve this inside of idle mode of operation in stable frequency band the BESS is designed to slightly charge or discharge during stable frequency band operation depending upon SOC.

The above design can be graphically visualized in the following figure.

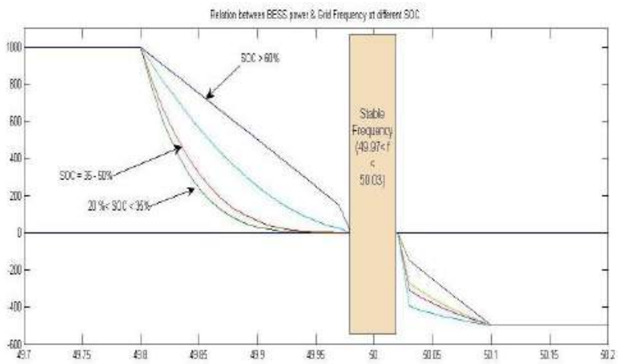


Figure 2: Power *vs* Frequency Characteristics (Ideal)

To keep the options open for applying frequency regulation in various scenarios, complete curve setting is kept settable.

VI. ACTUAL SYSTEM OUTPUTS

After commissioning of BESS for two technologies site data were analyzed to determine the effectiveness of respective BESS in frequency regulation application. Since both the systems are installed separately their control and monitoring system is separate. There is provision to record one minute data for different parameters like frequency, import / export power, import / export energy, SOC etc. There are 1440 data points each day. MATLAB is used to analyze this massive data.

A. Power vs Frequency

During frequency regulation operation, BESS should provide desired power output with reference to measured frequency & SOC. Figure 3 & 4 demonstrate scatter plot between power and frequency for both the systems. It can be observed that both the systems closely followed the power-frequency characteristic as elaborated in the previous section.

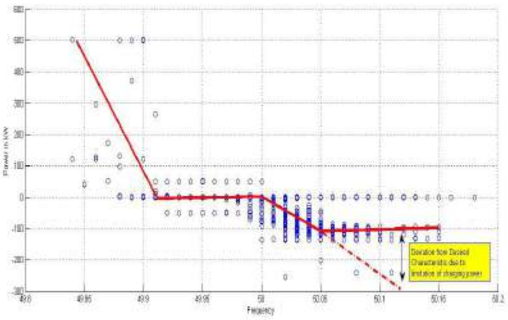


Figure 3: Actual Power vs Frequency Scatter Plot (Lithium Iron Phosphate)

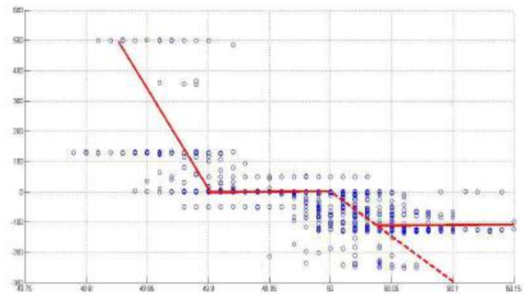


Figure 4: Actual Power vs Frequency Scatter Plot (Advanced Lead Acid)

B. Power vs Time

In this analysis an ideal power *vs* time characteristic is obtained through MATLAB simulation based on the measured frequency of the grid. Actual output of the BESS is drawn in time scale along with ideal output as a function of grid frequency and battery SOC. In the figure 5 & 6 graphical comparison is made between the actual system power output (shown in red) and ideal power output (shown in green). In some instances power output is restricted due to limitation of charging power which is not symmetrical with discharging power. Most of the time BESS actual output is as per design.

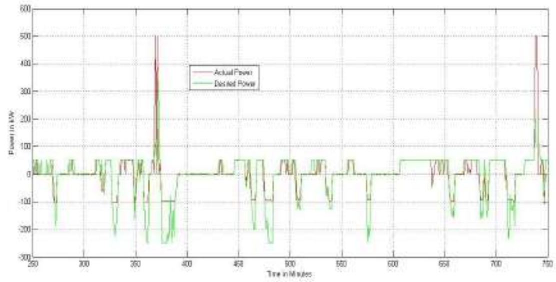


Figure 5: Power vs Time Characteristics (Lithium Iron Phosphate)

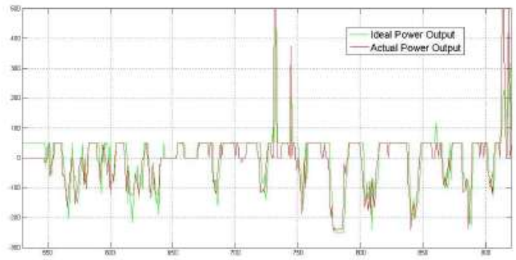


Figure 6: Power vs Time Characteristics (Advanced Lead Acid)

C. System Idle Time

Another important parameter is system idle time, since idle BESS indicates improper utilization of the asset. It is important to understand the situations in which the BESS remains idle. During the stable frequency band operation, the BESS is not idle as it is configured for slight charge/discharge mode. However, in a case where the grid frequency is low and the BESS SOC is too low to perform discharge function, the battery switches to idle mode. Similar case arises, when BESS SOC is too high and the grid frequency is also high. Charge, discharge and idle mode of operation is shown for a typical day in the figure 7 & 8.

The black, white and orange bars in the figure represent discharge, charge and idle mode of operation respectively.

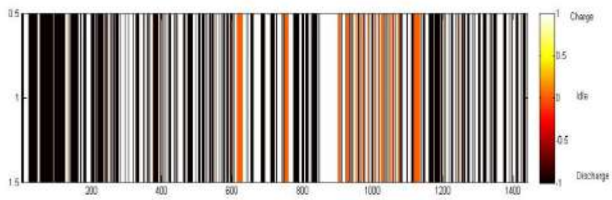


Figure 7: Charge, Discharge and Idle mode of operation (Lithium Iron Phosphate)

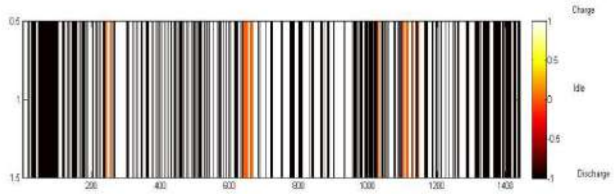


Figure 8: Charge, Discharge and Idle mode of operation (Advanced Lead Acid)

This analysis is very important during commercial operation. Frequency of the grid changes seasonally also and idle time analysis realigns frequency settings to utilize BESS upto potential.

VII. METRICS FOR ANALYSIS FOR BESS

A quantitative analysis is necessary for analyzing the performance of BESS in frequency regulation application. Using such quantifiable metrics a comparison can be drawn between different BESS technologies, highlighting their suitability in frequency regulation application.

The criteria which are considered for analysis and further comparison is presented in this section.

A. NRMSE Error

This parameter defines how closely the actual power output curve follows the ideal power output curve.

Normalized root mean square error is defined as:

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N}(Actual\ Power\ (i) - Ideal\ Power\ (i))^2}{N}}}{Capacity\ of\ BESS}$$

B. Losses

Losses in AC to AC can be considered as an important parameter as it is direct representative of the efficiency of the BESS technology.

Losses in BESS occur typically in two stages: Inside Battery Losses (DC-DC round trip losses) and PCS Losses on both ways. Typically, PCS efficiency of BESS is higher i.e. more than 96%. The AC-AC loss takes into account both the battery and PCS losses and is true representation of loss in BESS.

C. Idle Time

Idle time of BESS is encountered when SOC limits of the BESS is reached. A lower idle time means higher availability of BESS to support grid frequency.

VIII. RESULTS AND COMPARISON

A 3 month window period is considered for analysis of data of two different technologies and evaluating them over the indices as mentioned in the earlier section.

The results are tabulated as under.

Indices	**Advanced Lead Acid**	**Lithium Iron Phosphate**
Average Daily Energy Exchange	489 kWh	512 kWh
Idle Time	12%	10.4%
AC to AC Efficiency	75%	82.82%
NRMSE Error for output power *vs* time	18%	14%

The average energy exchange is dependent upon grid frequency pattern. Further, it is evident that Lithium Iron Phosphate performs better in terms of efficiency and accuracy of power output when compared to Advanced Lead Acid.

IX. FUTURE WORK

Losses in BESS may depend on several internal factors such as SOC, Temperature etc. Future work in this regard, may be carried out to find correlation between BESS losses and battery SOC and cell temperature.

Idle time in BESS occurs when SOC limit is reached and the battery cannot support further charge discharge operation. An optimal control strategy may be defined so as the battery idle time is minimized and it is available for service whenever the grid requires.

In the current pilot project more implementation of applications like voltage support, renewable firming, load following etc. are proposed, which would make this test bed more valuable.

Acknowledgement

The authors of this paper are deeply indebted to the management of Power Grid Corporation of India Limited for their support in publishing the contents of this paper.

References

[1] J. Bamukunde, S. Chowdhury, "A study on mitigation techniques for reduction and elimination of solar PV output fluctuations", AFRICON 2017 IEEE, pp. 1078-1083, 2017, ISSN 2153-0033

[2] R. P. Sasmal, S. Sen and A. Chakraborty, "Solar photovoltaic output smoothing: Using battery energy storage system," 2016 National Power Systems Conference (NPSC), Bhubaneswar, 2016, pp. 1-5.

doi: 10.1109/NPSC.2016.7858894.

[3] I. S. Jha, S. Sen, M. Tiwari, M. K. Singh, "Control strategy for Frequency Regulation using Battery Energy Storage with optimal utilization", 2014 IEEE 6th India International Conference on Power Electronics (IICPE), pp. 1-4, 2014.

[4] S. A. Abdelrazek and S. Kamalasadan, "Integrated PV Capacity Firming and Energy Time Shift Battery Energy Storage Management Using Energy-Oriented Optimization," in IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 2607-2617, May-June 2016.

[5] B. B. McKeon, J. Furukawa and S. Fenstermacher, "Advanced Lead–Acid Batteries and the Development of Grid-Scale Energy Storage Systems," in Proceedings of the IEEE, vol. 102, no. 6, pp. 951-963, June 2014

[6] D. I. Stroe, V. Knap, M. Swierczynski, A. I. Stroe and R. Teodorescu, "Suggested operation of grid-connected lithium-ion battery energy storage system for primary frequency regulation: Lifetime perspective," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, 2015, pp. 1105-1111.

[7] P. Alotto, M. Guarnieri, F. Moro and A. Stella, "Redox Flow Batteries for large scale energy storage," 2012 IEEE International Energy Conference and Exhibition (ENERGYCON), Florence, 2012, pp. 293-298.

CV

Head Researcher

Subir Sen is presently Executive Director (CTU Planning & Smart Grid) in Power Grid Corporation of India Limited. He holds the B.E. degree in Electrical Engineering from the Jadavpur University and M.E degree from the Indian Institute of Science in Bangalore and the Ph.D. degree from Indian Institute of Technology in Delhi. He has been actively engaged in transmission and distribution system planning, development, renewable integration, smart grid application, energy conversion and high voltage electrical power engineering in the last 3 decades. He is actively involved in development of National Grid, Green Energy Corridors and deployment of GIS, FACTS devices, dynamic compensation, energy storage, synchrophasor technology in India.

Associate Researcher

Indu Shekhar Jha is presently the Chairman & Managing director in Power Grid Corporation of India Ltd. Shri Jha is a renowned Power Sector professional possessing professional experience of over 38 years. Experience spans all the facets of power sector; conceptualization, planning, design, engineering, execution, monitoring, etc. Holding an Electrical Engineering degree from NIT, Jamshedpur he has contributed significantly in National Grid formation and introduction of innovative technologies such as HVDC, STATCOM, Flexible AC Transmission system, 1200kV AC, Smart Grid, Wide Area Measurement System(WAMS), Energy Efficiency etc.

Manish Kumar Tiwari is presently working as Assistant General Manager in Power Grid Corporation of India Limited. Graduated in 1994 and Post Graduated in 1996 from Maulana Azad College of Technology, Bhopal (Now MNIT), he has experience of more than 20 years in various fields of Power System viz. Construction/ Operation of EHV/UHV Substations, Design & Implementation of Smart Grid Projects, Energy Efficiency Technologies, Renewables and its integration etc.

Ankur Chakraborty is currently working as an Engineer in Smart Grid department of Power Grid Corporation of India Limited. He completed his B.E from Jadavpur University, Kolkata in 2014 and joined POWERGRID in the same year. He is actively involved in Smart Grid Pilot Project consultancies for various distribution utilities in India. He is also involved in research and analysis of suitability of application of Battery Energy Storage Systems in power systems.

Benefits of implementing Smart Grid in Indian Utilities - An analysis from the pilot projects

I.S.Jha S. Victor P. Selvakumar Henandra Agarwal Dr. Subir Sen
Power Grid Corporation of India Ltd.,
Gurgaon, India
subir@powergridindia.com

Abstract—**Most of the Indian Utilities require improvement in AT&C losses and improvement in reliability of power supply to end-consumers. Deployment of emerging technologies in managing utility business will improve overall efficiency and customer satisfaction level. It is expected that the far-reaching goals of modern Indian power system can be achieved by deployment of smart grids to manage the grids efficiently. In this direction, Government of India has taken lead in deployment of pilot smart grid projects in various states and some are in advance stages of completion.**

This paper presents some of the learning from various Smart Grid Pilots projects being implemented in India.

Keywords— Smart Grid, Distribution, Smart Meter

I. INTRODUCTION

Smart Grid is defined to include a variety of operational and energy efficient measures - including smart meters, smart appliances, renewable energy resources and energy efficiency resources.[1] Electronic power conditioning and control of the production and distribution of electricity are important aspects of the smart grid.

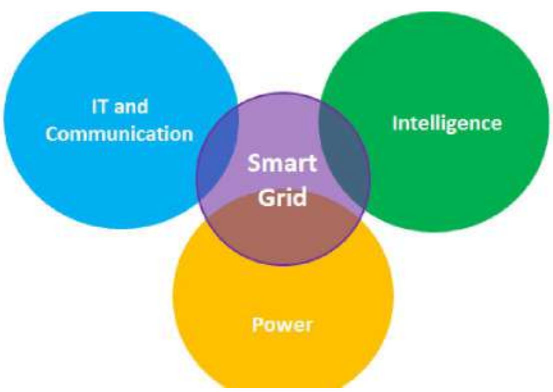


Figure 1: Smart Grid System

The emergence of IT and intelligent devices has offered immense opportunity for its synergic use to mitigate all the challenges. Today, two-way communication between devices and traffic of terabytes of data over wired/wireless networks is a reality. The integration of communication, computational and advances in power devices can be harnessed to develop Smart Grid; a grid which is smart enough to communicate with its users, managers and can take self-healing measures in case of contingencies to enable utilization of facilities to the extent possible.

II. SMART GRID ATTRIBUTES

The broad attributes of smart grid which are being demonstrated in pilot projects are as follows:

1. Advanced Metering Infrastructure (AMI)
2. Outage Management System (OMS)
3. Demand Side Management (DSM) & Demand Response (DR)

III. SMART GRID IN INDIA

Smart Grid Vision for India is: "*Transform the Indian power sector into a secure, adaptive, sustainable and digitally enabled ecosystem that provides reliable and quality energy for all with active participation of stakeholders*."[3] It is aligned to the Government's overreaching policy of "Access, Availability and Affordability of Quality Power for all".

In distribution sector various pilot smart grids are being developed at various states for different Utilities. Total twelve pilot projects are being funded under *Integrated Power Development Scheme* (IPDS) & four projects under *National Smart Grid Mission (NSGM).* Following major projects which are in advanced stages of implementation have been taken under consideration for analyses:

Table 1: Smart Grid Projects in final stages of implementation [2]

Utility Name	Pilot Project Location	No. of Smart Meters installed
1. CESC, Mysore	V.V. Mohalla (Additional City Area Division)	About 20,000 smart meters installed and commissioned
2. PED, Puducherry	Division No. 1	About 1,600 smart meters installed and commissioned
3. HPSEB, Himachal Pradesh	Kala Amb Industrial Area	About 1,200 smart meters installed
4. TSECL, Tripura	Electrical Division No. 1, Agartala	About 15,000 smart meters installed

A. Real time consumption monitoring

Smart grid facilitates real time monitoring of consumption at consumer, DT, feeder as well as area levels.

Real time monitoring of energy consumption patterns, various alarms associated with it have been made possible with AMI system. Utility operators can monitor the loading across the distribution network on real time basis and take the mitigating measures for any overloading or tampering anywhere in the grid. Moreover, historical data can also be fetched in graphical or tabular forms for further analysis.

Daily consumption patterns at area levels help the utility to take decisions regarding peak load management. These patterns further help the system in load forecasting as well.

Consumption patterns at consumer levels gives information to the utilities about sanctioned load violations & tampering.

B. Real time Energy Audit

One of the main benefits of Smart Grid is that it has facility for real time energy audit at area levels, feeder levels as well as transformer levels. Such audits help the utility in segregating and identifying areas contributing to more losses/ thefts.

Real time Distribution Transformer (DT) wise energy audit is made using Advanced Metering Infrastructure. An example of monthly audit of a 11kV feeder is shown at Figure 2.

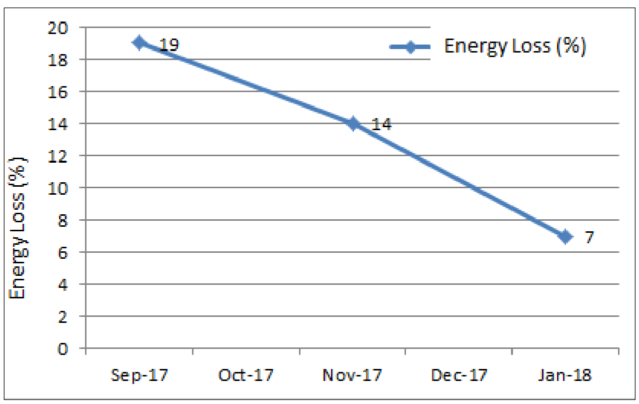


Figure 2: Percentage energy loss for a given 11kV feeder

From Nov 2017, one 11 kV feeder was monitored with around 95% of meter data availability. Major reduction in Energy loss and improvement in billing efficiency was recorded for the given feeder. The improvement from Sept 2017 to Jan 2018 was mainly due to availability of accurate and complete meter reading.

Further, such audit can also be performed at DT level. An example of real time DT wise energy audit is shown in Figure 3. Such audits can help in identifying and pointing out the consumers rendering losses to the system. Any abnormality, which is more than the normal technical loss can be identified as suspected and investigation can be carried out to identify the loss and to rectify that.

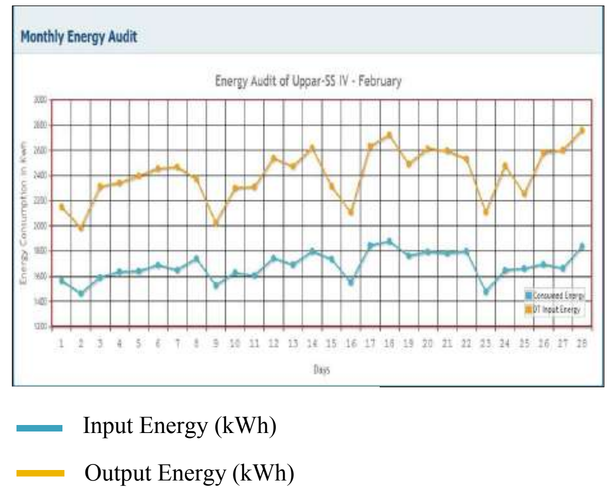


Figure 3: Real Time DT wise Energy Audit (at puducherry)

C. Load Forecasting

Load forecasting at distribution level is done using historical data. Unlike forecasting at National or State levels, this forecasting rely on the historical data from smart devices like Smart Meters, DTMUs, etc. Load forecasting has been implemented in Mysore project. The calculations for load forecasting involve the following:

- Analysis of the daily, monthly & yearly loads to forecast the peak load
- Feeder Load Forecasting based on the previous consumption patterns obtained from SCADA
- Transformer Load Forecasting based on the data from TMUs installed. This is a self-learning model.
- Forecasting takes care of the effects of Holiday, Rain, and Temperature etc.

A comparison of forecasted load vs. actual load is shown in Figure 4. It shows that a considerably accuracy of forecasting has been achieved in this project.

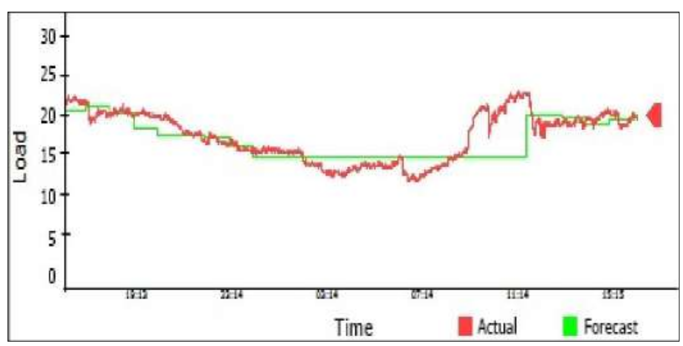


Figure 4: Project Area load vs load forecast

D. Outage Management System (OMS)

To bring down outage duration and ensure reliable supply to consumers, Outage Management System (OMS) software have been installed at control centers which are integrated with the field devices like Distribution Transformer Monitoring Unit (DTMU) and Fault Passage Indicators (FPI). DTMU monitors various parameters of distribution transformers (DT) like oil level, oil temperature, load, voltage, harmonics, unbalance etc. in real time. Daily average Loading and temperature profile monitored through a DTMU is shown in Figure 5 & Figure 6. FPI facilitates in quick detection and identification of faulty network. Outage information is sent to control center through GPRS communication at regular interval.

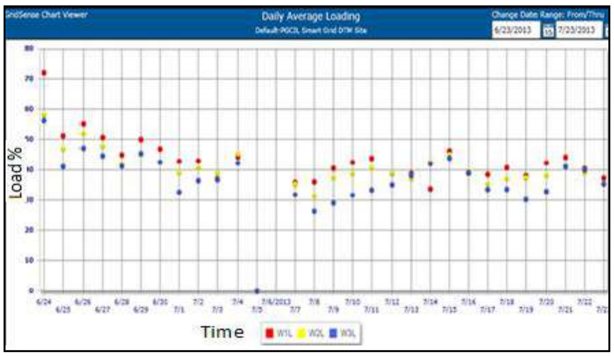


Figure 5: Daily Average Loading of a DT

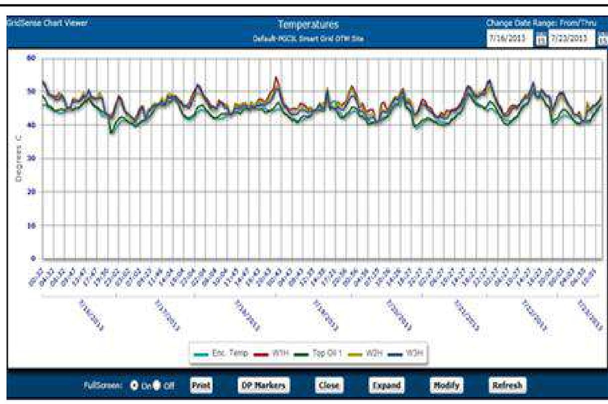


Figure 6: DT Temperature Monitoring through DTMU

Outage Management System (OMS) also facilitates Fault Management & Work Force Management which is done using smart devices like CFPI, sectionalizer, autorecloser & RTUs:

- CFPIs and RTUs are installed on 11 kV Feeders for real-time monitoring of network health
- Fault Occurrence on the 11kV line communicated through the RTU to the FMS at the SGCC
- Fault localization for operations support
- The WFM application notifies the Crew to respond to the fault

Field installation of fault management equipment is shown in Figure 7. OMS software helps the Utility to mobilize the field staff and Fault passage indicators further help the field staff to locate the fault quickly and minimize the restoration time.

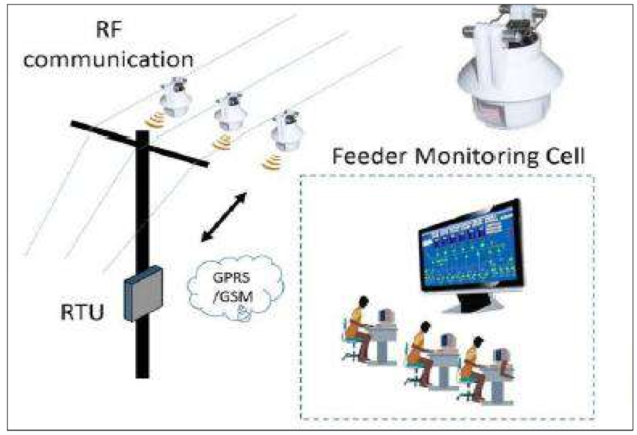


Figure 7: Fault Management/Work Force Management using CFPI

E. Real Time Asset Monitoring

Smart grid enables real time monitoring of assets. The most expensive asset is distribution transformer hence it is provided with special “Transformer Condition Monitoring System” (TCMS). Other assets like smart meters, data concentrator units (DCUs), FPIs, sectionalizer etc. can also be monitored remotely from control room.

The Transformer Condition Monitoring System (TCMS) provides the following parameters to control room on real time basis:

- Load Parameters
- Load balance /unbalance
- Energy dispensed
- Power Quality parameters
- Power on/off status
- Transformer Temperatures
- Surface temperatures
- Ambient temperature

Figure 8: Real time monitoring of percentage kVA and kW of Transformer

Figure 8 shows real time monitoring of kVA (%) and kW (%) of a 250kVA distribution transformer in Mysore. It was observed that the percentage loading of transformer was mostly within 20%. If any distribution transformer is loaded constantly less than 20%, then it is uneconomical for the utility. Such 250 kVA transformer must be replaced with a lower rating transformer and this way it cuts down the inventory cost of utility. The utility replaced this 250KVA transformer to 100 KVA based on this study.

Smart grid also helps utility in detecting unbalance in power supply as shown in Figure 9, which reduces the overall efficiency of the system. It facilitates the utility in planning mitigating measures for optimum utilization of the grid.

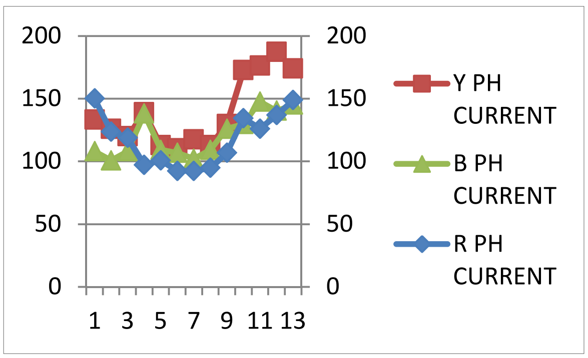


Figure 9: Unbalance in 3 phase supply

AMI also helped utility in detecting variation in voltage at consumer end as shown in Figure 10.

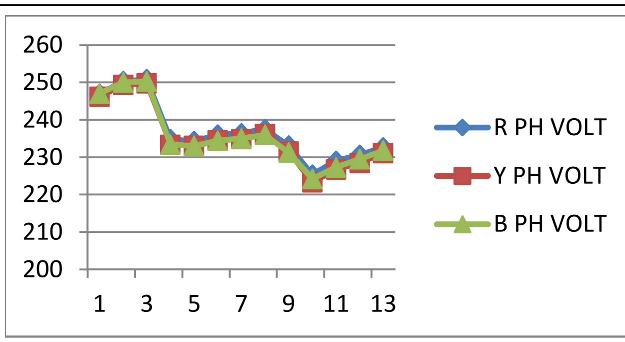


Figure 10: Voltage at Consumer End

F. Tangible Benefits of Smart Grid

Some of the tangible benefits on implementation of initial phase of Smart Grid pilot Projects are as summarized below:

a) Improved metering and collection efficiency: Metering efficiency increased by 14 % in the project area. This resulted in corresponding increase in billing efficiency.

b) Improved Billing Cycle: Remote meter reading through AMI has enabled simultaneous collection of meter reading for a large consumer base. Therefore, utility is working on modification of billing cycle that would improve collection and cash flows.

c) Detection of sanction load violation.

d) Many cases of tampering detected and mitigating measures taken.

These pilot projects are further helping in Indigenization of technology and evolution of a suitable commercial mechanism. The project also aims at preparing groundwork for policy advocacy, regulations, standards, and evolution of a commercial mechanism among other things. It is also pertinent to mention that there is no resistance from customers end for installation of smart meters and rather they have expressed satisfaction based on the inputs received from the meters.

IV. ACKNOWLEDGEMENT

Authors are thankful to the management of POWERGRID for granting permission to present the paper. Views expressed in this paper are of the authors only and need not necessarily be that of the management of POWERGRID.

REFERENCES

[1] "Federal Energy Regulatory Commission Assessment of Demand Response & Advanced Metering" (PDF). United States Federal Energy Regulatory Commission. United States Federal Energy Regulatory Commission.

[2] http://www.indiasmartgrid.org/nsgm.php

[3] “Smart Grid Vision for India”, Ministry of Power (MoP), Govt. of India, August, 2013

Synchrophasor measrement based Analytics for Indian Power Grid

I.S. Jha, [1] Subir Sen[2], Vineeta Agarwal[3],Awanish Kumar[4]

Power Grid Corporation of India Ltd.

awanish.kumar@powergridindia.com[4]

Abstract— **Present transmission grid is an interconnected network for large power transfer across the geographically spread regions. This has introduced complexity in system operations. The expectation of smart technologies in transmission is to have self-healing capabilities which means in case of equipment failure, isolation of transmission lines and generation sources, sudden change in demand etc., the system should recover and remain stable. Measurement and monitoring technologies play a key role in achieving smart grid features. Such advance technology will improve situational awareness by enhanced visualisation system to the operator and will facilitate in actuating control signals to improve reliability and efficiency thereby moving towards self-healing.**

This paper presents development of PMUs based measurement along with analytical applications for the Indian Grid. The paper also highlights merits of individual analytics along with illustrations from PMU data deployed in the Indian grid.

Keywords— Phasor Measurement Unit (PMU), Wide Area Measurement System (WAMS), Smart Grid, Phasor Data Concentrator (PDC), Unified Real Time Dynamic State Measurement (URTDSM)

I. Introduction

Synchronized measurements are the next generation of paradigm shift technology, enabling improvements in planning, operating and maintaining the Electric Grid. The real-time measurements have lot of potential applications and would help the system operator and planner in general. Some of the applications that are studied & discussed in literature are:

- Optimization towards transmission corridor capability.
- Identification of voltage instability
- Load shedding and other load control techniques such as demand response mechanisms to manage a power system stable operation & economics.
- Increase the reliability of the power grid by detecting faults early, preventing local events allowing for isolation of operative system, and the prevention of power outages.
- Monitoring of Inter-area oscillations
- Adaptive islanding
- Network model validation.

WAMS (Wide Area Measurement System) & its utilisation using big data techniques are important thrust area of research among utilities & academics across world. In line with the international findings & suggestions from experts, following analytical applications are taken up at first as a part of research & development with premier academic institute.

- Line Parameter Estimation
- Vulnerability analysis of distance relays
- Linear state estimator
- Supervised zone-3 distance protection
- CT/CVT calibration
- Control Schemes for improving system security (based on angular, voltage and frequency instability)

The work done so far on the analytics & experience gain in deploying the analytics is briefly discussed in this paper.

II. SYNCHROPHASOR MEASUREMENTS

Synchrophasor measurement is a time synchronized measurements across the widely spread power system network. Time synchronization allows phasors at different locations to be time-aligned and thus provide a comprehensive view of the entire grid. Phasor Measurement Unit (PMU) is the basic device used in Synchrophasor measurements that samples the voltage and current signal at field and converts them into phasors. These phasors are time tagged through a pulse from GPS and streamed at the frequency of 25 to 50 cycles per second. Phasor information is referenced with the GPS signal and transmitted in IEEE 37.118 format .Phasor Data Concentrator (PDC) collects the information from multiple PMU & PDCs, align the data by time tag and create a synchronized system wide snapshot.

Data from PMU are well suited for activating local and centralized control thereby making existing grid smarter. In India PMU pilots in all 5 regions were done with few PMU at different locations & it was observed that visualisation & situational awareness has increased manifold with pilots commissioning. Further Synchrophasor data is being utilized in offline mode for forensic analysis of faults, post-dispatch analysis of grid performance and, detection and analysis of oscillations in the power system. Gaining Experience from the pilot & recognising the need of WAMS applications in Indian Power System, URTDSM (Unified Real Time Dynamic State Measurement) scheme has been taken up for wide area measurements. The scheme includes installation of more than 1700 PMUs on substations at 400kV level and above in the State & Central grids, all generating stations at 220kV level and above HVDC terminals, important inter-regional connection points, inter-national connection points etc., provision of PDC at all SLDCs, RLDCs and NLDC along with visualization aids. This shall facilitate an URTDSM towards improved system operation. Monitoring, Visualization and analytics plays a key role in providing intelligent information to operator for secure & reliable grid operation. The paper discusses in brief the important visualization tools & analytics being planned under URTDSM project for Indian Power Grid.

III. PMU ANALYTICS

a) Line Parameter Estimation

In transmission system accurate line parameter information is required in line protection for relay settings, in network model, load flow analysis tool etc. Incorrect line parameter can lead to erroneous results in each of these applications. In the proposed analytics Line Parameters are estimated using Total Least Square Methods with measurements from PMU [1], [2]. The test setup to estimate the line parameters was carried out with following different field conditions:

- Open circuit test with Line opened from one end & charged from other end
- Short Circuit test (Line to Ground fault)-for zero sequence parameter

The test was conducted on Balipara-Bongaigaon line & the results obtained through PMU data are shown on graphical interface being developed for Line Parameter Estimation analytics (Figure 1). The estimated values have been found in line with the field measured values.

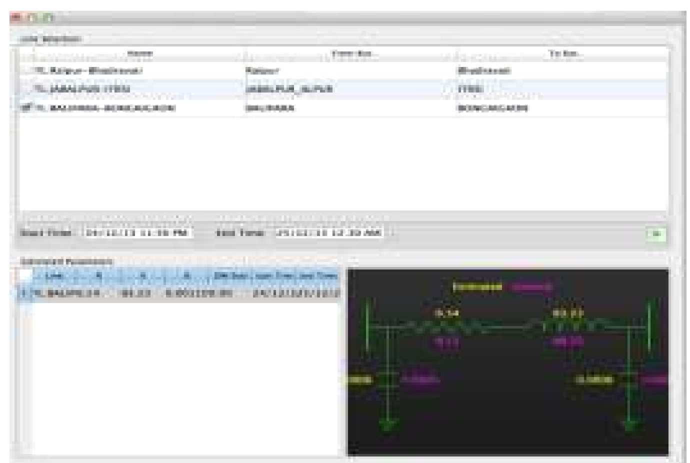


Figure 1: Line Parameter Estimation Analytics

The tool is designed to operate on historical data. The duration of data (like 1 hr, 6 hr etc.) can be configured in the developed tool. The analytics can be configured to run on-demand based on different loading conditions of the line, time of the day etc. It is also possible to process the transmission lines in batch or group and store the evaluated parameters for further analysis.

b) Vulnerability Analysis of Distance Relay (VADR)

Relays are configured with bias towards dependability, which means that they can issue false trip signal due to remote fault or under high stress. Also, with changing network conditions over the passage of time may render relay vulnerable. The mal-operation of such relays can pose threat for grid security.

The aim of this module is to use PMU based measurements to identify such relays that are vulnerable to insecure tripping in the event of remote faults.

The vulnerable relays are identified by monitoring their apparent impedances. In normal situation, the trajectory of apparent impedance will be confined within a very small region, i.e. almost stationary, and that too at a faraway distance. Fault in the associated line or in a neighboring line will cause impedance to drop. Fault on same line will cause the impedance to enter Zone-1 characteristics while that on a neighboring line will lead to Zone-3 being entered. Apart from fault, events like power swings and load encroachment can also cause the relay trajectory to get into the proximity of Zone-3 or even enter it. If the impedance remains in close vicinity for long duration then it indicates that a bigger kick to the system or during more stressed condition, trajectory may enter Zone-3 and remain there long enough for relay to operate. Hence, such events, where apparent impedance gets closer to the Zone-3 indicates vulnerability of the relays. The module basically identifies such vulnerabilities and logs them.

The relay characteristics from the actual relays are modeled in the analytics (Figure 2). This analytics module continuously checks the vulnerability of relays during stressed condition. Hence, it can expose hidden failures of relays before it can cause any bigger damage to system. A power swing event has been captured by the analytics (as depicted in Figure 2) where impedance trajectory can be seen entering into zone-3 of the relay.

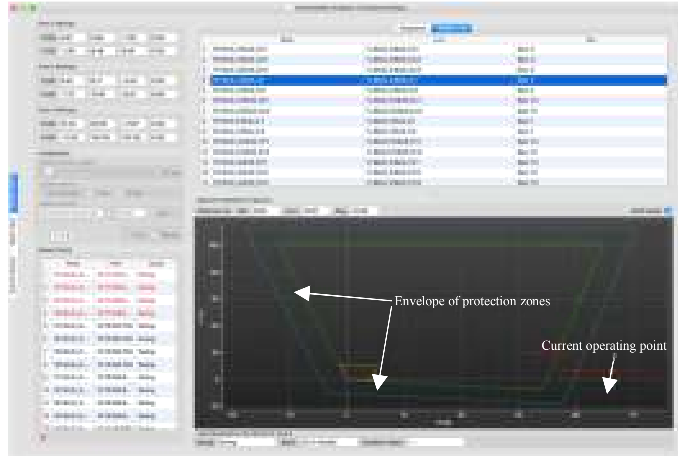


Figure 2: VADR Analytics-Single view

The above figure (Figure 2) shows the client side (user interface) of the analytics which can be invoked on-demand by the user, however, server side of the analytics has been programmed efficiently for continuous run on each sample (40 msec interval) of real-time PMU data. A dedicated analytics server with redundant hardware & software along with its interface with PDC on IEEE 37.118 protocol0 has been established to fetch real-time PMU data.

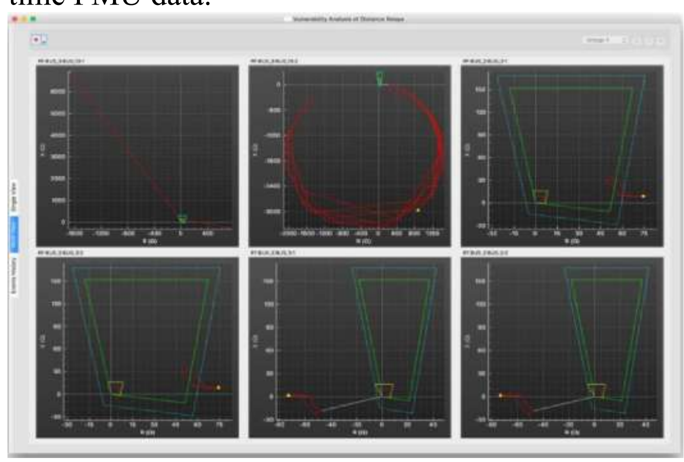


Figure 3: VADR Analytics-Multiview

The user interface has been built with the functionality such as Multiview where multiple relays can be grouped & visualised simultaneously (Figure 3). Events like power swings, load encroachments, faults etc. are characterised and stored in server for analysis.

c) *Linear State Estimation*

Traditionally, a state estimator uses asynchronous measurements of real and reactive power flows and voltage magnitudes. This makes the state estimator non-linear and hence iterative techniques are required. It can suffer from convergence issues. With PMUs in place, it is possible to synchronously measure voltage and current phasors. As a result, state estimation becomes a linear problem and hence can be solved in a single step (non-iterative). The various stages in Linear State Estimator available are as shown in Figure 4.

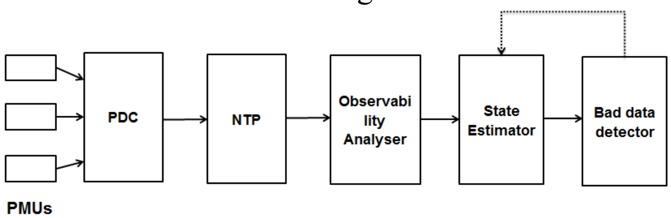


Figure 4: Various stages in state estimation computation

As presented above, the various stages & their functionalities can be described briefly as:

Observability Analyzer: Based on the available measurements, this module computes extent of observability, i.e. buses whose voltages can be estimated.

Network Topology Processor: An NTP processes real time circuit breaker status to obtain current transmission network topology [3].

Bad Data Detector: In rare events, it may happen that few measurements are significantly erroneous, say due to instrumentation failure. This module will help to first identify presence of any bad data and if yes, tries to locate the source of bad data.

Visualization of state estimator output can be shown in tabular as well as graphical form. Power system conditions can be played-back along with the topology connectivity and flow measurement. This analytics helps in detecting islands by means of alarms & warnings for model inconsistencies & limit violation. The various views available in the user interface are shown below in Figure 5 & Figure 6.

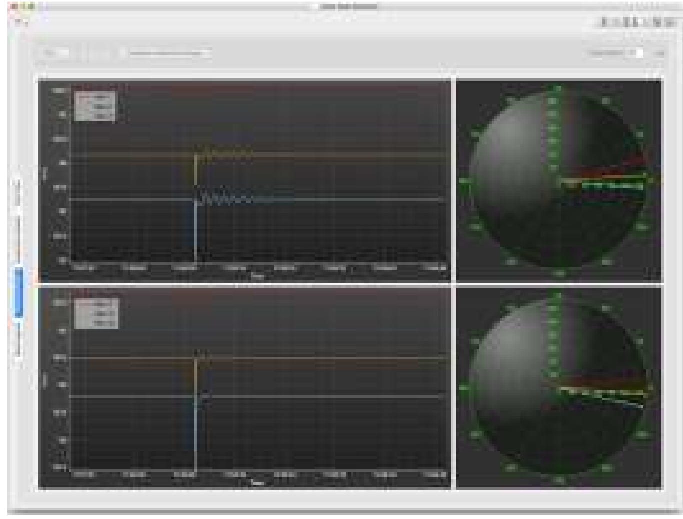


Figure 5: LSE output Trending plot (Magnitude and Angle)

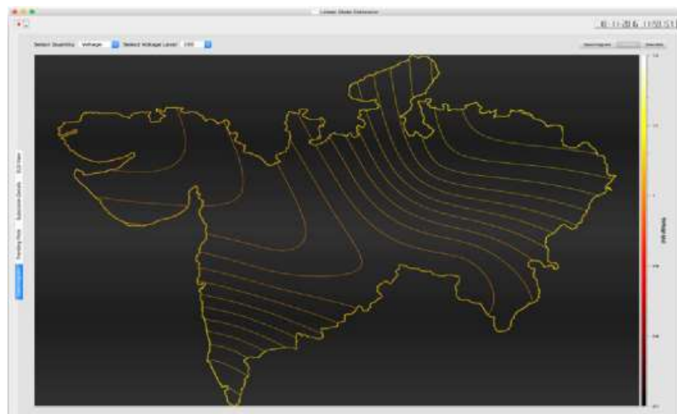


Figure 6: LSE output contour view

d) *Supervised Zone-3 distance protection*

This analytic will implement an adaptive remote backup protection scheme to avoid unwanted zone-3 tripping due to quasi-stationary conditions like load encroachment or electromechanical oscillations like power swings. This analytics will work on real-time PMU data. Following are the features of this module.

1. Identification of presence of persistent fault in the observable system.
2. With PMUs placed at both ends of the transmission lines, differential currents can be computed to identify fault and decide whether the Zone-3 of the back-up relay should be blocked or not. Once, the Zone-3 is blocked, the relay won't operate even if it sees low impedance

3. The software will generate control signal for blocking of Zone-3 protection based on system condition and adopted protection philosophy

In the below Figure 7 shows utilization of field PMU data to demonstrate propagation of signal which is being generated to block relay when there is no fault in the target line.

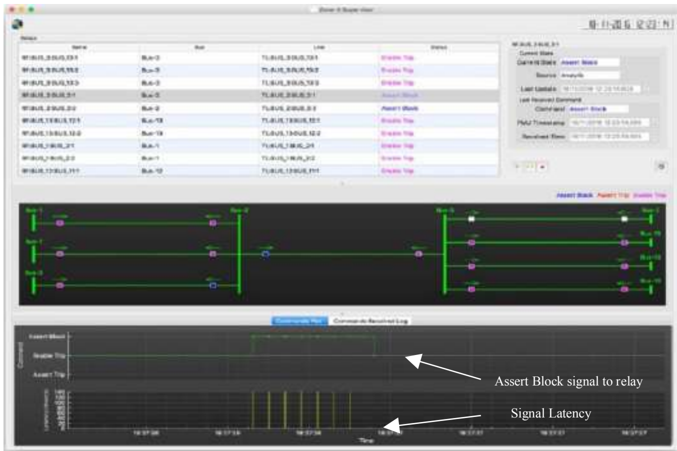


Figure 7: Command View of Pilot Zone-3 analytics

e) CT/CVT Calibration

Instrument transformers, especially CVTs, suffer from drift in characteristics under different operating conditions resulting in biased state estimation. This module will evaluate the accuracy of these instruments using highly accurate Synchrophasor measurement.

The errors will be logged and reported to a system operator. Internal corrections for state estimation will be done and facility to update measurements using correction factor will be provided.

f) Control Schemes for improving system security

Control schemes are fast and high impact schemes to ensure system integrity, or at least minimize the adverse effects of a disturbance. Global signals provided by synchrophasors will allow for more reliable decision making. Controls, involve automatic actions taken in relatively short time (2-3 Sec) where direct operator intervention may not be feasible. The module will continuously monitor and analyse the stability (like voltage & angular) based on the trajectories of various parameters like voltage, current, breaker status etc. and detect events which may harm the system integrity. Based on the analysis of the evolving trajectories a decision on whether to take an automatic control action and its quantum & location has to be taken by such a scheme.

Examples of controls are adaptive load tripping, generation tripping, and utilization of short term capabilities of HVDC/ FACTS, adaptive protection schemes/philosophies and controlled system separation.

IV. Conclusion

The deployment of PMUs under URTDSM scheme is under progress. Analytics such as Line Parameter Estimation, Vulnerability analysis of distance Relay, Linear State Estimation & Supervised Zone-3 distance protection have been developed in association with IIT Bombay & are being deployed on analytics server at control centers across India to analyze & observe the performance. The other applications CT/CVT calibration & control scheme are under development stage. Based on pilot deployment experiences & field inputs, these applications are being fine-tuned to address challenges posed by highly dynamic & fast growing Indian Power Grid.

V. Acknowledgement

Authors are thankful to the management of POWERGRID for granting permission to present the paper. Views expressed in this paper are of the authors only and need not necessarily be that of the management of POWERGRID.

References

[1] D. Lan, B. TianShu, and Z. DaoNong, “Transmission Line Parameters Identification Based on Moving-Window TLS and PMU Data,” in The International Conference on Advanced Power System Automation and Protection, vol. 3, Oct. 2011, pp. 2187–2191.

[2] G. H. Golub and C. F. V. Loan, “An analysis of the total least squares problem,” SIAM Jornal on Numerical Analysis, vol. 17, no. 1, pp. 883–893, Dec. 1980.

[3] S. Pandit, S. A. Soman, and S. A. Khaparde, “Object-oriented network topology processor,” IEEE Computer Application in Power, vol. 14, no. 2, pp. 42–46, Apr. 2001.

[4] C37.118–2005: IEEE Standard for Synchrophasors for Power Systems , IEEE Std., 2006.

CV of Head Researcher

Subir Sen is presently Executive Director (CTU Planning & Smart Grid) in Power Grid Corporation of India Limited. He holds the B.E. degree in Electrical Engineering from the Jadavpur University and M.E degree from the Indian Institute of Science in Bangalore and the Ph.D. degree from Indian Institute of Technology in Delhi. He has been actively engaged in transmission and distribution system planning, development, renewable integration, smart grid application, energy conversion and high voltage electrical power engineering in the last 3 decades. He is actively involved in development of National Grid, Green Energy Corridors and deployment of GIS, FACTS devices, dynamic compensation, energy storage, synchrophasor technology in India.

.

DAY 2: 21ST FEB 2018

SESSION 2:

GRID OPERATION

Research Paper

On

"Optimization of Energy harvesting from Solar Micro Grids through Distributed Storage & Vehicle Grid Integration Strategy with Demand Response / Predictive Scheduling Framework"

Submitted by

Dr. V. Manikandan*, Dr. S. Elango, Dr. G. Manavaalan

Coimbatore Institute of Technology, Coimbatore-641 014

Er. A. D. Thirumoorthy, *Technical adviser, IWPA*

Er.D.Vijeswaran, AEEE, TANGEDCO, Govt. of Tamilandu

Mr. S. Ravichandran, Intrepreneur (Power Equipment designer)

Dr.Rajit Gadh, Director, SMERC, UCLA, USA

**Corresponding Author: manikantan.cit@gmail.com*

Submitted to

International R & D Conclave

on

Emerging Opportunities and Challenges of R & D in Indian Power

Ministry of Power, Government of India

I. Objective:

Design & Demonstration of innovative Electric Vehicle Charging Grid integrated with Solar Micro grid having both ON GRID & OFF GRID option that allows Development of Plug in Devices / products and its related energy services on establishing a Research Bed.

II. Project Description

The Micro-Grid consists of Renewable generation, energy Storage units and demand management through a low voltage distribution network. At CIT, a micro grid platform being developed to control and communicate with smart devices in the micro-grid using various standards / protocols that include Solar Power Generation Forecasting, Smart Lighting Control and Load Control Algorithms. Also this platform allows Monitoring, Control, and User behavior analytics of Electricity operated home appliances such Washer, Dryer, Air-conditioners through a Smart Wireless Hub.

Micro Grid, Garage &User Friendly Research Platform that allows Development of Plug in Devices / Facilities to perform Charging, Remote Monitoring & Control of Electric Vehicle Charging through IoT. The Plug in Devices collect critical data that include Energy consumptions and Power Quality related variables and transfer it to Cloud that helps the user to schedule optimized, aggregated charging algorithms and control the Micro Grid Network.

CIT's Vehicle to Grid research is focused on demonstrating the possibility Of Vehicle to Grid (V2G) Power flow from Popular Electric Vehicles and Mobile Batteries replacing Mobile DG Sets in Telecom Sites. We are exploring how to achieve the maximum V2G power flow from each Charging station while addressing the challenges including response time and power sharing control. Also our research is focused on facilitating a variety of applications such as reactive power compensation, voltage regulation and distributed storage to strengthen the Power grid and Lead EV usage to an entirely novel and smart way.

The proposed R&D work is classified in to four categories:

i. *Distributed Storage:*

With the introduction of V2G, EVs are virtual distributed generators. They can store power within their batteries and feed the power back to the grid when necessary. As V2G usually introduce voltage change, back feeding power to the grid from multiple EVs needs to be carefully controlled to meet distribution voltage constrains.

ii. *Stochastic modeling of user behavior*:

One of the major differences between an EV and a stationary battery is the fact that the EVs power availability is not guaranteed. On the other hand, energy available for V2G is highly stochastic. This stochastic nature of EV owner behavior is currently being studied for better EV integration to Micro Grid / Power grid.

iii. *Load sharing control:*

When several EVs are generating power and supporting multiple loads, the load sharing of each EV needs to be carefully studied. As loads are always fluctuating, controllers need to be designed to share the load proportionally among multiple EVs.

iv. *Ancillary Services:*

To maximize the Micro Grid / EV owner benefits, the potential of using EVs to provide ancillary services needs to be researched. The ancillary services that an EV can provide are highly dependent on the V2G response time. Furthermore, algorithms need to be designed that take into consideration both maximizing ancillary services and meeting EV-owner energy demands.

III. Implementation Strategy

A. Details of Project Location:

- ***Simulation & Pilot Model***: CIT Campus, Coimbatore, Tamil Nadu.
- ***Deployment at site level :*** Kondaas Automation Pvt. Ltd., Toyoto Show Room, Chennai Main Road, Kumbakonam, Kumabakonam District, Tamil Nadu - 612 501. (LoI:Annexure-1)

B. Stage of development :

Initial concept of system design & its demonstration within campus with development of electric vehicle charging grid equipped with remote monitoring, command & control center. Deployment of PoC at client site and then scale up for standard economic level of micro-grid / a suitable industrial platform.

C. Lead Implementing Institute:

Name: Coimbatore Institute of Technology, Coimbatore, Tamil Nadu, INDIA

Status: Government Aided Autonomous Institution

Year of Starting: 1956

D. Partnering Organizations:

- M/s. Kondaas Automation Pvt. Ltd., Coimbatore. (LoI: Annexure-1)
- Tamil Nadu Generation and Distribution Corporation Ltd (TANGEDCO), Government of Tamil Nadu.
- Indian Wind Power Association (IWPA)

E. Technology Partner

- Smart Grid Energy Research Centre (SMERC), UCLA, USA

IV. Expected Outcomes

A. Short Term gains:

The Projects will be the improved efficiency in Demand Response & the quantum of power converted into Ancillary Services which will be estimated around 10% to 15% of the Renewable Energy generation in Kwh. Cost may vary depending on location, operational conditions and its power tariff of respective category.

B. Long term gains:

i. Ensured Power connected to user /grid that enable the User / Grid to plan their loads.
ii. Data generated by Connected Devices / Plug-ins enables to assess the user behavior & improve the effective usage of precious energy.
iii. Distributed Storage concepts will minimize the investment cost of the Government &its supervision to maintain the storage.
iv. Strengthen the Government Drive on Electric Vehicles to minimize fossil fuel usage
v. Tested and Proven solutions will be made available for Charging the batteries
vi. Reduction of Carbon Foot Print
vii. Reduction of Energy Theft / T&D loss of Grid power when RES available in the local loop
viii. Consumer will get the Power Back up and stay independent of their power requirement
ignoring the dependability of expensive and unstable grid power in remote areas
ix. Realizing and ensuring the commercial feasibility of the Government Vision of 100% Lighting across the country by 2020

V. Uniqueness of the Approach

CIT has tied up with Kondaas Automation Pvt. Ltd. & TANGENCO (TNEB) have agreed to involve in research and ready to share their inputs on the current requirements, problems they face in Integration of RES with Grid Power, Power Tariff related issues and other Load Shedding

/ Tripping related matters. The proposed consortium enables Early & Focused access to Research, Data, Demonstration Bed / Partnership, Usage of IPR information at lesser cost and establishment of Test Bed.

Based on the discussions had with the all stake holders a practical & need of the hour approach is planned with following components methodically. This will create a Smart, Distributed Local Control System to Manage, Maximize benefit of these Assets in the Distribution System

- Demand Response equipped with automated load control of the Buildings, Electrical Appliances, RES & its Integration with Energy Storage.
- Micro Grid Control with communications linked with sense, control, and integration of smart loads.
- Distributed Energy Storage, the advent of distributed solar, local energy storage, Electric Vehicles Charging, etc.,
- Battery Energy Storage System (BESS) is effectively optimized; algorithms are required to manage energy flows in & Out of BESS which is a unique research area under Indian Climatic & Operational Conditions.
- Grid Ready EV Integration will address the demands of Energy & Cost Conscious Indian Consumers who are new to this concept especially in electrical Automobile sector.

VI. Results Indicators

As EV concept for Indian Market is new measurable Result Indicators are yet to be established. However we estimate as follows:

- Increased Renewable Energy Capacity by optimization will be around 10% to 15%.
- Increased Access is being planned in every stage of the Research which will reflect in the solution on completion of the project for sure.

- Energy Savings and its Commercial feasibility are linked to local conditions. However the savings in Kwh will be established in our deployment model.
- Clean Energy Drive is embedded in the Project to achieve 100% of its applications. However its percentage against total energy is yet to be established
- We have taken up a New, Innovative & focused Research Area where the Government is setting its goal and approaching Automobile Industry to adopt. Our research findings will catalyze the drive as we have access to latest information on proven technologies.

VII. Monitoring and Evaluation approach

ABT meter with communication will give necessary information from the plant to the concerned and the performance can be remotely monitored.

VIII. Project sustainability and long- term viability

While selecting the components of the project necessary care will be taken that the life of the project should be around 20 years which is a good life for any electrical equipment.

IX. Financial requirements:

S.No	Description	Amount (Rs in Lakhs)	Reference
1.	Budget sought by CIT, Coimbatore, India	242.58	Pl. refer Annexure-2
	Budget Required	**242.58**	
2.	Contribution of Consortium	285.74	Pl. refer Annexure-3
	Total Budget	**528.32**	

X. Project Risks

- We do not anticipate any risk in the project as the power system components and battery media / technology proposed to use in this project are well established and proven across the world.

- Since the storage element (battery) in a micro-grid is costly, to encourage micro-grid installation and operation, the Government of India needs to provide subsidy for the participating private companies.
- The plug-in- electrical vehicle (PEV) concept is new to our country and since we have not achieved self-sustenance in meeting power demand of the people, the PEV concept will take substantial time to evolve in future. The installation and operating cost of the vehicle grid project is another bottle-neck for a developing nation like ours.
- Since the micro-sources connected to micro-grid are highly intermittent in nature, an efficient load frequency control has to be employed to prevent any black-outs or islanding of regional grids.
- Once PoC is ensured, the existing regulatory norms should be amended for micro-grid to grid integration.

XI. Social Inclusion :

Energy storage and charging solutions of Plug-in Electric Vehicle (PEV) will help to drive the locomotive car segment in our country which is the main focus of the Government of India. The PEVs are user friendly, and they can be easily handled by women and illiterate population. The PEVs are driver friendly and they have few controls for efficient maneuvering in thickly populated Indian roads. Unlike fossil fuel driven vehicles, they cannot be raced at dangerously high speeds, and hence they are not prone to accidents. E-rickshaws that are driven mostly by women are already popular in our country. The PEVs are eco-friendly so that they substantially reduce the carbon foot print in our country. The meeting of power demand of urban domestic and industrial consumers from power stations located at remote will lead to substantial transmission and distribution (T and D) losses. On the other hand, the micro-grid integrated with PEVs and other renewable energy sources will efficiently cater the power requirement of a locality in an urban area, and will indirectly pave way for reduction in T and D losses. The use of PEVs will culminate to empowerment of women population in our country transforming our country slowly into a self-sustainable and developed nation. When technical and commercial feasibility of micro-grid established in the days to come, the Government of India will light-up the whole nation by 2020.

XII. Conclusion

In general 10% to 15% of the renewable energy is left waste due to non-availability of energy storage systems in India. If proper energy storage is identified and integrated into the system it could used by many renewable energy generators to store energy and use it whenever required. Here, the solution of the project will help the client to save Rs. 8000 / day on diesel consumption. Effectively, the pay-back of this project could be in four years.

Team Members:

Principal Investigator & Team Members	Dr.V.Manikandan, is serving as a faculty in the department of EEE, CIT for more than two decades. The PI has guided seven Doctoral Scholars in the last nine years, and three of them have contributed significantly in control of interface circuits for green power evacuation from non-conventional energy sources like wind and solar power that are basically uncertain in nature. The research outcomes over these years have been published in refereed international journals. Some of the research works have been presented in leading international conferences in India and abroad. The PI has mobilized more than Rs. 3.48 Crores in last four years from various Indian funding agencies like AICTE, UGC, DST, etc. for executing various research projects, conduction of faculty development programmes, infrastructure developmental activities in the Institute campus and in the neighboring ecosystem. The PI was the principal member in bringing up a state-of the-art 180kW solar power unit in the Institute campus. The PI has consultancy experience on Energy auditing and Energy optimization. The areas of interest of PI include modelling and synthesis of efficient power electronic conversion circuits to cater power interface between PV/Wind sources and grid, development of soft-computing based control strategies for smart power systems, and embedded electronics. **Team Members:** • Dr. V. Manikandan | PI | RES and optimization. • Dr. S. Elango | Co-PI | Power Quality.

	• Dr. G. Manavaalan |Co-PI | Control Systems and Embedded Systems. • Er. A. D. Thirumoorthy | Technical adviser from IWPA | Mentor. • Er. D. Vijeswaran | Asst. Exe. Engr. from TANGEDCO | Operation and Maintenance| To provide necessary support services for implementation. • Mr. S. Ravichandran | Intrepreneur with 32+ years of experience in Energy Management, Power Equipment Design and Development | Mentor for deployment of solution at the client site. • Dr.Rajit Gadh, Director, SMERC, UCLA ,USA | Technology Partner **Past performance:** • Design, Implementation and Maintenance of 180 kW solar at CIT campus, Rs. 1.3 Cr | V. Manikandan, and S. Elango. • Design and Development of DVR in association with CDAC, Trivandrum: implemented at Jaganath Textiles, Coimbatore, Rs. 81 L | A. D. Thirumoorthy, and E.Chandrasekaran. • 300 kVA Passive Filter Design for Harmonic Mitigation at M/S Suba Plastics, Coimbatore, Rs. 2.5L | V. Manikandan, and S. Elango. • Software Controller Board Design for WEDM, Concord United Products Private Limited, Bangalore, Rs. 5.5 L | G. Manavaalan.
Industry Collaborator	• Kondaas Automation Private Limited, Coimbatore. • Tamil Nadu Generation and Distribution Corporation Ltd (TANGEDCO), Government of Tamil Nadu. • IWPA ***Contribution:*** • Necessary test bed. • Sharing of load data for big data analytics process for the selected region. • Seed grant. • Manpower support for implementation part. • Necessary support services for deployment.

Reference:

1. http://www.cea.nic.in/reports/others/planning/resd/resd_comm_reports/report.pdf
2. S.Elango and M. Venugopal, "Design and implementation of Three Phase Three Level Shunt Active Power Filter for harmonic reduction," IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 1377-1383. doi: 10.1109/IECON.2014.7048681
3. Elango Sundaram, Manikandan Venugopal, "On design and implementation of three phase three level shunt active power filter for harmonic reduction using synchronous reference frame theory" International Journal of Electric Power and Energy Systems, Vol.81, 2016, pp. 40-47.
4. Shi, Wenbo, Na Li, Chi-Cheng Chu, and Rajit Gadh. "Real-time energy management in microgrids." IEEE Transactions on Smart Grid 8, no. 1 (2017): 228-238.
5. Lee, Eun-Kyu, Wenbo Shi, Rajit Gadh, and Wooseong Kim. "Design and Implementation of a Microgrid Energy Management System." Sustainability 8, no. 11 (2016): 1143.
6. Wang, Yubo, et al. "Optimal energy management for Microgrid with stationary and mobile storages." Transmission and Distribution Conference and Exposition (T&D), 2016 IEEE/PES. IEEE, 2016.
7. Wang, Bin, Yubo Wang, HamidrezaNazaripouya, Charlie Qiu, Chi-Cheng Chu, and Rajit Gadh. "Predictive Scheduling Framework for Electric Vehicles With Uncertainties of User Behaviors." IEEE Internet of Things Journal 4, no. 1 (2017): 52-63.
8. Huang, Rui, Wenbo Shi, Daoyuan Yao, Chi-Cheng Chu, Rajit Gadh, Yu-jin Song, and Yoon-dong Sung. "Design and implementation of communication architecture in a distributed energy resource system using IEC 61850 standard." International Journal of Energy Research 40, no. 5 (2016): 692-701.
9. Shi, Wenbo, et al. "Distributed optimal energy management in microgrids." IEEE Transactions on Smart Grid 6.3 (2015): 1137-1146.
10. N. Hatziargyriou, H. Asano, R. Iravani and C. Marnay, "Microgrids," in IEEE Power and Energy Magazine, vol. 5, no. 4, pp. 78-94, July-Aug. 2007.

Annexure – 1 LoI from M/s. Kondass Automation Pvt. Limited

kondaas Since 1995

Kondaas Automation Pvt. Ltd.,

5 B, Sri Alamelu Nagar,Kamarajar Road,Coimbatore 641 015
Phone : 0422- 2574000,5000,6000
email : info@kondaas.com URL: www.kondaas.com

LETTER OF INTENT (LOI)

TO WHOMSOEVER IT MAY CONCERN

Thank you for your invitation extending the opportunity to be one of your preferred network partners.

Our Company "Kondaas Automation Pvt Ltd" is actively in the manufacturing sector since 1995 and one of the key player under brand name KONDAAS.

We are happy to hear that Coimbatore Institute of Technology (CIT), Coimbatore, India & SMERC, University of California, Los Angels, USA have taken up our need of the hour research on **"Optimization of Energy Harvesting Solar Micro Grids through Distributed Storage and Vehicle Grid Integration Strategy with Demand Response / Predictive Scheduling Framework"**

In this regard, we are happy to be an associate with you and assure to provide best support from M/s. Kondaas Automation Pvt. Ltd, by providing necessary test bed, sharing our load data to your big data analytic process for the selected location. Also, we are please to extend the following activities with our team members.

1. Support by participation of training & awareness programme as delegates & sponsors.
2. Arranging visits our facility to understand the industrial needs of our stakeholders.
3. Access to our R & D facility centre for developing solutions.
4. Participation in dissemination activities.
5. Support services for deployment at the client site

In case any information is required on our infrastructure needs; kindly contact our manufacturing head Mr. N. Sridhar to get required information..Assuring you our best support at all times and earnestly seeking to work with you.

For Kondaas Automation (P) Ltd,

27th Sept 2017

Annexure- 2: Budget sought by Coimbatore Institute of Technology (CIT), Coimbatore.

S. No.	Item Head	1st Year	2nd Year	3rd Year	Total (Rs. In Lakhs)
Capital Component					
1	Permanent Equipment (located in lab / implementing organization)	65.00	76.13*		141.13
2	Plant Cost / Fabricated Systems / Demonstration Models *(located at beneficiary location)*				
A'	*Subtotal (capital items)*	**65.00**	**76.13**	**-**	**141.13**
General Component					
1	Manpower	11.88	11.88	11.88	35.64
2	Consumables	1.00	3.51*	0.20	4.71
3	Contingencies	1.00	1.00	1.00	3.00
4	Domestic Travel	2.00	1.00	2.00	5.00
5	International Travel to participate MI countries.	3.00	16.80	4.00	23.80
6	Other Cost, if any	-	11.10*	10.70	21.80
7	Overhead	1.50	3.00	3.00	7.50
B'	*Subtotal (General)*	**20.38**	**48.29**	**32.78**	**101.45**
C'	**Total cost of the project (A' + B')**	**85.38**	**124.42**	**32.78**	**242.58**

* Includes 50% of cost for site project. (Details: Annexure-4)

Annexure- 3: Contribution by Consortium

<table>
<tr><td>Budget Details</td><td>

In Kind:

Rs. 130 Lakhs worth of 180 kW Solar systems is available at CIT for pilot study.
Rs. 39 Lakhs worth of Research Equipment’s / Software are available at CIT.

Cash:

Rs. 25 Lakhs by CIT – pilot project.
Rs. 90.74 Lakhs by Kondaas Automation Pvt. Limited – 50% of the project deployment cost.
Rs. 1Lakh by IWPA

</td></tr>
<tr><td>Total Amount</td><td>Rs. 285.74 Lakhs</td></tr>
</table>

Annexure- 4: Budget for site level deployment.

S.No	Items	*Cost in Rs. Lakhs*
a)	*Equipment / Demonstration Models:*	
	SMF Battery - 600 Ah (Qty: 300)	33.00
	Inverter - 200 kVA	29.26
	Solar Panel 200 kW	90.00
	Total	**152.26**
b)	*Consumables:*	
	Cables	2.36
	LT Panel extension	3.54
	Lightning Arrestor	0.77
	Earthing	0.35
	Total	**7.02**
c)	*Others:*	
	Installation and Civil Works	16.00
	Service	6.20
	Total	**22.20**
	Grant Total (a+b+c)	**181.48**

(50% of the project deployment cost will be contributed by Kondaas Automation Pvt. Limited)

RELIABILITY ASSESSMENT OF INDIAN POWER SYSTEM FOR RENEWABLE INTEGRATION IN 2022

Dr. Ankita Samui, Rushikesh Deshpande, Arun Unni, Dr. Ravi Segal: GE Energy Consulting

Deepak Gupta, Disha Agarwal: Shakti Sustainable Energy Foundation

ABSTRACT

Multi-Area Reliability Simulation (GE-MARS^{TM}) tool developed by GE can be used to accurately estimate the reliability of interconnected large-scale power systems. The basis of MARS is Monte Carlo sequential simulation which steps throughout the year chronologically to evaluate system reliability. Key MARS output includes the indices like hourly Loss of Load Expectation (LOLE) in days/year and hours/years, Loss of Energy Expectation (LOEE) in MWh/year, frequency (outages/year) and duration (hours/outage). These indices are estimated for isolated as well as interconnected system. In this paper, the transmission and generation adequacy assessment is performed to evaluate the effect of planned large scale renewable integration in 2022 on the reliability of the Indian power system. Major outcomes of the study like inter-regional maximum flow and number of limiting hours of transmission lines indicates the requirement of transmission system strengthening while the reliability index LOLE (hours/years) signifies the generation base expansion for an area.

KEYWORDS: MARS, LOLE, LOEE, Renwable Integration, Reliability analysis

INTRODUCTION

Reliability evaluation of engineering systems are critical for satisfactory performance. Systems designed or planned based on reliability criteria ensure operations with acceptable interruptions. Power system reliability evaluation is a complex process which considers number of input parameters like technology, forced outage rate, scheduled outages (for generation systems) and transmission links, limits, transmission outages (for transmission system). Results of these studies indicates the amount of time the load is not served (hours/year or days/year). Typical outputs of the reliability evaluation study are LOLE, LOEE, number of interruptions and its duration. Results of reliability evaluation study assist power system planning authorities to understand system adequacy on the backdrop of pre-established reliability criteria. Further, system planning can be revisited to strengthen transmission system or generation base.

This paper discusses the study of reliability evaluation of Indian power system on the background of India’s ambitious target of installation of 160 GW of Wind and Solar Renewable Energy (RE) resources by year 2022. This will significantly increase RE presence in generation portfolio (to 175 GW) [1]. Typically, with the addition of thermal generation capacity, reliability of power system increases. This may not be the case with RE due to intermittent generation pattern. RE may not be available to serve the load when required due to wind or sun light un-availability. Such behavior of RE makes reliability evaluations essential for RE rich systems.

In this study, reliability evaluation is performed with GE's reliability evaluation software GE MARS. Indian grid with generators and transmission links was modelled and scenario based analysis was conducted to calculate LOLE in year 2022 for two cases:

1. Transmission adequacy assessment (100% RE target achieved) and
2. Generation adequacy assessment (70% RE target achieved).

LOLE levels in all regions and states are calculated which in turn indicates the level of generation and transmission system adequacy of the Indian power system. The intra-regional and inter-regional transmission line capacities of limited lines are augmented in transmission adequacy assessment scenario to meet the desired LOLE criteria of 17.5 hours / year.

TOOL DESCRIPTION

MARS is a powerful simulation tool available as a commercial licensed software from GE. MARS was developed for utilities of New York State in the late 1980s. Large power systems with different parameters can be effectively simulated in MARS. Maximum allowable dimensions of different power system parameters are indicated in Table-1.

Table-1: Maximum Allowable Dimension in MARS

Parameter	Maximum Dimensions
Areas	500
Pools	15
Thermal Units	10,000
Hydro Units	700
Pump Storage Units	20
Unit type	100
Area interface	150

GE MARS is based on a sequential Monte Carlo simulation, which provides a detailed representation of the hourly loads, generating units, and interfaces between the interconnected areas. In the sequential Monte Carlo simulation, chronological system histories are developed by combining randomly generated operating histories of the generating units with the inter-area transfer limits and the hourly chronological loads. The detailed operating sequence of MARS is shown in the Figure-1. In MARS, the studied year is simulated repeatedly by Monte Carlo simulation until the measure of convergence falls within a specified tolerance. The mathematical expression of convergence criteria (€), considered in Monte Carlo Simulation is given in the Equation-1.

Reliability analysis of power system considers availability of system element as the fundamental basis for calculation. Thermal unit's availability can be described by the capacity states in which the unit can operate. A maximum of eleven capacity states are allowed for each unit. The unit is fully available in state 1, with the other states representing decreasing amounts of available capacity as governed by the outages of various unit components. Sequential Monte Carlo simulation recognizes the fact that a unit's capacity state in each hour is dependent on its state in previous hours and influences its state in future hours. It thus requires the additional information that is contained in the transition rate data.

$$I_i = \text{Value of reliability index obtained from simulation data for year } i$$

$$N = \text{Number of times year has been simulated}$$

$$\bar{I} = \sum_{i=1}^{N} I_i/N = \text{Estimate of expected value of index I}$$

$$S^2 = \sum_{i=1}^{N} \left[(I_i - \bar{I})^2\right]/N = \text{Sample variance}$$

$$S_{\bar{I}} = \sqrt{(S^2/N)} = \text{Standard deviation of estimate } \bar{I}$$

$$S_{\bar{I}}/\bar{I} = \text{Standard error of estimate } \bar{I} \quad \ldots (1)$$

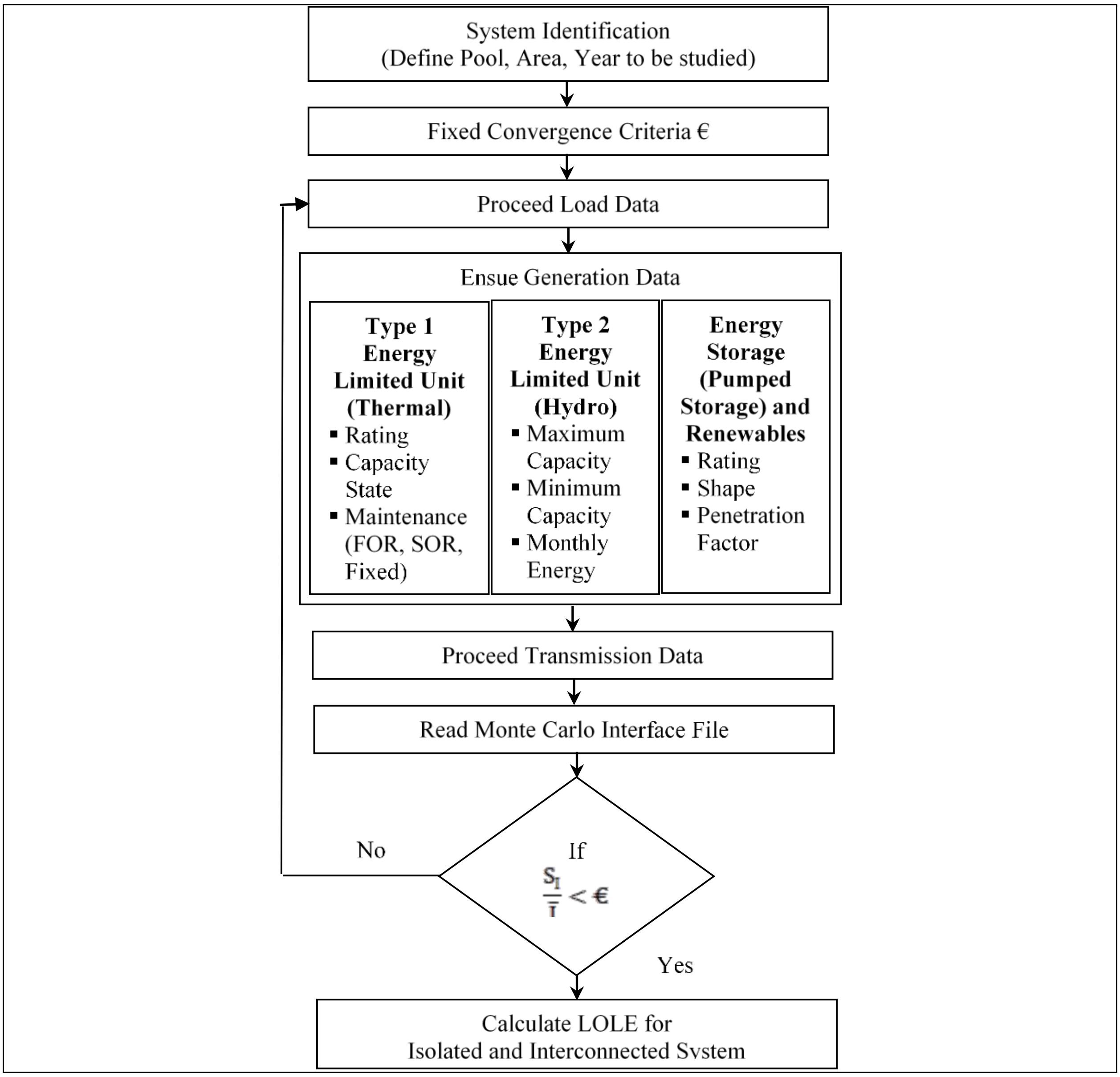


Figure-1: Operating Sequence of MARS

MARS model calculates following reliability indices:

a. Daily LOLE (days/year)
b. Hourly LOLE (hours/year)
c. LOEE (MWh/year)
d. Frequency (of outage) (outages/year)
e. Duration (of outage) (hours/outage)

Indices are calculated for area and pool on isolated as well as interconnected basis.

SYSTEM STUDIED

The impact of targeted 160 GW of wind and solar integration in Indian Power system by 2022 is studied in GE-MARS software. The Indian power grid is an extremely large and complex system. The underlying model represents the integration of five electrical regions of India. In MARS, 5 regions (Northern, Western, Southern, Eastern and North-Eastern) are represented as pools while states in the regions are represented as areas. The total installed capacity on all India basis is considered as 469 GW by 2022 and breakup based on technology is shown in Figure-2. In this mix of generation capacity, fossil fuel generation will comprise of the coal based capacity (48%) and ~5% of gas based generation capacity. As per the MNRE targets of renewable generation capacity (wind and solar), RE capacity will be the second largest installed capacity by 2022 followed by Hydro generation (11%).

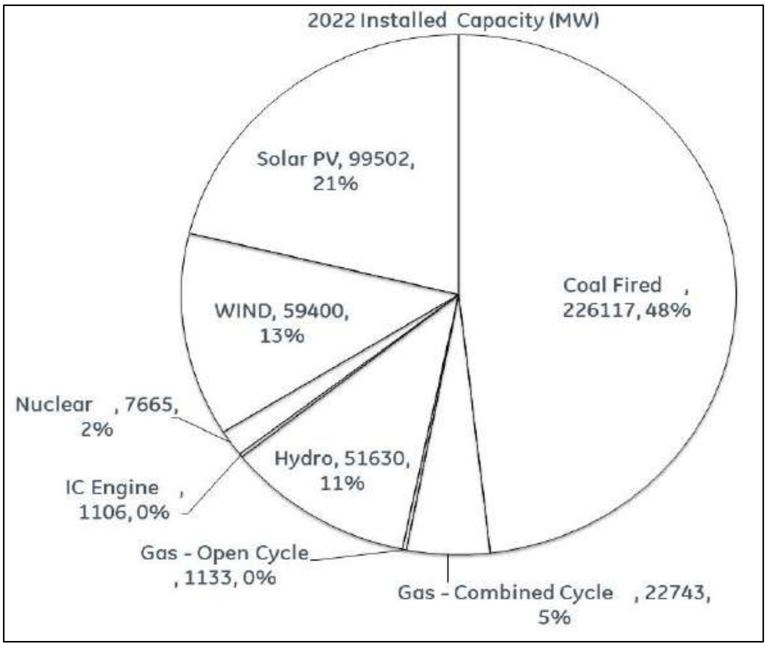


Figure-2: All India Installed capacity of 2022

Data Collection

- The data pertaining to the current demand, installed capacity, transmission capacity etc. was collected from various sources available in the public domain such as the State Utility’s website, reports published by various central agencies such as CEA, POSOCO, Power Grid, NTPC, NHPC, DVC, THDC etc.
- The planned thermal generation capacity is considered as per the projections of the CEA, and also the respective state’s “24x7 Power For All’ document [2].
- The demand projections for future years up to 2019; were used from the data available in the ‘24x7 Power for All’ reports [2] of the respective states, and then extrapolated the

same up to 2022. Also, the projections under the '18th Electric Power Survey' report issued by CEA for the demand scenario were considered for the study. The values considered are given in the Table-2.

- Inter-regional connections and the overall modelling approach is shown in Figure-3.
- Figure-4 shows the interstate transmission links and value of the transmission limits. The Inter region transmission capacity is based on the CEA 20-year (2016-36) Perspective Transmission planning report [3]. Inter-state limits are as per power flow simulation results for 2021-22 from the CEA planning report. Maximum values from the four quarterly values has been considered for simulations.
- The Wind generation potential is available in the states of Gujarat, Maharashtra and Madhya Pradesh in the Western Region. In the Northern Region, only the state of Rajasthan has the potential for wind generation. The hourly generation profile was obtained from the 'Report on green energy corridors – PGCIL (Vol-1)' [4].
- For the preparation of the Solar data set for the MAPS model, the National Renewable Energy Laboratory (NREL) data converted from hourly GHI values to corresponding kW values in 'HOMER' (Hybrid Optimization Model for Multiple Energy Resources) software was utilized [5].

Table-2: Region-wise Peak Demand and Energy Requirement

Region	**Peak Demand (MW)**		**Energy Requirement (GWh)**	
	2022	**Avg Yr-on-Yr Growth**	**2022**	**Avg Yr-on-Yr Growth**
South	66,622	10.60%	422,798	7.71%
West	67,439	5.10%	471,643	5.48%
North	85,932	8.60%	539,604	9.07%
East	27,187	5.50%	175,800	5.06%
N-E	5,974	26.80%	32,086	22.77%
India	**238,370**	**7.90%**	**1,641,931**	**7.28%**

Acronyms used in Figure-4

- Northern Region: UK: Uttarakhand, UP: Uttar Pradesh, Del: Delhi, PJ: Punjab, RJ: Rajasthan, HP: Himachal Pradesh, JK: Jammu & Kashmir, HR: Haryana
- Western Region : GUJ: Gujarat, MP: Madhya Pradesh, MAH: Maharastra, CGS: Chhatisgarh
- Southern Region: TEG: Telengana, AP: Andhra Pradesh, KAR: Karnataka, TN: Tamil Nadu, KRLA: Kerala
- Western Region: ODSA: Odisha, JH: Jharkhand, WB: West Bengal, BHR: Bihar, SKM: Sikkim

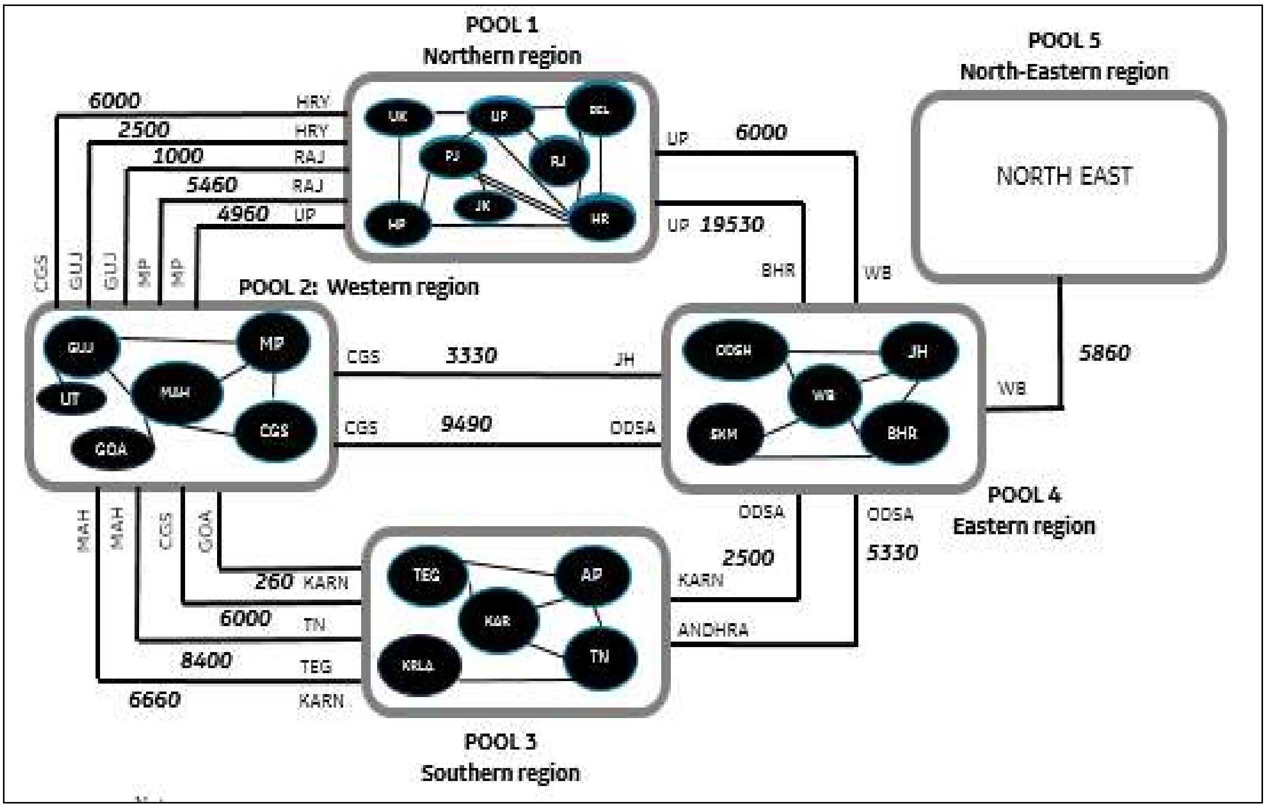


Figure-3: Inter-regional CEA Transmission Limits

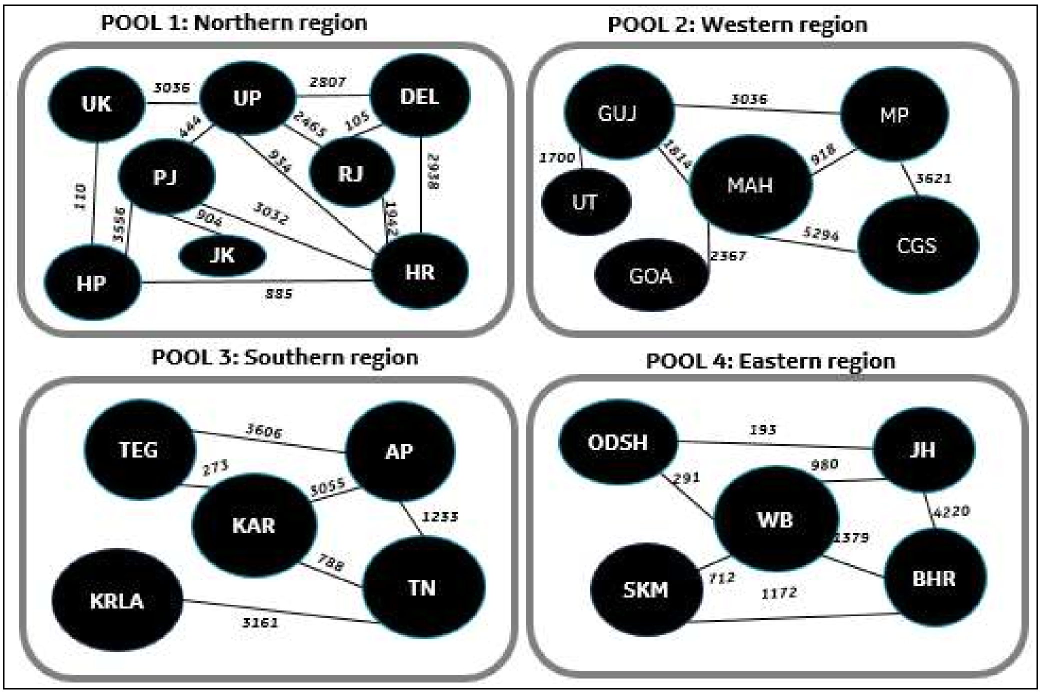


Figure-4: Inter-state CEA Transmission Limits

MARS MODELLING ASSUMPTIONS

The key reference points to all India MARS model are mentioned below:

- Thermal generation units are classified into 5 categories. They are represented in the MARS database with a two-state model with an expected forced outage rate (EFOR). Details are mentioned in Table-3 and Table-4.
- Scheduled outage rates for each technology (each generating stations) are distinct and estimated from historical data wherever available.
- Hydro projects were modelled based on the design energy data available for the projects from the public domain.
- As per the current provisions pertaining to the dispatch of wind and solar projects in India, these projects have been designated the 'must-run' status. There is no spilled energy considered for these plants.
- Southern Region States have the largest cumulative target of 28 GW, followed by Western Region (22.6 GW) and Northern Region (8.6 GW). With regards to the individual State targets, Tamil Nadu (11.9 GW) is the highest, followed by Gujarat (8.8 GW), Rajasthan (8.6 GW) and Maharashtra (7.6 GW).
- The 100 GW solar target includes the Utility-scale solar and roof-top solar targets.

Table-3: Number of States for Thermal Generation Technologies

Sr No.	**Technology**	**Number of Capacity States**	**CAPACITY STATES**	
			1	**2**
1	Gas Open Cycle	2	100%	0%
2	Coal	2	100%	0%
3	Gas Combined Cycle	2	100%	0%
4	Diesel	2	100%	0%
5	Nuclear	2	100%	0%

Table-4: Forced Outage Rates for Thermal Generation Technologies

Sr No.	**Technology**	**Number of Capacity States**	**FORCED OUTAGE RATE**	
			1	**2**
1	Gas Open Cycle	2	2.96%	0%
2	Coal	2	4.00%	0%
3	Gas Combined Cycle	2	3.33%	0%
4	Diesel	2	2.96%	0%
5	Nuclear	2	8.10%	0%

ANALYSIS OF RESULTS

In this study, MARS is used to evaluate reliability of the system from transmission and generation adequacy assessment perspectives. For planning purposes, the target LOLE is considered as 0.2% per year or 17.5 Hrs./Year. This reliability criterion is also considered to illustrate the requirement of augmentation of the transmission line capacities for enhanced reliability in system operations. The value of the convergence index € considered is 0.05 for this study. MARS has an ability to calculate reliability indices such as; LOLE (days/year), LOEE, frequency, duration etc., for each area on isolated basis. In this section LOLE (hours/year) calculation results are represented only on interconnected basis.

Transmission Adequacy Asessment

The objective of this case is to evaluate the system reliability considering transmission infrastructure sufficiency. For this case:

- Transmission constraints for inter-regional and inter-state connections are considered as per CEA report.
- 100% RE capacity in 2022 (160GW: Wind + Solar) is considered.

Key results of this case are LOLE and inter-regional maximum flows. LOLE values are shown in Table-5. Further LOLE values are used to estimate transmission system augmentation to achieve reliability criteria of 17.5 Hrs./Year.

Table-5: Transmission Adequacy Assessment Considering CEA Limits

Area/ States	**Transmission Adequacy Assessment with CEA Limits**				
	LOLE (Days /year)	**LOLE (Hours/year)**	LOEE (MWh/ year)	Frequency (outage/ year)	Duration (Hours / outage
Goa	128	**269**	9859	108	2
UT East	17	**12**	44	12	1
WESTERN REGION	139	**280**	9904	118	2
Kerala	44	**694**	240514	207	3
Tamil Nadu	39	**358**	422054	105	3
SOUTHERN REGION	44	**694**	662568	207	3
Rajasthan	16	**37**	20253	25	2
Punjab	42	**281**	152490	69	4
Haryana	33	**166**	96051	44	4
Delhi	37	**195**	74447	50	4
Jammu & Kashmir	182	**2413**	1532882	241	10
NORTHERN REGION	196	**2588**	1876123	264	10
EASTERN REGION	0	**0**	0	0	0
NORTH EASTERN REGION	0	**0**	0	0	0

Key observations from results are:

- *Western Region:* LOLE values seen in Goa and UT are mainly due to transmission limitations.
- *Southern Region:* Kerala and Tamil Nadu have reliability issues for <10% time annually
- LOLE values seen in *Northern region* mainly in the state of J&K.
- *Eastern and North-East* regions have surplus capacity; thus, no LOLE values.

Based on the above observations, strengthening of transmission lines as indicated in

Table-6 is considered for simulations to achieve a target LOLE of 17.5 hours/year at an all India level. LOLE values after transmission system augmentation are shown in Table-7.

Table-6: Transmission Line Strengthening Requirements

Transmission Lines	**CEA Limits**	**Recommended Limits from MARS Analysis**
Gujarat - Rajasthan	1000	1800
Gujarat - Haryana	2500	3500
Karnataka - Goa	260	300
Uttar Pradesh - Delhi	2807	3800
Rajasthan - Delhi	105	500
Himachal - Punjab	3556	5500
Punjab – Jammu & Kashmir	**904**	**2800**
Maharashtra - Goa	616	700
Karnataka – Tamil Nadu	**788**	**3000**
Andhra Pradesh – Tamil Nadu	**1233**	**3500**
Kerala – Tamil Nadu	**3161**	**5000**

Table-7: Transmission Adequacy Assessment Results (Post Transmission System Augmentation)

Area /States	LOLE (Days /year)	**LOLE (Hours/year)**	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours / outage)
Goa	3	**8**	311	2	4
UT East	17	**12**	44	12	1
WESTERN REGION	17	**12**	355	14	1
Kerala	0	**15**	2087	7	2
Tamil Nadu	0	**15**	7195	7	2
SOUTHERN REGION	0	**15**	9283	7	2
Rajasthan	5	**7**	1903	6	1
Punjab	5	**10**	2406	7	1
Haryana	5	**8**	2392	6	1
Delhi	5	**8**	1419	6	1
Jammu & Kashmir	5	**10**	691	7	1
NORTHERN REGION	5	**10**	8812	7	1
EASTERN REGION	0	**0**	0	0	0
NORTH EASTERN REGION	0	**0**	0	0	0

Generation Adequacy Asessment

Generation adequacy assessment involves the evaluation of system reliability from the perspective of generation capacity. For this case:

- Transmission constraints for inter-regional and inter-state connections are considered as per CEA report.
- 70% RE capacity in 2022 (Wind + Solar) is considered

The purpose of this case is to compute LOLE, inter-regional maximum flows and the number of limiting hours for all cases if partial RE installation target is achieved. LOLE values are shown in Table-8.

Table-8: Generation Adequacy Assessment (Considering CEA Limits)

Area/ States	**Generation Adequacy Assessment**				
	LOLE (Days /year)	**LOLE (Hours/year)**	LOEE (MWh/ year)	Frequency (outage/ year)	Duration (Hours / outage)
Goa	128	**281**	10387	112	3
UT East	18	**12**	48	12	1
WESTERN REGION	140	**292**	10435	122	2
Kerala	52	**790**	280787	225	4
Tamil Nadu	46	**480**	537537	134	4
SOUTHERN REGION	52	**790**	818324	225	4
Rajasthan	16	**44**	24015	27	2
Punjab	42	**294**	159434	69	4
Haryana	33	**169**	97457	45	4
Delhi	37	**200**	75729	52	4
Jammu & Kashmir	183	**2641**	1667129	211	13
NORTHERN REGION	197	**2829**	2023763	235	12
EASTERN REGION	0	**0**	0	0	0
NORTH EASTERN REGION	0	**0**	0	0	0

Figure-5 shows the regional links (Northern and Western regions) where flows are getting limited. Majority of the power flows are limited between the states of Gujarat - Rajasthan and Gujarat – Haryana in Northern and Western region. Transmission links shown as dotted lines limited flows for more than 10% of time in a year.

Key observations from results are:

- *Western region:* LOLE values appears in Goa and UT due to transmission limitation.
- *Southern region:* Kerala and Tamil Nadu have reliability issues, LOLE values higher than in transmission assessment case due to lower RE levels.
- *Northern region:* J&K have significant reliability issue as LOLE values in Northern region are very high mainly in this state.
- *Eastern and North-East* regions: Surplus generation capacity of makes LOLE values to be zero.

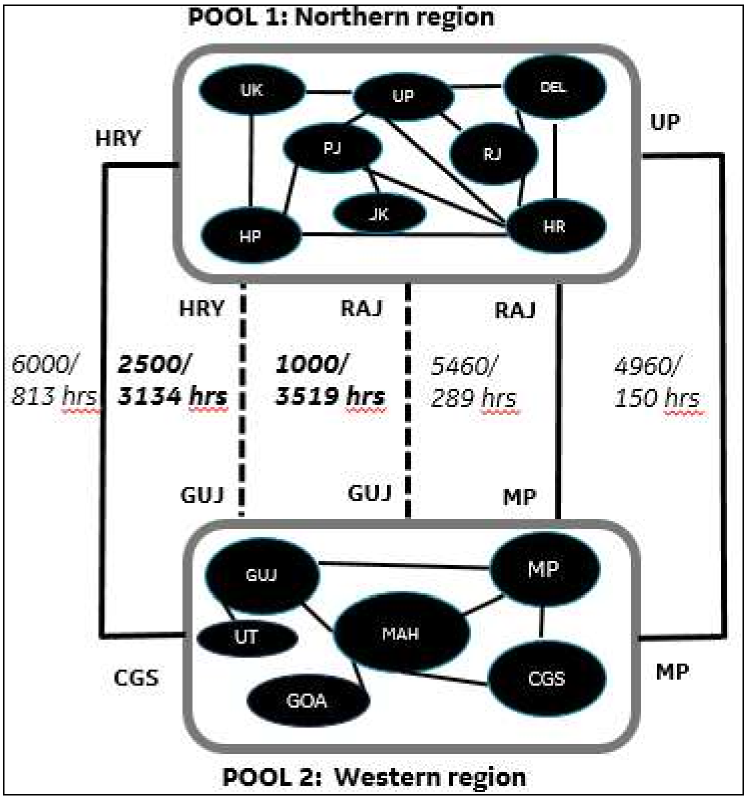


Figure-5: Inter-region Limiting Hours for the Regional Links (Line Capacities/Hours Limited)

Key Observations

The key observations of transmission and generation adequacy assessment are mentioned below:

Northern Region

- States in the Northern Region experience significant LOLE due to limitation of transmission capacity between states.
- The State of Jammu & Kashmir is interconnected only with Punjab hit the limit for ~1800 hours/ year is the cause of highest LOLE in J&K.
- To maintain LOLE of Jammu & Kashmir to the target level ~ 2,000 MW transmission capacity from Punjab to Jammu & Kashmir line is required.
- High demand in Northern Region makes it a net importer. A requirement of 1000 MW and 800 MW transmission capacity addition of the inter-region transmission lines connecting Gujarat to Haryana and Rajasthan respectively is required as per reliability prospective.

Western Region

- High installed capacity of Thermal and Renewables capacity in Western region ensures reliability in the region.
- Western region is net exporter to Southern and Northern Regions.
- Limited transmission connectivity to Goa and the Union Territory of DD and DNH is reflected through the LOLE values for Western Region. To bring the LOLE of Goa to the target LOLE level, ~ 100 MW transmission capacity addition to the interconnected line is sufficient.

Southern Region

- States of Tamil Nadu and Kerala have the Highest LOLE values in Southern region.

- Transmission capacity addition of 2212 MW, 2267 MW and 1839 MW to Karnataka – Tamil Nadu, Andhra Pradesh – Tamil Nadu and Kerala – Tamil Nadu lines respectively is required to meet target LOLE.

Eastern Region

- For this region, the LOLE is within limits as the region has large installed capacity compared to the region load.

CONCLUSIONS

Reliability evaluation of large and complex power system of India in light with the targeted 160GW of RE integration is performed with reliability evaluation tool MARS. Two cases of 'transmission adequacy assessment' and 'generation adequacy assessment' were simulated. Transmission adequacy assessment case was used to understand transmission system augmentation requirement to achieve desired reliability target (of 17.5 Hrs./Year). It may be concluded that; Northern and Southern region may face reliability issues (in terms of generation adequacy) in 2022 and they will be net importers of power. On the other hand, surplus power will be available in Western, Eastern and North-Eastern regions of India. To make Indian power system more reliable and balanced with respect to inter-reginal import and export perspective transmission capacity addition may be required to achieve target LOLE level as per the planning reliability criteria.

ACKNOWLEDGMENTS

The analysis presented under this paper has been conducted as part of a larger study titled 'Integrating RE modelling with power sector planning for India' supported by Shakti Sustainable Energy Foundation and conducted by the Energy Consulting group of General Electric Company. This study began in early 2016, with an objective to identify strategies to optimize the power sector plans and minimize the cost associated with integrating Wind and Solar in the system. This study was carried out using proprietary software tools of by General Electric Company. The views and opinions expressed in this paper are those of the authors and do not necessarily reflect the institutional views of the Shakti Sustainable Energy Foundation and General Electric Company.

REFERENCES

1. Tentative State-wise break-up of Renewable Power target to be achieved by the year 2022 http://mnre.gov.in/file-manager/UserFiles/Tentative-State-wise-break-up-of-Renewable-Power-by-2022.pdf
2. 24x7 Power For All documents http://www.powerforall.co.in/AccessFolder/HomeScreenReport.aspx?TYPE=PD&ID=ALL
3. The perspective Transmission Plan (2016-36) prepared by CEA , January 2016 http://www.cea.nic.in/reports/others/ps/pspa2/ptp.pdf
4. Transmission Plan for Envisaged Renewable Capacity by PGCIL July 2012. http://www.powergridindia.com/sites/default/files/Our_Business/Smart_Grid/Vol_1.pdf
5. The HOMER microgrid software by NREL. https://www.homerenergy.com/homer-pro.html

BIOGRAPHIES

Dr. Ankita Samui (ankita.samui1@ge.com, 9980055268) is the head researcher for this study. She is an Application Engineer in the Power Economics team of GE Energy Consulting, India. She is involved in generation & transmission planning studies for various power markets. She holds B.Tech., ME and PhD degree from WBUT, BIT Mesra and IIT Bhubaneswar, respectively.

Rushikesh Deshpande (rushikeshshrikant.deshpande@ge.com, 9686422299) the co-head researcher for this study. He is a Senior Engineer in the Power Economics team of GE Energy Consulting, India. He is engaged with production simulation, reliability assessment studies, financial evaluation for thermal and renewable projects, and microgrid assessment projects. He holds the B.E. degree in Electrical Engineering from Nagpur University and M.Sc. degree in Electrical Power Systems from the University of Manchester, UK.

Arun Unni (arun.unni@ge.com, 9731399644) leads the Power Economics team of GE Energy Consulting, India and has over 21 years of experience in the power sector. He has led various consultancy studies covering power demand projection, generation & transmission planning, and production simulation analysis and modelling for various power markets. He holds a B.E. degree from the Delhi Institute of Technology, and an advanced Management program from IIM Bangalore.

Dr. Ravi Segal (ravi.segal@ge.com, 9611988922) is currently the Business Leader in the GE Energy Consulting organization covering India, ASEAN and China. He works on studies related to grid performance improvement and long-term generation and transmission planning studies. He holds B.E. and M.E. in Electrical Engineering from Punjab Engineering College and Ph.D. from IIT, Delhi.

Deepak Gupta (deepak@shaktifoundation.in, 011-47474009) is the Senior Program Manager at Shakti Sustainable Energy Foundation. He leads and provides strategic guidance to Shakti's power sector program – focused on distribution utility aspects, renewable energy, and rural energy access. With more than fifteen years of experience in the renewable energy and environment sector, he has played strategic roles in the areas of project development, technology, commercial, and financing aspects across the value chain. Deepak has been an integral part of several initiatives and committees of the Government of India, including those on drafting of National Renewable Energy Bill and wind potential assessment, Renewable Energy Roadmap for India, and is member of the National Steering Committee (NSC) for Renewable Sector in Technology Need Assessment (TNA) project of TIFAC. He holds a M. Tech. from IIT, Delhi and an MBA from the Faculty of Management Studies, Delhi University.

Disha Agarwal (disha@shaktifoundation.in, 011-47474046) is Program Associate at Shakti Sustainable Energy Foundation. She has close to six years of experience in renewable energy policy, regulation, grid integration and finance. She has contributed to several initiatives and committees of the Government of India, including those on wind potential re-assessment, India's Renewable Electricity Roadmap 2030, and Financing 175 GW RE by 2022. She holds a Masters in Renewable Energy Engineering and Management from TERI University, New Delhi.

Power Quality Monitoring and Assessment as per CEA Guidelines

Vikram K. Nawadkar, Nikhil S. Gujar, Shefali Talati
Electrical Research And Development Association
Vadodara, INDIA
vikram.nawadkar@erda.org

Naresh Panchal, Pulin Shah, V Nandakishore Reddy
Suzlon Power Infrastructure Ltd.
Pune, INDIA
pnaresh@suzlon.com; spulin@suzlon.com

Abstract—**Power quality issues (i.e. harmonics in current and voltage, flicker and DC current injection) that arise when renewable generations like wind farms are interconnected with grid.**
This work is focused on field measurement and assessment of above stated power quality parameters at the point of common coupling. Two case studies are presented where the measurements were done as per IEC 61000-4-30:2008.
The measurement period was selected during high wind season i.e. between April to September for twosites having installed capacity of 100 MW and 200 MW respectively.

Keywords—flicker emission; DC current injection; current harmonics; point of common coupling; solar power plants; wind generating stations

I. INTRODUCTION

Electricity demand in India is increasing day by day, as it is used in almost every apparatus. As the equipment instruments used are becoming more advanced, they require interference free electricity supply. To meet the higher electricity demand, renewable energy sources like solar and wind are installed. It is necessary that electric power must be of acceptable quality to guarantee the correct behavior of the equipment connected to the power distribution system. The increasing penetration rate of renewable energy sources in the power grid is raising technical problems, such as voltage regulation, network protection coordination, loss of mains detection, etc.

As penetration of wind energy is increasing, the impact of the wind turbines on network operation and power quality is becoming important. Due to the output power variations of wind turbines, voltage fluctuations are produced. The capability of the power system to absorb these perturbations is dependent on the fault level at the point of common coupling. In weak networks or in power systems with high wind generation penetration, the integration of these sources can be limited by the flicker level which must not exceed the standard limit.

In India, Central Electricity Authority (CEA) has formulated guidelines to control the power quality when connecting renewable generating stations to the grid. The guideline covers following requirements:

- The harmonic current injection from a generating station shall not exceed the limit specified in IEEE 519:2014
- The generating stations shall not inject DC current greater than 0.5% of the full rated output at the interconnection point
- The generating station shall not introduce flicker beyond the limits specified in IEC 61000-3-7:2008.

II. POWER QUALITY SCENARIO IN WIND FARMS-ERDA'S PERSPECTIVE

In India, utilities are following CEA guidelines for power quality of wind farms. The power quality studies are most important for utilities, since they are committed to their customers to preserve power quality. Most of the wind farms are connected to 132 kV & 220 kV grids. The entry into production from many of these wind farms lead to deep implications of the impact of disturbances produced by the wind turbines in the network connection mode.

Detailed field measurement was carried out at two different wind farms in India. The generating capacity of wind farms are as follows.

Wind farm details	
Wind farm	**Generating capacity in MW**
A	100
B	200

Case 1: Wind farm A

The farm is having a total of 46 numbers of wind turbines interconnected. The installed capacity of farm is 100 MW. The farm is interconnected with utility line of 132 kV at PCC. The measurements were carried out during high wind season i.e. in the month of June. The detailed measurements were carried out as per IEC 61000-4-30:2008.The measurement period was set to minimum seven days and the background quality of grid was also measured for period of 6 hours when major changes in load in the grid were expected. This is essential to evaluate the background voltage harmonics and Flicker in the system without the wind farm connected to grid.

The above measurement will be useful in assessing the contribution from the wind farm, after completing the power quality measurements with the wind farm connected to grid and generating up to80% of the installed capacity of the wind farm. The electrical line diagram of plant is shown in Fig.1

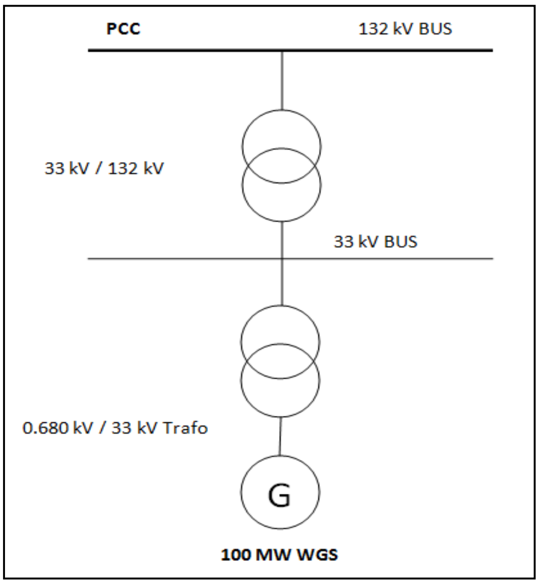


Fig.1. Simplified Electric Diagram of Network

A. Flicker

For flicker measurement, instrument must register every 10 minutes flicker severity indicators for short duration (P_{st}) and every 120 minutes flicker severity indicators for long duration (P_{lt}) and it must meet the requirement as in [3]. The minimum measurement period should be one week. However, shorter measurement period might be needed for assessing emissions under specific conditions. Such shorter periods should represent the expected operation over the longer assessment period (i.e. a week). The measured data should not exceed the limit as in [1].

For current harmonics measurement, instrument must perform Fast Fourier Transform of the current signal for window width of 10 cycles for 50 Hz systems [5]. The measured data is to be compared with the limits as in [6].

For DC current measurement, instrument must perform Fast Fourier Transform of the current signal and extract the DC component from the signal.

The standard [1] proposes the limits for flicker emission severity i.e. Epst (short term flicker) and Eplt (long term flicker), as:

Epst = 0.8

Eplt = 0.6

Which were made at PCC where wind farm was working in continuous mode of operation. As it is a three phase system, average value of flicker severities have been considered. By analyzing the measured data it was observed that values of P_{st} & P_{lt} are within the emission limits.

B. Current Harmonics

The inverter used in wind farm converts DC current into AC in accordance with electrical characteristics of the grid to which they are connected. Lower harmonic current improves the power quality of the system. The standard [6] proposes the limits for the current harmonics as well as voltage harmonics.

Current harmonics were measured at PCC for the same load cycle as performed for the flicker measurement. The maximum power exported by wind farm to PCC was observed as 70 MW.The measured current harmonic distortion I_{THD} was then converted to current demand distortion I_{TDD} by using (1). The limit set by [6] for this case, is 2.5%.Calculation of current demand distortion (I_{TDD}) is as follows:

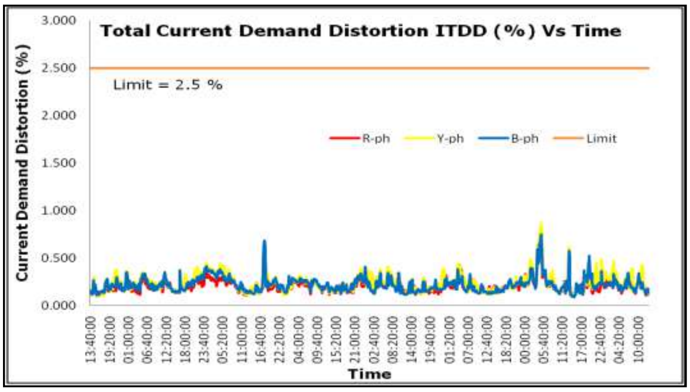
$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + ...}}{I_L} \times 100\% \qquad (1)$$

Where,

I_2,I_3,I_4 are current harmonic orders

I_L is the demand load current

Graph 1 shows the relevant results compared with the standard [6] limit.

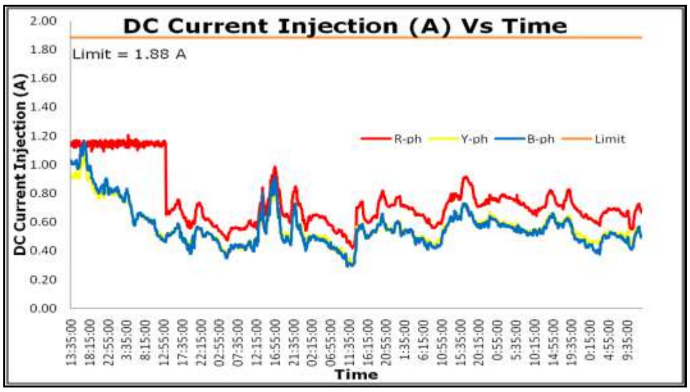


Graph 1. Current Demand Distortion I_{TDD} Compared With Limit

It is seen that current demand distortion I_{TDD} is below the limit. This shows that inverters used in the wind turbine generators of the wind farm are as per the relevant standard and the current harmonics generated by these inverters are below acceptable limit.

C. DC Current Injection

It has been observed that while converting DC current into AC, inverter shifts the AC signal and a DC offset gets added. This DC shifted AC current can cause problems to the equipment's/loads connected to the grid. A CEA guideline does not allow injecting DC current greater than 0.5 % of the full rated output at the interconnection point. Graph shows the DC current measured at PCC in comparison with the limit value of 1.88 A. It is seen that the DC current injection is well below its limits for all three phases.



Graph 2. Current DC Current Injection Compared With Limit

Case 2: Wind farm B

The farm is having total 95 numbers of interconnected wind turbines. The installed capacity of farm is 200 MW. The farm is interconnected with utility line of 220 kV at PCC. The measurements were carried out during high wind season i.e. in the month of July. The detailed measurements were carried out as per IEC 61000-4-30:2008. The measurement period was set to minimum seven days and the background quality of grid was also measured for period of 6 hours where measure load in grid was changed. The electrical single line diagram of the plant is shown in Fig.2

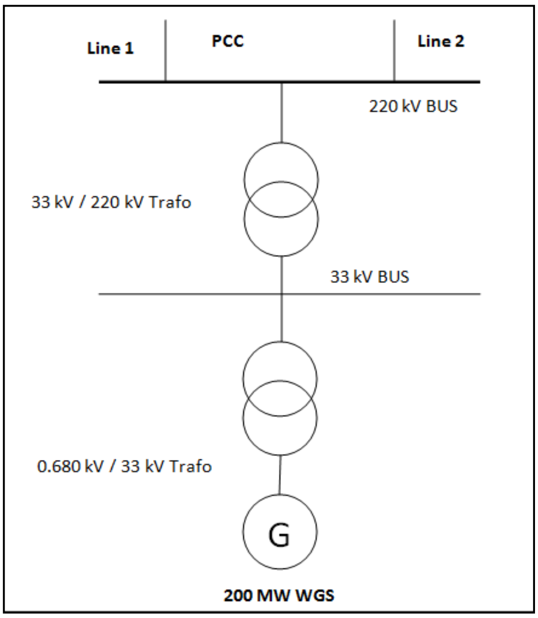


Fig. 2. Simplified Electric Diagram of Network

A. Flicker

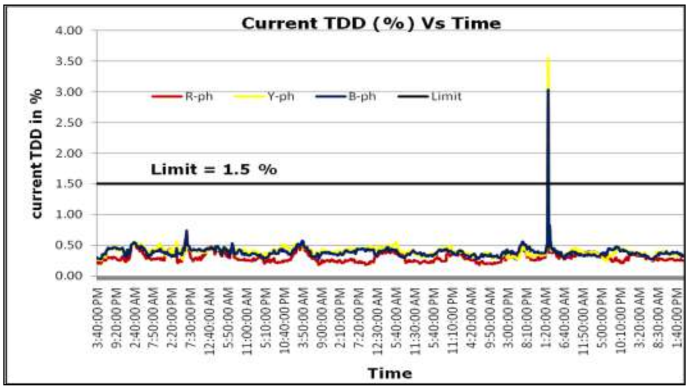
The standard [1] proposes the limits for flicker emission severity i.e. Epst (short term flicker) 0.8 and Eplt (long term flicker) as 0.6. The standard [1] proposes that 95% probability values of P_{st} and P_{lt} should not exceed the emission limits E_{pst} and E_{plt} respectively. By analyzing the measured data it was found that values of P_{st} & Plt are within the emission limits.

B. Current Harmonics

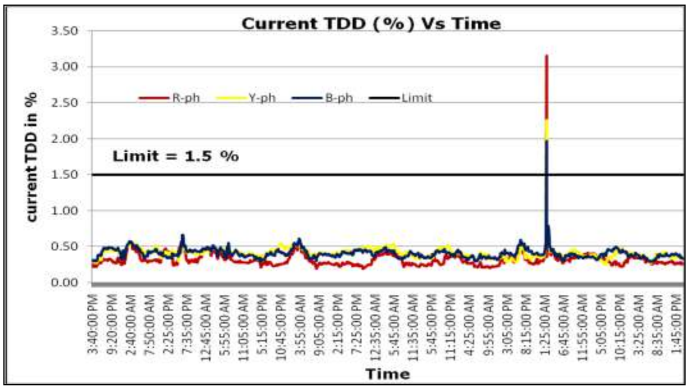
The standard [6] proposes the limits for the current harmonics as well as voltage harmonics.

Current harmonics were measured at PCC for the same load cycle as performed for the flicker measurement. The maximum power exported by wind farm to PCC was observed at line 1 was 71 MW and at line 2 was 69MW.The measured current harmonic distortion I_{THD} was then converted to current demand distortion I_{TDD} by using (1). The limit set by standard (1) for this case, is 1.5%.

Graph 3&4 show the results obtained compared with the standard [6] limit.



Graph 3. Current Demand Distortion I_{TDD} Compared With Limit for Line 1

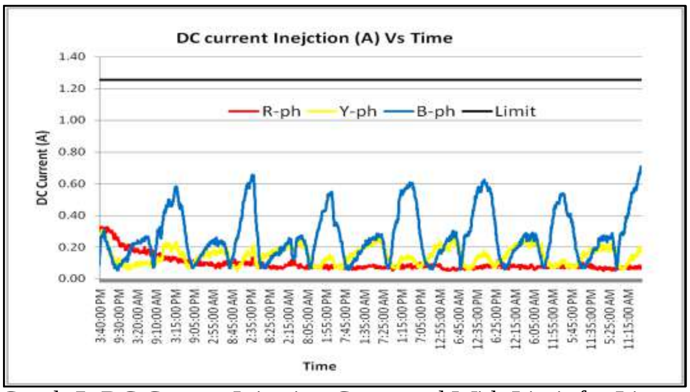


Graph 4. Current Demand Distortion I_{TDD} Compared With Limit for Line 2

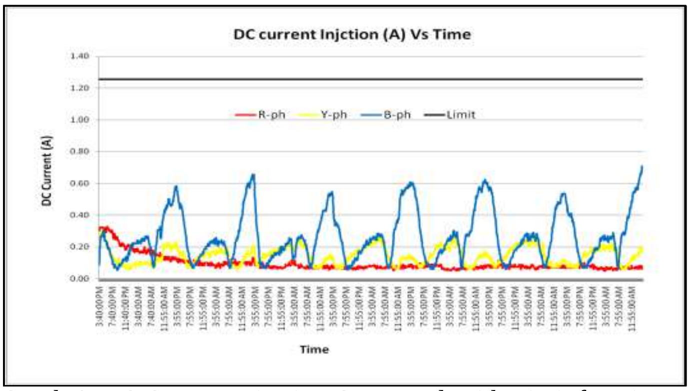
It is observed that current demand distortion I_{TDD} is below the limit. This shows that inverters used in the wind farm are as per the relevant standard and the current harmonics generated by these inverters are within acceptable limit.

C. DC Current Injection

CEA guideline does not allow injecting DC current greater than 0.5 % of the full rated output at the interconnection point. Graphs shows the DC current measured at PCC in comparison with the limit value of 1.26 A for Line 1 & 1.25 A for Line 2.



Graph 5. DC Current Injection Compared With Limit for Line 1



Graph 6. DC Current Injection Compared With Limit for Line 2

The DC current injections at PCC are found within limit as per CEA guidelines.

To summarize, different cases with two different grid voltage levels are discussed as given in Table I below

Table I: Summary of observations for cases 1-2

Case	Generating capacity (MW)	PCC grid level (kV)	Observation
A	100	132	Flicker, current harmonics and DC current injections are within limit
B	200	220	Flicker, current harmonics and DC current injections are within limit

III. Conclusions

In this paper, results of power quality evaluation for two different cases of renewable generations are discussed.

The voltage flicker due to output power variations for continuous operation of wind turbine is analyzed. The injection of DC current and current harmonics at PCC is also measured and discussed.

For cases 1& 2, the wind farms are meeting all the requirements. The flicker values, current harmonics and DC current injections are within limit.

Background quality of power was also observed and voltage harmonics and flicker values are found within limit.

IV. Recommendations

In the present regulations, the background power quality measurements, without the wind farm under question connected to grid are not included. There may be instances, where the power quality parameters are beyond the limits in the grid itself. By measuring those (with the wind farm under shut down) immediately prior to the measurements at the operating wind farm connected to grid, will help in evaluating as to how much the wind farm is contributing.

If this practice is not established, there could be instances, where the power quality is beyond limits in the grid itself and the wind farm is held responsible for the same. As the penetration of wind and solar generation is increasing in various parts of the grid, the above practice will be helpful in identifying the source of the power quality parameters that have gone beyond acceptable limits.

It is also our recommendation that the above test of background power quality need be witnessed by the utility representatives.

V. References

[1] IEC 61000-3-7:2008, “Limits – Assesment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems”

[2] IEC 61400-21:2008, “Measurement and assesment of power quality charaterisitcs of grid connected wind turbines”

[3] IEC 61000-4-15:2010, “Testing and measurement techniques – Flickermeter – Functional and design specifications”

[4] IEC 61000-4-30:2008, “Testing and measurement techniques – Power quality measurement method”

[5] IEC 61000-4-7:2009, “Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply system and equipment connected thereto”

[6] IEEE std 519™ -2014, “IEEE recommended Practice and Requirements for Harmonic Control in Electric Power Systems”

[7] Nikhil S. Gujar, Asheesh R. Dhaneria, Puran N. Gajera, Satish H. Chetwani, “Experience on power quality measurement and assesment of Renewable energy generations in India”, 2016 CIGRE C4 International Colloquium on EMC, Lightning and Power Quality considereations for Renewable Energy Systems, Curitiba, Brazil

Enhancing Flexibility of Transmission System using Power Flow Controller & Dynamic Line Rating

Mohan Babu Paladugu, Power System Analyst | mohanbabu.paladugu@sterlite.com | +91 9717002621
Anantha Kumar R, Manager – Technical | ananthakumar.r@sterlite.com | +91 8155006177
Sterlite Power Transmission Limited, New Delhi

Objective:

- Increase flexibility and capacity of existing power grid.
- Increase network flexibility for grid users at optimised OPEX, which allows for a larger share of RES and increased security of supply.
- Manage congestion within the grid without affecting system reliability.
- Defer CAPEX to build new lines by harnessing the hidden capacities of the existing system.

Introduction:

The integration of intrinsically variable R.E generations shall bring unpredictability in the form of sizeable fluctuations in power flows in transmission networks. It shall also further increase the need for grid reinforcement to guarantee security of supply. The power flows vary with time, seasonal variations as well as daily variations. The network additions to cater these power flows cannot be an economical solution always. Advanced transmission technologies must be tested, and the management of existing infrastructure must be improved. The new technologies like **Dynamic line ratings (DLR)** and **modular power flow control devices (PFCs)** are being tested, implemented and are being successful in their operations in many parts of the world. This paper focus on the idea of integration of both Dynamic line rating and Power Flow controllers to enhance the flexibility of existing transmission infrastructure, along with details of DLR & PFCs and variables effecting the loading limits of conductors.

Concept – Integration of Technologies

- The loadings of the transmission system depend on several variables like wind velocity, ambient temperature, solar radiation etc. and hence the capacity of the transmission line cannot be a static rather can be a dynamic rating. Reliable monitoring by network operators is a precondition to exploit this extra capacity.
- Some **Dynamic line rating devices (DLR)** are quick and easy to install and can precisely monitor a network's transmission capacity in real time. The resulting measurements are more accurate and open the possibility of exploiting additional capacity without compromising on safety margins. It should be noted that DLR technologies is not a substitute of grid development, but a complementary method to better exploit exiting infrastructures.

Fig1: DLR Sensor, Source: Ampacimon

- **Power flow controlling devices (PFCs):** While devices like phase shifting transformers (PSTs) can be used to control power flows, alleviate congestion and free up available capacity, some advanced modular power flow devices are being successfully operated and are providing several advantages over traditional solutions, such as rapid deployment, scalability and redeployment. These modular power flow control solutions are being installed within meshed transmission and sub transmission networks and enables the operator to adjust transmission line reactance in real time to change power flows in the network.

Fig2: PFC installed on Transmission line, Source: Ref [1]

- **Integration of both Technologies (DLR + PFCs):** With the integration of both the technologies, where PFCs could serve to route power flows through additional capacities provided by DLRs, the flexibility of the transmission system can be enhanced, and hidden capacities of the transmission system can be exploited.

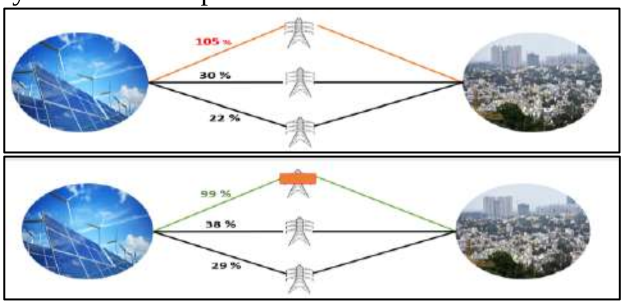


Fig3: Technology solving line overload

Conductor Loading:

Thermal current limit of conductor is defined as maximum amount of electrical current a conductor can carry before sustaining immediate or progressive deterioration.

Thermal rating of bare overhead conductor is a function of,

- Conductor material properties
- Conductor diameter
- Conductor surface conditions
- Ambient weather conditions

The first two of these properties are specific to chemical and physical properties. The third may vary with time, and that variation is dependent upon ambient atmospheric conditions other than weather. The fourth, weather, varies greatly with the season. If we consider that the conductor is mechanically properly designed, and sag is not a limiting factor for temperatures below the maximum allowable temperature of the conductor, then the weather conditions have the dominant effect on line's ampacity. The weather conditions directly influence on cooling power, mainly through convective cooling provided by wind.

The typical equation that describes the change of temperature in non-steady state condition is as follows,

$$\frac{dT_c}{dt} = \frac{1}{mC_p}[R(T_c)I^2 + q_s - q_c - q_r$$

Where,

q_s = Solar heat gain

q_c = Convection heat loss

q_r = Radiated heat loss

The above equation describes that when the heating is greater than cooling, the temperature will rise proportionally to the mass and specific heat of the conductor and vice versa. Since the atmospheric conditions around the conductor constantly vary as well as the conductor load, the temperature of the conductor also varies accordingly. The conductor temperature may vary not only with the line current but also the weather conditions may have significant impact.

<u>Dynamic Line Rating (DLR)</u>

DLR technologies can monitor the line parameters along with the external parameters like weather conditions to determine the real-time capacity of the line. The parameters can be monitored though direct and indirect methods.

Direct measurements are based on the measurement of the conductor temperature or least one physical parameter of the line which is directly related to it such as sag, mechanical tension, vibration frequency or ground clearance.

Conductor Temperature measurement: This is one the direct method of monitoring conductor parameters. This method requires installation of devices on the conductor, which can be powered by the magnetic field generated by the line current. The conductor temperature can be measured through,

- Temperature Sensors: Temperature sensors measures the conductor temperature and transmit the measurements to a central station via radio communication. These sensors are point sensors that can be installed at specific locations over the span of line sections.
- Optical fibre: the temperature measurement through optical cables, is carried out by the analysis of the phenomenon of scattering produced by a correct laser beam sent into the optical fibre.

Line Tension Methods: This direct measurement method involves the measurement of mechanical tension line. This method uses the load cells, which measure the mechanical tension and transmit the information to the control centre. The transmitted data is used for the calculation of temperature and therefore of the real-time ampacity.

Line Sag Methods: This direct method measures the sag in the fixed spans of the line by using optical sensors, ultrasonic or radar.

Vibration Frequency: This is one of the direct measurement method. The analysis of the conductor vibration can be used to detect the fundamental frequency of the span, which is a function solely of sag.

Indirect methods use weather parameters, measured by weather monitoring devices, and the load current to calculate the temperature of the conductor, through theoretical methods. These indirect measurements are also simplest to implement as they do not need to be installed on the line itself and can be installed on the towers. The measurement devices measure the speed & direction of wind, ambient temperature and the solar radiation. The wind speed is the one important factor in determining the temperature of the conductor, hence these devices should provide measurements with good accuracy.

The direct methods provide a true information of the physical quantity of the line being monitored, but it is necessary to install the sensors at multiple locations along the line. Indirect measurement methods use weather stations that are not directly installed on the conductor and measures for a span of area which can cover major portion of major span of conductor. Optimal utilization of both the methods can fetch better results to estimate real time capacity of the transmission lines.

<u>Power Flow Controllers (PFCs)</u>

The power flow controllers being discussed in the paper are basically series FACT devices which are modular and are easy to deploy, monitor and redeploy. These devices are clipped onto line conductors, typically at each end of multiple spans and can be installed or relocated in a very short time. These devices.

Traditional devices like example Fixed series capacitors and phase shifting transformers can enhance power flow and stability in the system but imposes challenges in terms of scalability, sizing, deployment, operational issues. requires enough space in substations for installation and these devices are designed for specific locations.

The modular series FACT devices are installed on each phase of the conductors. These devices inject reactance and push power away from the transmission circuit, thus controlling the power

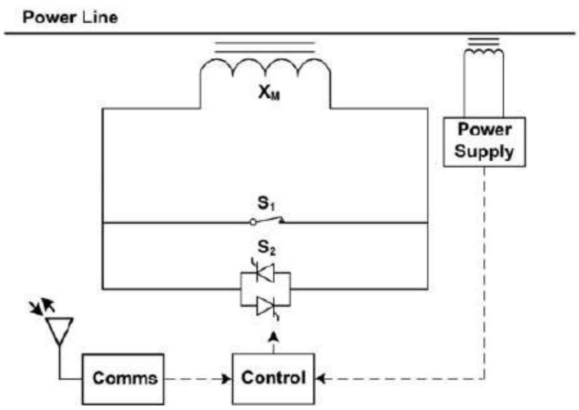


Figure 4: Equivalent circuit of PFC, Source: Ref [2]

Figure 5: Series FACT device clipped on Transmission Line Source: Ref [2]

The device consists of a split transformer hung from the conductor. Main power conductor forms the primary winding of the transformer. When the secondary winding is shorted, the unit operates in monitoring mode and negligible inductance is coupled in series with the line. When the secondary winding is opened, the magnetizing inductance of the transformer is coupled in series with the line and the unit operates in injection mode. While and individual device have a very small effect on impedance of a line phase adding numbers of them can change reactive impedance by several percent.

These devices can be operated in injection mode or in monitoring mode by controlling either through preprogramed current threshold or manual remote control of the devices from operating centres.

Integration of Technologies (DLR + PFCs)

The Integration of technologies is explored to enhance the flexibility of the system operation. A multi measure approach would enable networks to accommodate larger volumes of power and transport it to the demand centres, making better use of existing assets.

The trend towards using seasonally adjusted ratings and ambient adjusted ratings reflect that traditional static line ratings are often or usually over conservative. The ratings provided by Dynamic line rating technology combined with forecasting tools, can be logical extension of the above trend, by providing actual capacity ratings based on actual conductor behaviour and forecasted weather conditions.

In case of renewable generation (RE), the congestion is created due to seasonal variations and the lines are underutilized during the rest of period. As power flow devices are modular and can be controlled remotely, these devices can help in controlling the power flows i.e., routing the power flows in other paths with spare capacities, where these spare capacity data can be provided by the DLR technologies along with forecasting tools in real time. During high RE generation these technologies can be cumulative, enabling greater flows to pass through what had previously been considered as a congested line. Due to their compact nature the same set of devices can be installed and reinstalled at critical locations whenever required.

These technologies either by integration or individually can be implemented to harness hidden capacities, however overloaded lines in critical corridors should be dealt with uprating methods i.e., either by increasing the thermal capacity of line or voltage upgradation.

Future Work - Intention

- Identification of case where there are overloading for a short time due to integration of RE generation.
- Gathering of network data required for the power system studies. Network data like transmission system connectivity, generation and load data, transmission system equipment parameters.
- Network model and simulation studies, Transmission line forecasting techniques and algorithms.
- Stakeholder engagement and real-time pilot project by combination of installing the DLRs, PFCs and forecasting techniques.

Typical case with Assumptions, where Multiple Technologies can be implemented:

The evacuation network near the Nagjheri hydro power, which is in northern part of Karnataka is being severely overloaded as per the operational feedback report published by National Load Despatch Centre. The hydro generation present in the vicinity are Nagjheri (Installed capacity:900MW), Kodasally (Installed capacity120MW), Kadra (Installed capacity150MW) and there is a nuclear generation at Kaiga with installed capacity of 800MW. The total installed capacity in the vicinity is around 2050MW.

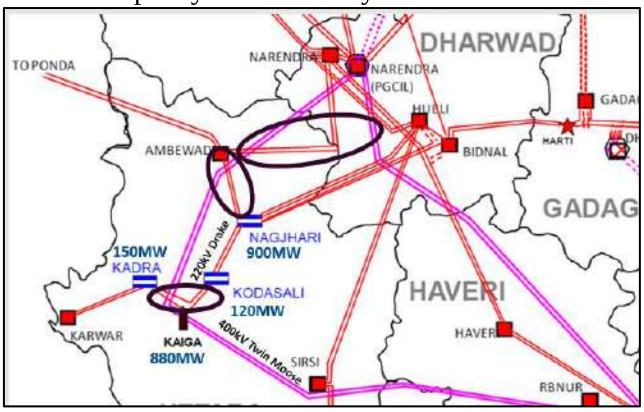


Figure 6: Network Map near Nagjheri

The lines that are being severely overloaded as per the report (ref [4]) are 220kV Nagjheri – Ambewadi D/C, 220kV Ambewadi – Narendra D/C, 220kV Kaiga – Kodasally S/C and 220kV Kadra – Kodasally S/C. From the SLD it is can be seen that there is high capacity 400kV corridor connected between Kaiga – Narendra and Kaiga – Gutty. The lines can be overloaded assuming that the power is taking the route through 220kV although a 400kV connection is available.

The thermal capacity of 400kV Twin Moose varies from 874MW at ambient temperature of 45^0C to 1108MW at ambient temperature of 30^0C [ref 5]. There are two interconnected high capacity 400kV corridors available in the system.

For this case with the integration of technologies like DLR and Power flow controllers, the power may be routed from the overloaded 220kV lines to high capacity 400kV corridor along with reconductoring few corridors with high performance conductors. The DLR technology along with forecasting tools can provide the dynamic thermal capacity available and the PFCs can route the power to 400kV corridor. The application of technology, design of the PFCs and optimal location of DLRs along with reconductoring can be identified through system studies along with the stakeholder engagement.

Conclusion

The Government of India has presently set an installed capacity target of 1,75,000 MW from renewable energy (RE) sources by 2022. This includes 1,00,000 MW from solar, 60,000 MW from wind, 10,000 MW from biomass and 5000 MW from small hydro power. Within the target of 100,000 MW for solar energy, 40,000 MW would be from solar roof tops and the balance 60,000 MW would be from utility level grid connected solar.

Category	Capacity addition				
	2017-18	2018-19	2019-20	2020-21	2021-22*
Solar					
Rooftop	5,000	6,000	7,000	8,000	8100
Ground Mounted Solar	10,000	10,000	10,000	9,500	7637
Total Solar	**15,000**	**16,000**	**17,000**	**17,500**	**15,737**
Wind	4,700	5,300	6,000	6,700	6,334
Biomass	750	850	950	1,000	1,005
SHP	100	100	100	100	100
TOTAL	**20,550**	**22,250**	**24,050**	**25,300**	**23,176**

*the capacity has been adjusted to arrive at total capacity from RES of 1,75000MW by 2021-22

Figure 7: Year Wise targets of Renewable Energy Sources. Source: Draft National Electricity plan, Central Electricity Authority

To integrate these huge targets of RE generations, there is an emerging need for rethinking, in designing the system to enhance the existing capacity through uprate/upgrade, with the support of new technologies & their integration, along with strengthening of the grid.

References

[1] CIGRE US National Committee 2015 Grid of the Future Symposium- Flexibility in wind power Interconnection Utilizing Scalable Power Flow Control

[2] CIGRE US National Committee 2015 Grid of the Future Symposium- Initial Field Trails of Distributed Series Reactors and implications for Future Applications.

[3] Dynamic line rating for overhead lines – V6 – entsoe

[4] Operational feedback Transmission Constraints – October 2017, Report by National Load Despatch Centre.

[5] Operational guidelines for determination of TTC, ATC and TRM for the short-term Horizon (0-3 months) by CEA.

Biographies

Mohan Babu Paladugu is a Power Systems professional having extensively worked on Transmission Planning, Load Flow Analysis, Short Circuit Analysis, Transient Stability, Power system protection and Harmonic Analysis. Mohan has expert skills on simulation software such as MiPower, ETAP, PSSE etc. Over past 6 years, Mohan has gained experience of working with Power Consulting, Power Generation & Power Transmission companies. He is currently associated with Sterlite Power Transmission Limited and responsible for facilitation and integration of next generation technologies in power grids.

Anantha Kumar R is a metallurgy and material science professional having extensively worked on development of various HTLS technology. Anantha has expert skills on design techno-commercial overhead conductor through PLS CADD. Over past 7years, he has gained experience of working on HPC/LOW LOSS CONDUCTOR /HTLS /PA Rod development and Steel manufacturing companies. He is currently associated with Sterlite Power Transmission Limited and responsible for design and development of overhead conductor especially HTLS conductors.

Load Accessed Directional Relay (LADR) – An Innovative Approach to Power System Stability.

P.K.PATTANAIK
Deputy General Manager (Elect.)
Odisha Power Transmission Corporation Ltd. (Bhubaneswar)

1. Abstract:

Reliability and Stability are the important aspects for the study of electrical power system. To maintain stable and reliable power, every utility/company should secure competitive electrical equipment with reliable protection scheme to accommodate the rapidly changing power system network situations. Many utilities use interconnected tie lines, ring main network etc.. to enhance the system reliability and stability. But this inter-connected network has its own advantages and disadvantages. One of the major disadvantages of the system is to attain proper relay co-ordination in the system as per the abnormal change of the electrical parameters during the situation of either of fault occurrence or abnormal condition. Sometimes the fault on any line causes the tripping of the other healthy lines connected in the system which results in cascade tripping due to mismatch of Supply and Demand in the network. Instances of complete black out of the system have also been observed due to the tripping of the important line/lines.

Similarly the situation of over loading, sometimes develops in the distributing sub-stations due to the tripping of distribution transformers or inter-connected lines. For this condition, the other available healthy system also trips on over loading and causes the system disturbance or black out etc. The power evacuation from the generating station is also the critical situation for the outage of the system network.

*So, to avoid the precarious conditions as described above, an innovative design approach have been selected in the protection schemes. This concept is named as LADR (**Load Accessed Directional Relay**). The basic of the concept lies on the study of rate of change of current (dI/dt) during the abnormal condition. Both the abnormal conditions, say the condition of fault and the condition of over loading is different on the consideration of rate of change of current and voltage (dI/dt, dV/dt). So both situation could be discriminated from the study of these changes.*

The detail of the concept has been dealt in this paper with suitable example of the network. More over the applications of this concept as utilized for the following conditions have also been described with various case studies.

- ***Distribution Grid sub-station's power control***
- ***Transmission load flow control***
- ***Un-interrupted power supply Distribution Network.***
- ***Power Generation control***
- ***Network System stability during disturbance.***
- ***Special Protection Scheme (SPS) with WAMS for inter-connected networks***

2. Introduction

Power is a critical resource for economic development in a liberalized environment for any developing country like India. Availability of Electrical Power has become the prime need to develop the economic status for competing with others in various National/International activities. Power systems are large, highly complex, ever-changing structures that must respond continuously in real time. Electricity must be produced and delivered instantaneously when it is demanded by a load. Another distinctive feature of the electricity system is its inherent dynamic effects, which must be considered at all times even though they are difficult to explain and fully anticipate. Power outages are not acceptable, so the system must also tolerate sudden disruptions caused by equipment failure or weather. Further, the system must perform as economically as possible, with outages and restorations monitored accurately.

The problem of restoring power systems after a complete or partial blackout is as old as the power industry itself. In recent years, due to economic competition and deregulation, power systems are operated closer and closer to their limits. At the same time, power systems have increased in size and complexity. Both factors increase the risk of major power outages. After a blackout, power needs to be restored as quickly and reliably as possible, and consequently, detailed restoration plans are necessary.

In recent years, there has also been an increasing demand in the power industry for the automation and integration of tools for power system planning and operation. This is particularly true for studies in power system restoration where a great number of simulations, taking into account different power system configuration have been carried out. In the past, these simulations were mostly performed using power-flow analysis, in order to find a suitable restoration sequence. However, several problems encountered during practical restoration procedures were found to be related to dynamic effects. On the one hand, simple rules that help to quickly assess these problems are needed. On the other hand, accurate modelling techniques are necessary in order to carry out time-domain simulations of restoration studies configurations.

Due to the deregulation of the power industry worldwide, and the almost revolutionary changes in the industry structure, power systems are operated closer and closer to their limits. Furthermore, in recent years, they have grown considerably in size and complexity. This has led to an increasing number of major blackouts, such as the large power outages in Northern Regional Grid of India failed 30.07.2012 & Northern, Eastern , North Eastern Regional Grid of India on 31.07.2012.Disturbances that can cause such power blackouts are natural disasters, line overloads, system instabilities, etc. Furthermore, temporary faults such as lightning, even if cleared immediately, can initiate to a partial or complete outage, involving network separation into several subsystems, and load shedding. After power blackouts, the system has to be restored as quickly and efficiently as possible.. Although power outages differ in cause and scale, virtually every utility has experienced blackouts and gone through restoration procedures. As a consequence, there is an increasing interest in systematic restoration procedures, tools, and models for on-line restoration, as well as for restoration planning. A speedy, effective, and orderly restoration process reduces the impact of a power outage on the public and the economy, while reducing the probability of equipment damage.

India as a whole has already identified the changes coming up in the power sector and geared up to tap the emerging technologies in various aspects of applications. Our nation has already complied its vision and enlisted many of the initiatives that have already hit the road of progress.

3. Basic Concept of LADR:-

This relay works on the principle of change in electrical parameters *(dI/dt, dV/dt)* on the system. Similar to conventional directional relay (67), this relay also requires both current and voltage parameters for its working operation. The pick up direction depends upon the flow of current and voltage direction. As per the requirement of the protection scheme, the relay can be set either in forward or in reverse direction. This LADR is programmed on the basis of change of current and voltage on the system. The change of electrical parameters on the system occur due to the following causes

1. Over current drawal due to rise of consumer load on a healthy system with no appreciable change of voltage in the system.

2. Change of electrical parameters (Voltage and Current) due to outage of one or more ties/feeders on the system for fault condition.

3. Change of electrical parameters (Voltage and Current) due to sudden rise of fault current and dip in the voltage in the system.

The rate of change of current due to the rise of load in the system becomes slow as compared to the rate of change of current due to fault in the system. So, di/dt (Rate of change of current) decides the parameters to the logic function of the relay, either to change the plug setting to next groups or to issue the trip command without change of setting. The discrimination between the di/dt for both the condition is clearly indicative and becomes suitable to develop the logic function. Not only the rate of change of current, but the change of voltage also discriminates the situation and activates the logic as required by the user.

Relay is so programmed that when current rises beyond certain limit without the change of appreciable band of voltage, due to isolation of a part or parts of the network system or due to rise of load demand in the system, then PSM (Plug Setting Multiplier) changes accordingly to meet the extra load demands on the system. This change of PSM can be programmed till to the electrical current carrying strength of the line conductor or as per the required final limit of the current in the conductor. But for the condition of fault in the line the relay issues trip command directly without change of PSM and accordingly isolates the faulty line, as because the change of parameters become totally different as that of normal rise of load.

4. Basic on Directional O/C Protection (67, 67N)

Directional O/C protection requires the responses from both voltage and current transformers in the system. For the design of the operating time characteristics, the following formula is used as the working function for IDMTL Relay.

As per IEC 255-4, BS 142, 3.2)

Value of 'K' and 'C'

$$t = \frac{K \times Tm}{(I/Is)^c - 1}$$

Where t= operating time in seconds
I = fault current in Ampere
Is = Start Current = 1.1 Ib in Ampere
Tm= Time multiplier
K,c = Factors

Table- 01 Data on Constant		
Type	**K**	**C**
Normal Inverse	0.14	0.02
Very Inverse	13.5	1.0
Extremely Inverse	80	2.0
Long Inverse	120	1.0

In general for O/C relay, 90^0 relay connection is

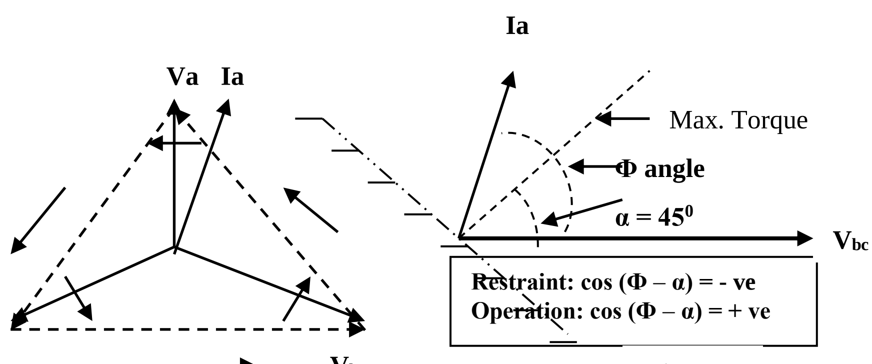


Fig- 01

used with MTA be 45^0 (lead) and for E/F relay, relay connection is also used as 90^0 but relay characteristics angle is taken as 12.5^0 (Lag).

4.1. Explanation:- (Refer Fig-01)

For 'A' phase element, comparing Ia with Vbc at relay location, determines direction of the element.

Similarly for the directional ground fault element, it is Io and Vo.

The operation and restraint of the relay depends upon the torque angle and maximum sensitivity will occur when $\Phi = \alpha$.

4.2. Programming of LADR

LADR can be programmed for setting of different values in groups. The selection groups can be chosen as per the requirement of the protection scheme and the associated network in the system. The change of group setting is done by the signal either received internally from the logic equation or from the external triggering by certain binary input signals. Two binary inputs are required for the purpose of changing four set of groups. One binary input must be set for Group Bit 0 and other for Group Bit 1. (Refer Fig-02)

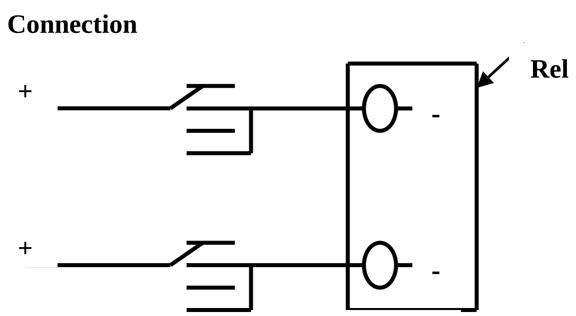


Fig- 02

The setting groups can be selected as per the requirement of the load on the system. The characteristic of this type of relay is to change the setting and also becomes ready to adopt with the new setting quickly. The algorithm and truth table could be programmed in present system of soft commands of GOOSE signal, depending upon the inter-operability system.

5. Application of the Relay Concept.

By the consideration of the requirements, this concept and programme in the relay can be utilized for different applications in Grid sub-stations, Transmission lines, interconnected networks etc.. The details of the applications are described below.

- *Distribution Grid sub-station's power control*
- *Transmission load flow control*
- *Un-interrupted power supply Distribution Network.*
- *Power Generation control*
- *Network System stability during disturbance.*
- *Special Protection Scheme (SPS) with WAMS for inter-connected networks*

5.1. Distribution Grid sub-station's power control

Every EHT Grid Sub-stations are generally equipped with Feeder bays (Load Links) and Transformers/ Generators/ Motors Bays (Equipment Links). For the protection of these links, two categories of relays are generally used in the system (Main and Back up Protection). For the situation like tripping of any one or more number of bays due to fault in the system, causes over loading of the other healthy links in the network. So the system stability gets hampered and many a time's it has been observed with the complete blackout of the system.

This situation of over load tripping can be controlled by the use of LADR concept in the relay by the change over of plug settings automatically according to the load demand on the system. During this condition the pre defined logic gets activated for maintaining the power system stability in the system.

5.1.1 Typical Design for Sub-Station Loads (with 2 Transformers)

Consider the tripping of the transformer no.1 and over loading situation of transformer no.2. With the present situation and relay co-ordination principle, the O/L back up relay on the available transformer changes its plug setting automatically to the next desired setting to accommodate the extra rise of the load in the healthy transformer. Some times the over loading values becomes more than the next desired and allowable setting. For such case at the time of tripping of the 1st transformer, it issues simultaneous trip command to the down stream out going feeders, called TARGET FEEDERS as desired by the user. The selection of these feeders can be done from the study of the load pattern and importance of the feeders in the system network. (Refer Fig -03)

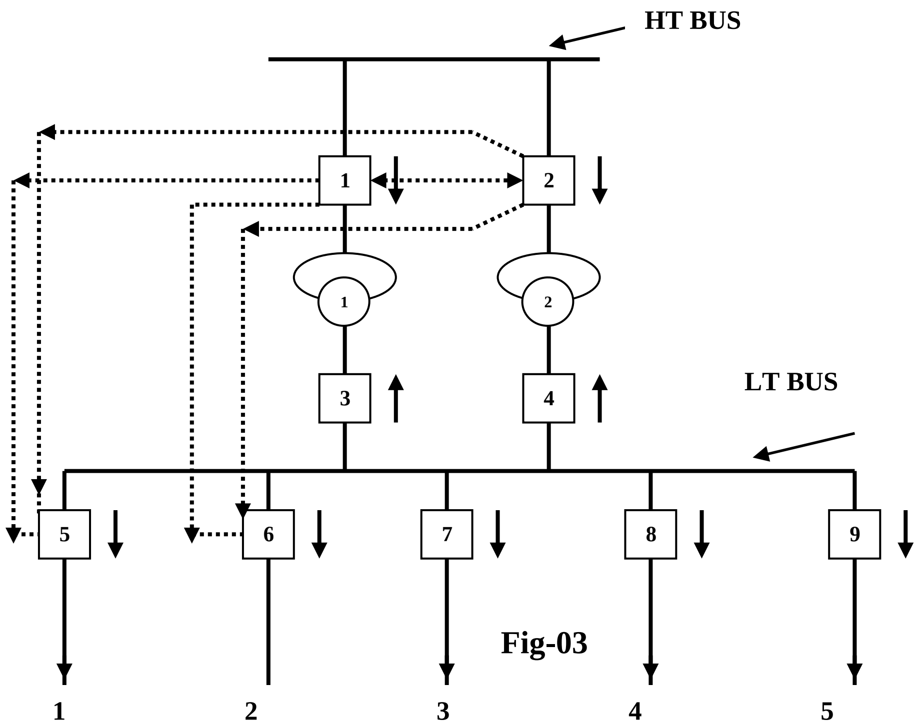


Fig-03

5.1.1.a. Practical Situation of Over Loading on the Grid Sub-Station

At this grid Sub-Station over loading situation of the transformers are resulted due to the following different conditions.

Situation 1 :-
One of the Hydel Station has been in connection with this grid sub-station by 2 nos of 132 KV tie lines (feeder No 2 & 3). Generating units of the power house remain in synchronization with the system loads. During normal operating condition, due to any reason if the generator units at the power house trip, then load drawal on the 132 KV tie lines may increase suddenly and in result may cause overloading of the transformers.

Situation 2 :-
In normal operating condition of both the transformers in service, if any one of the transformer trips, then over loading situation will result on the healthy transformer. Such situation may also cause tripping of the transformer and system disturbance in the healthy network.

5.1.1.b. <u>DATA FOR A 220/132/33 KV GRID SUB-STATION</u>

1. **Sub-Station Load**
   a. Maximum station load :- 180 MW
   b. Minimum station load :- 100 MW
   c. Average station load :- 140 MW

2. **132 KV system Load**
   a. Feeder –One :- 50 MW
   b. Feeder –Two :- 60 MW
   c. Feeder –Three :- 60 MW
   d. Feeder –Four - 35 MW
   e. Feeder –Five 35MW
   f. Feeder –Six :- 20 MW
   g. Feeder –Seven :- 12 MW
   h. Feeder –Eight ;- 20 MW

3. **Available System**
   a. 2 Nos of Transformers of rating (2x100MVA)= **200 MVA**
   b. Power factor on the system = 0.90
   c. Available Full Load rating = (200x0.90)= 180MW

d. Allowable loading of each transformer on the basis of (120% for 30minutes@) = 100x0.9x1.2)= **108MW**

e. Target feeders on the basis of load pattern and importance :-**Feeder No. 5 and 6**

f. Additional Feeder for safety cut-off:- FEEDER- 7(Seven)

5.1.1.c. Scheduling of the Load and Tripping Pattern

For the situation of the tripping of any one of the transformer, the O/L relay on the available transformer should be designed to accommodate the load up to 108 MW. So the transformer load should be tracked or scheduled from the normal operating condition with the individual loading of (108/2 = 54 MW). The available relay (51 -1 & 51-2) on the transformer in normal condition starts to pick up from the individual loading of **52#** MW. The contacts of these relays provide binary input to the directional B/U relays and changes the PSM (Plug Setting Multiplier) to the next desired higher setting (120% as desired). For the case of tripping of any transformer, the O/L situation on the system starts to cause tripping of the target 132 KV down stream feeders, till to the limiting value of 90 MW (safety continuous loading of the transformer). If this allowable limiting condition attains, then the additional safety cut-off feeder does not trip.

During this allowable time of 30 minutes, the down stream users may be requested to reduce the load to avoid the tripping of the additional safety cut-off feeder. Sometimes due to failure of communication, non-availability of operational staffs or failures operational equipments (Like non-operation of breakers, isolators etc...) may lead to the situation of over loading on the available transformer. But this situation will not affect the transformer and cause the tripping of the additional safety cut-off feeder and in result to reduce the load below the desired setting.

For the concept of over loading due to the situation 1 as described above, the overload relay available on 132 KV Feeder No 2 &3 being in pick up condition will cause the

Tripping Schedule

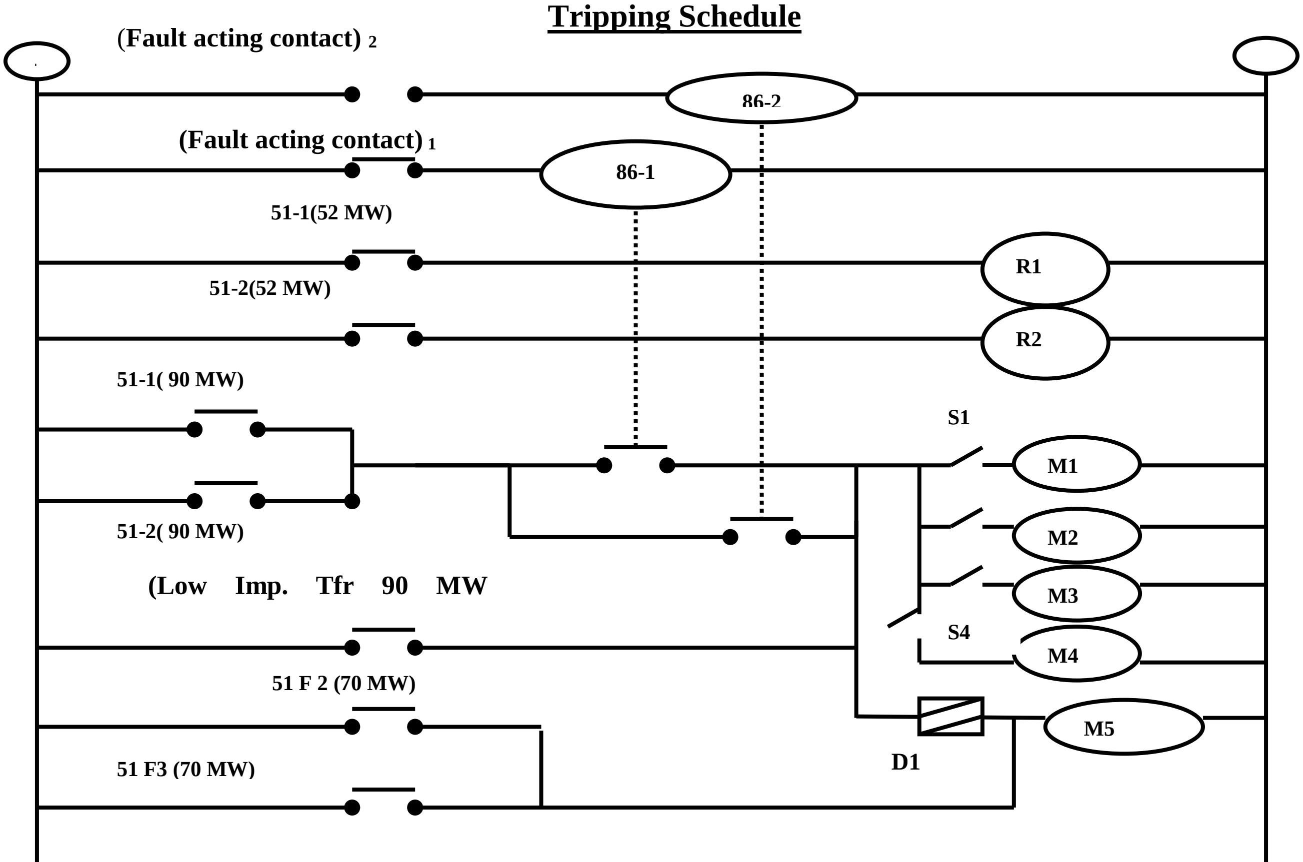


Fig -04

tripping of the 132 KV Safety Cut-Off feeder. Hence reduction of approximate load of 35 MW (Maximum) will cause the relaxation O/L situation of the transformers.

Moreover another safety factor has also been taken into consideration i.e. for any reason if the transformer having low % impedance draws a load of 90 MW then also the over loading relay on the system will issue the tripping command to the target feeders to cut down the extra load as explained in the tripping schedule diagram.

52[#]:- Actual load calculation for tracking purpose is 54 MW, but for safety side of the binary in put pick up condition for the back up relay, 52 MW has been considered in this system.

In the schedule diagram: (refer Fig-04)

86-1 :- Master trip Relay of 220side of Transformer-1

86-2 :- Master trip Relay of 220side of Transformer-2

R1:- Over Load Back Up Directional Relay on Transformer-1

R2:- Over Load Back Up Directional Relay on Transformer-2

M1,M2, M3, M4 :- Master trip Relay of 132 KV Target Feeders

M5:- Master trip Relay of 132 KV Additional Safety Cut-off Feeder

D1:- On Delay 30 minutes Timer

S1,S2,S3,S4 :- Selection Switch For Trip selection.

51-1(52 MW):- Non-Directional Over Load Relay setting for 52 MW Load on TRF-1

51-2(52 MW):- Non-Directional Over Load Relay setting for 52 MW Load on TRF-2

51-1(90 MW):- Non-Directional Over Load Relay setting for 90 MW Load on TRF-1

51-2(90 MW):- Non-Directional Over Load Relay setting for 90 MW Load on TRF-2.

5.1.2. Sub- Station with 3 Transformers (Ref Fig- 05)

Scheduling and tripping pattern for the situation with 3 transformers becomes very easy and flexible due to the availability of more outgoing feeders from the system. Tripping of any one of

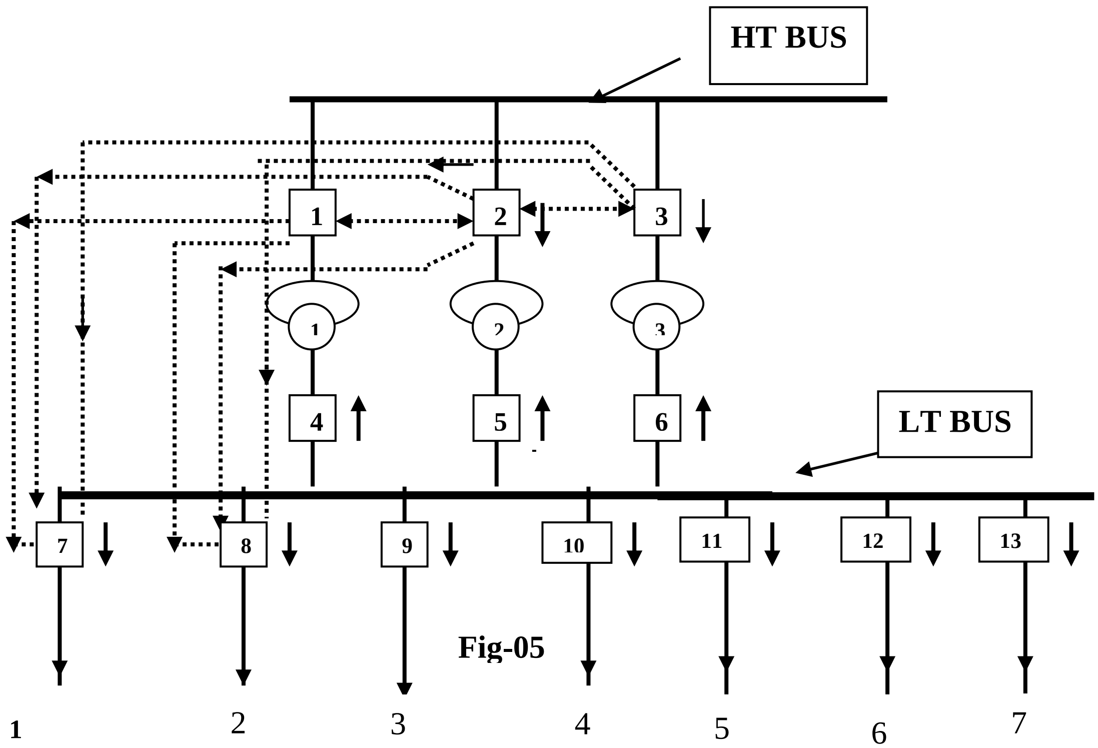


Fig-05

the transformer causes over loading situation on the rest available healthy transformers within the allowable limit of 120% load for 30 minutes. So none of the feeders are required to be targeted and only additional feeder is used for safety cut-off of the system load.

More over within the allowable 30 minutes of restriction, the downstream end users can be requested to cut-down the loads to maintain the availability loads on the transformers within the safety limit of 100% or below.

5.1.2.a. DATA FOR A 220/132KV GRID SUB-STATION

1. **Sub-Station Load**

a. Maximum station load :- 220 MW
b. Minimum station load :- 190 MW
c. Average station load :- 210 MW

2. 132 KV system Load

a) 132 KV FEEDER ONE: - 40 MW
b) 132 KV FEEDER TWO: - 40 MW
c) 132 KV FEEDER THREE:- 88 MW
d) 132 KV FEEDER FOUR 88 MW
e) 132 KV FEEDER FIVE:- 48 MW
f) 132 KV FEEDER SIX 48MW
g) 132 KV FEEDER SEVEN:- 72 MW

3. Available System

a. 3 Nos of Transformers of rating (3x100MVA)= **300 MVA**
b. Power factor on the system = 0.90
c. Available Full Load rating = (300x0.90)= **270MW**
d. Allowable loading of each transformer on the basis of (120% for 30minutes[@]) = (100x0.9x1.2)= **108MW**
e. Target feeders on the basis of load pattern and importance :-
   I. 132 KV FEEDER NO – ONE
   II. 132 KV FEEDER NO – TWO
f. Additional Feeder for safety cut-off :- 132 KV FEEDER No –SEVEN

Special Note: - In normal condition FEEDER No 5 & 6 contribute the load of 40 MW (Max.) to the system because of Source connected in the form of CPP.

5.1.2.b. PRACTICAL SITUATION OF OVER LOADING AT THIS GRID SUB-STATION

At this Sub-Station over loading situation on the transformers are resulted due to the following different conditions.

Situation 1 :-
Generating units (CPP) have been in connection with this grid sub-station by 2 nos of 132 KV tie lines 9 FEEDER NO 5 & 6. Generating units of the CPP remain in synchronization with the system loads and during normal operating condition, both feeders contribute the load of 40 MW (2x20) (Max.) to the system. But due to any reason, if any one or more than one generator units at the CPP trip, then instead of contributing the load to the system, the tie lines start drawing the load from the system. This drawal on the 132 KV tie lines increases suddenly and causes overloading on the transformers. The load rises even to the magnitude of 96 MW (2x48 MW).

Situation 2 :-
In normal operating condition of, if any one of the transformer trips, then over loading situation will result on the healthy transformers. Such situation may cause tripping of the healthy transformers and result system disturbance in the healthy network.

5.1.2.c. Scheduling of the Load and Tripping Pattern

At this grid, scheduling should be done on the basis of allowable loading of two transformers (2x108 MW). For the situation of the tripping of any one of the transformer, the O/L relay on the available transformers should be designed to accommodate the load up to 216 MW. So the transformer load should be tracked or scheduled from the normal operating condition with the individual loading of (216/3 = 72 MW). The available relay (51-1 & 51-2) on the transformers in normal condition start to pick up from the individual loading of **70**[#] MW. The contacts of these relays provide binary input to the directional B/U relays and change the PSM (Plug Setting Multiplier) to the next desired higher setting (120% as desired). At the same time these contacts being in series to the tripping path of the target 132 KV down stream feeders, become ready to cut down the loads over and above to the limiting value of 216 MW. However after tripping of the system another feeder being the additional safety cut-off feeder trips on time delay of 30 minutes to reduce the load of the existing transformer to the allowable continuous rating. The actuation of the tripping circuit depends upon certain minimum load on the system (200 MW as desired)

During this allowable time of 30 minutes, the downstream users may be requested to reduce the load to avoid the tripping of the additional safety cut-off feeder. Sometimes due to failure of communication, non-availability of operational staffs or failures operational equipment (Like non-operation of breakers, isolators etc...) may lead to the situation of over loading on the available transformers. But this situation will not occur because of the facility of additional safety cut-off feeder, which trips after time delay of allowable 30 minutes and reduces the load below the desired setting.

For the concept of over loading due to the **situation 1** as described above, the net maximum burden load becomes 136 MW (2x20 + 2x48) along with the system's maximum load of 260 MW. So during this situation total load becomes 356 MW (136 +220). But on the basis of allowable loading of 120% for 30 minutes, all the three transformers can accommodate the load of 324 MW (3x108 MW). Now it requires the shading of extra 32 MW (356-324MW) from the decided target feeders.

From the described target feeders, the 132 KV FEEDER NO SEVEN can be considered as the main target for the study of our system load and under safety target it can be taken as 60 MW instead of maximum consideration of 72 MW. Now the allowable 32 MW load is well within the available target of 60 MW. So the system disturbance can be avoided. More over for the extra safety margin to the system the additional safety cut-off feeder becomes ready to cut down the load still further within allowable time delay of 30 minutes duration.

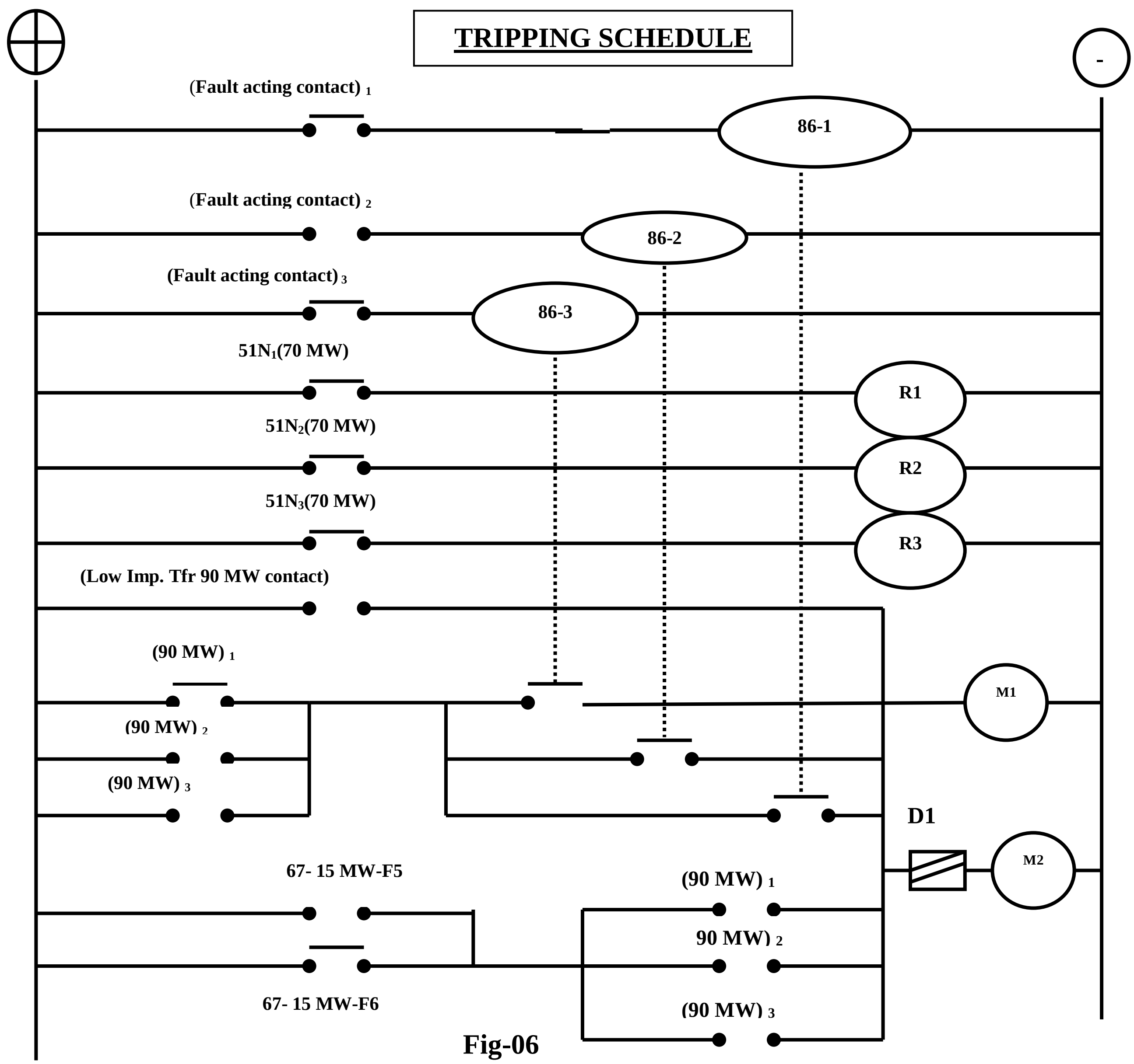


Fig-06

Some times for the **situation 1** the total burden load remains well within the allowable limit capacity of each transformer (say 100 MW).The total allowable load with all the transformers in running condition becomes 300 MW (3x100). Now the FEEDER No 5 & 6 ties can draw extra of 40 MW (300 – 220-2x20) before the over loading situation on the system develops. But for system stability, this 40 MW load can be tracked by the back up directional relay on the Feeder ties from the safe individual load of 15 MW (30/2).

Moreover another safety factor has also been taken into consideration i.e. for any reason if the transformer having low % impedance draws a load of 100 MW then also the over loading relay on the system will issue the tripping command to the target feeder to cut down the extra load as explained in the tripping schedule diagram.

$70^{\#}$:- Actual load calculation for tracking purpose is72 MW, but for safety side of the binary in put pick up condition for the back up relay, 52 MW has been considered in this system. The Over load relays are always set as per the current magnitude corresponding to the load.

IN THE FOLLOWING TRIPPING SCHEDULE:- (refer Fig 06)

86-1 :- Master trip Relay of 220side of Transformer-1
86-2 :- Master trip Relay of 220side of Transformer-2
86-3 :- Master trip Relay of 220side of Transformer-3
R1:- Over Load Back Up Directional Relay on Transformer-1
R2:- Over Load Back Up Directional Relay on Transformer-2
R3:- Over Load Back Up Directional Relay on Transformer-3
M1:- Master trip Relay of 132 KV Target Feeder-1 (FEEDER NO -SEVEN)
M2:- Master trip Relay of 132 KV Additional Safety Cut-off (FEEDER NO- EIGHT)
D1:- On Delay 30 minutes Timer
51-1 (70 MW):- Non-Directional Over Load Relay setting for 70 MW Load on Transformer-1
51-2(70 MW):- Non-Directional Over Load Relay setting for 70 MW Load on Transformer-2
51-3(70 MW):- Non-Directional Over Load Relay setting for 70 MW Load on Transformer-3
(90 MW)$_1$:- Non-Directional Over Load Relay setting for 90 MW Load on Transformer-1
(90 MW)$_2$:- Non-Directional Over Load Relay setting for 90 MW Load on Transformer-2
(90 MW)$_3$:- Non-Directional Over Load Relay setting for 90 MW Load on Transformer-3
67-1(15 MW):- Directional Over Load Relay setting for 15 MW Load on 132 KV RSP-1
67-2(15 MW):- Directional Over Load Relay setting for 15 MW Load on 132 KV RSP-2

Special Remark: - ***The relays on the system require proper co-ordination to avoid the un-wanted tripping of the healthy system. For the case fault, the faulty part should only be tripped without affecting the other network on the system.***

5.2.Typical Design for FEEDER Loads.

Consider the case of two different stations being inter-connected by means of three feeders as like shown in the figure. These feeders are equipped with Distance Protection relays as the Main protection and O/C relays are the back up protection with LADR concept.

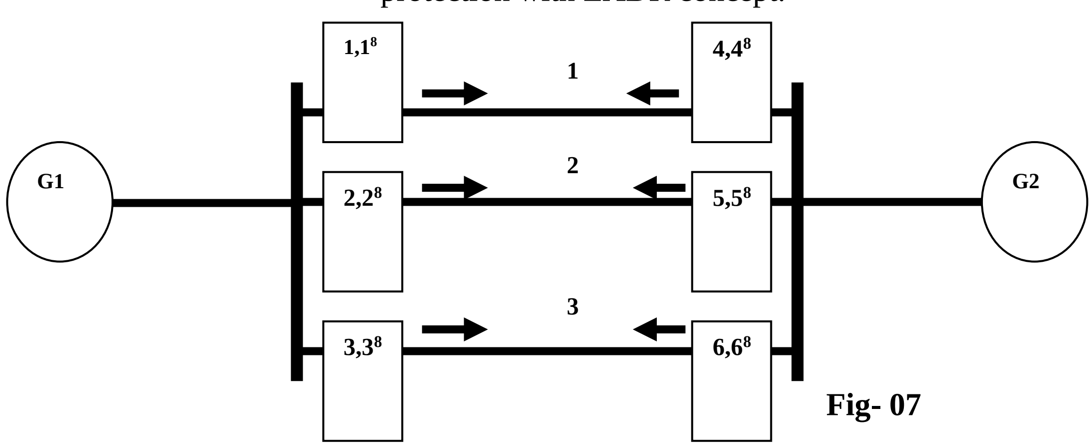


Fig- 07

Here 1,2,3,4,5,6 – All Load Accessed Directional Relays (LADRs)
1*,2*,3*,4*,5*,6* - Main Distance Protection Relays.

5.2.a. Fault Realization and Programme (Refer Fig-07)

For the case of fault on the line No.1, the distance protection relay 1*, 4* actuate and isolate the faulty part from the system. But due to reduction of tie link, rest of the two lines share the extra loads, with a result of rise in load current on the line. But because of LADR at both ends of line 2 &3, the said relays are sensed by the external trigger from the DP relays with conditional rise of load current on the system and other logical conditions in the system. So, the next group settings are activated automatically to accommodate the extra rise of current in the system.

Similarly with the available of two lines say 2 & 3, if the fault occurs on any one of the line, then the LADR on the healthy line being actuated with next settings, manages the extra loads till to the current carrying strength of the line conductor or to the desired value of power flow. But for the condition of actual fault on the line, the LADR instead of changing the setting to next group, issues trip command for isolation of fault in the system.

For a system network, the use of LADR at different tie/interconnected lines can also be programmed by studying the regular power flow for the fault in different part or parts of the line. According to the study, the logical condition can be fed to the LADR for obtaining smooth and stable power.

5.3. Development of Un-interrupted Power Supply

This relay can also be utilized for inter-connected ring main system to develop the un-interrupted power supply to the distribution network. A practical case study has been explained to avail UPS (Uninterrupted Power supply) to limited part of Western ODISHA. The available distribution network scheme, system equipments have been coordinated among them for optimization of the system stability. Particularly the use of NTR (Nodal Transformer), LADR (Load Accessed Directional Relays), and #RLADR with fault free Auto closing breaker scheme can achieve the stable and reliable power.

5.3.1. Major Distribution load centers (Distribution S/S)

1) 33/11 KV S/S, AINTHAPALI
2) 33/11 KV S/S, PUTIBANDH
3) 33/11 KV S/S, CHERUAPADA
4) 33/11 KV S/S, DHAMA
5) 33/11 KV S/S, GOSHALA
6) 33/11 KV S/S, HIRAKUD
7) 33/11 KV S/S, BURLA

The command areas of distribution under these Sub-Stations are the most important area of Sambalpur Electrical Division. The townships come under this group are {**1)Sambalpur 2) Burla 3) Hirakud}**

The main concept of providing uninterrupted power supply to these areas is to use inter connected tie lines with major distribution substations.

5.3.2.**Inter connected System:**

For this system the associated and related S/S are connected with one or multiple ties. Feeding sources also play the important role to cater the required supplies to the distribution network. So the connections of one or more feeding sources to the net work are also required to develop the scheme successful.

5.3.3. Design Criteria

For designing the system as per the concepts described above the following points are to be considered.

a) Location, Size & character of large loads
b) Location Size & character of small loads
c) Expected load growth of the area
d) Location of bulk power supplies.

e) Location and capacity of existing distribution equipment (Transformers, Circuit Breakers, Isolators, and Electrical Equipment)
f) Available site for Sub-Stations
g) Topography (Available route for distribution circuits)
h) Capacity of Distribution Networks (Electrical & Mechanical)
i) Capacity of control Equipment
j) Capacity and limitation of protection schemes.

5.3.4. **Some Innovative Concepts**

Many utilities use interconnected tie lines, ring main network etc.. to enhance the system reliability and stability. But the ring main system has its own advantages and disadvantages. One of the major disadvantages of the system is to attain proper relay co-ordination in the system. Some times for the fault on any line, causes over loading of the other lines connected in the system which results in cascade tripping in the system. Instances of complete black out of the system have also been observed due to the tripping of an important line. This situation of overload tripping and corresponding effect of cascade tripping or black out not only causes heavy loss to the utility but also results difficult situation to normalize the network.

Similarly the situation of over loading also develops in the distributing sub-stations due to the tripping of distribution transformers. For the condition of tripping of any one of the transformer, the other available healthy transformer/transformers also trips/trip on over loading and causes/cause the system disturbance or black out etc..

To avoid the precarious conditions as described above, some of the innovative design approach have been selected in the over current relay protection schemes and system network. The concepts like use of NODAL TRANSFORMERS (NTR), LOAD ACCESSED DIRECTIONAL RELAYS (LADR) and Fault Free Auto closing of breaker scheme are the special innovative ideas to develop the uninterrupted power supply scheme.

5.3.4.a. Concept of NODAL TRANSFORMER (NTr)

The transformers are the important equipment that decides the required rating of power transformation at the suitable level of voltage supply. Particularly the transformers available at the major Grid sub stations are called the NODAL TRANSFORMERS (NTr). The transformers available at the distribution sub-stations are called Sub- nodal transformers (Sub- NTr). The design criteria like the capacity of the NTr depends upon the following factors

a) Location, Size & character of large loads and total loads on the system
b) Future load growth
c) Location and capacity of existing **Sub-nodal transformers (Sub- NTr)**
d) Capacity of Distribution Networks (Electrical & Mechanical)
e) Topography (Available route for distribution circuits)
f) Available site for Sub-Stations

5.3.4.b. Concept of Load Accessed Directional Relays (LADR)

These relays are programmed on the basis of change of electrical parameters on the system. Generally the change of current on any tie line occurs due to the following causes.

1. Over current drawal, due to rise of consumers load on a healthy system.
2. Change of electrical parameters due to outage of one or more ties/feeders on the systems for fault conditions.

Relays are so programmed that when current rises beyond certain limit due to isolation of a part or parts of the network system, then PSM (Plug Setting Multiplier) changes accordingly to meet the extra load demands on the system. But for usual rise of current with non-isolation of any part of the network, the relays respond to the existing PSM.

5.3.4.c. Concept of Restricted Load Accessed Directional Relays(RLADR)

These relays have same characteristics as that of LADR with certain limitations. It responds due to over drawal of limiting current. In this study, these relays are to be used on 11KV-interconnected tie, which takes load current if only when 33KV Bus get faulted. But 11KV network has certain limitation to carry the load current .So when such exigency arises; the outgoing feeders on the 11KV Bus are automatically shaded in rotation according to the available limit of loads on the 11KV tie. The kind of load shedding rotation is pre-programmed in the RLADR.

5.3.5. Concept of Fault Free Auto closing of breaker scheme

By the use of sensitive and innovative concepts like NTr, LADR and RLADR and with inter connected tie lines to major sub-stations , the un-interrupted power supply can be achieved to different load centers. So, it can be considered that for the case of fault on any tie, power supply interruption does not affect to the system. So, quick restoration / reclosing of the breaker for power flow on the tie does not become important. Moreover, reclosing of the breaker with wrong design of the dead time and reclaim time, sometimes results with severe damage to the equipments and also converts transient faults into permanent faults. For the case of permanent fault on the system, every shot of closing of the breaker results electrical and mechanical stresses on the system, which causes the reduction of life span of the equipments. So it is always advantageous to close the breaker for a fault free feeder

For the new idea of fault free auto closing of the breaker, the fault detector circuits are installed on the network, which automatically detects the presence of fault on the circuit and accordingly sends signal for operation of the breakers. For any faulty feeder, the fault detector circuit continuously monitors the status of the feeder and blocks the signal for closing of the breaker till to the time of clearance of the fault. After clearance of the fault, signal is automatically extended for closing of the breaker. This method of monitoring the status of the fault on the feeder and deciding out put signal for breaker operation is repeated automatically with interval of every 5 minutes.

5.3.6. Practical Study of Interconnection: -

Under this practical study the following Distribution S/S, Bulk supply Stations, Transmission Lines, and Load Areas have been associated. The existing network and its associated equipment are required to be reviewed for further study of system stability. The up-coming networks (Proposed networks) have also been taken under this Study.

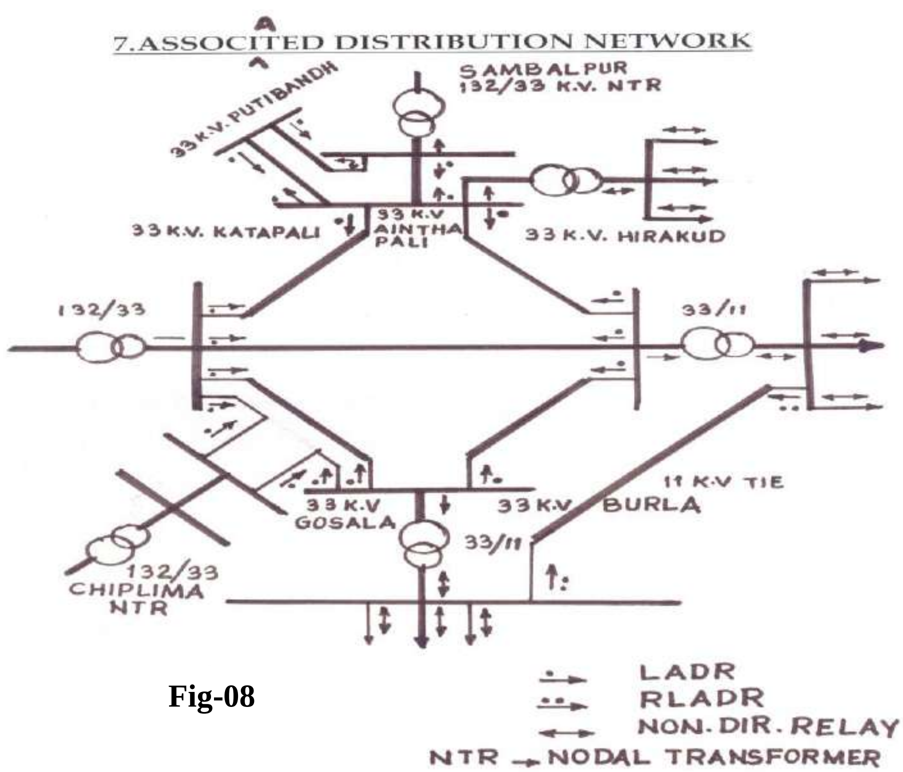


Fig-08

5.3.7. Associated Distribution S/S: -

- 33/11KV AINTHAPALI
- 33/11KV PUTIBANDHA
- 33/11KV DHAMA
- 33/11KV HIRAKUD
- 33/11KV BURLA (PROPOSED)
- 33/11KV GOSALA
- 33KV BUS, KATAPALI

5.3.8. Associated Bulk supplies:

- HIRAKUD GENERATING STATION
- CHIPLIMA GENERATING STATION

5.3.9. Associated Transmission S/S: -

- 220/132/33KV KATAPALI GRID SUB- STATION
- 132/33KV SAMBALPUR GRID SUB-STATION
- 132/33KV CHIPLIMA GRID SUBSTATION

5.3.10. Associated load areas: -

- Sambalpur Township
- Burla Township
- Hirakud Township

5.3.11. Stability and Reliability Study of Bulk Supply Source

In general, generating stations are inter-connected to different systems to meet the chaos and load fluctuations in the network. The occurrence of faults to EHV networks is very rare. From the System Study of fault analysis, it has been seen that 1 to 2 % of annual System Disturbances are resulted due to 5 to 10 % of fault occurrence on the EHV lines. So this factor gives us a positive clear-cut image regarding the stability and reliability of bulk supply source on any network.

Moreover, the two associated sources such described have also been connected with other sources of ER of power supply. So these two bulky sources can be considered as the stable and reliable sources for our study.

Generally the EHV Networks, come under the Transmission Systems, in which occurrence of fault is very rare. So reliability of the Transmission network in comparison to the Distribution System is more. At present all the bulk sources like B.PADAR Station, KATAPALI Station, THERUVALI Station, and Proposed BOLANGIR station are interconnected to the command area of our study. So the available bulk supply could be considered as the stable source for our study.

5.3.12. Associated Distribution Network: -

This part is the final sensitive point for catering the loads to different consumers. So its interconnection plays the important role on reliability of the supply system.
The design of Protection & Control Scheme depends upon the following factors.

- Capacity of NTR (Nodal Transformer)
- Capacity of Distribution Networks (Electrical & Mechanical properties)
- Loading Schedule on the network system.
- Physical realization of network system

Here the associated distribution networks with existing system and required modified system have been explained below to obtain the uninterrupted power supply to the major townships.

5.3.13. Fault realization of the Network: - Refer Fig no 08

For the case of fault on any part of the network, the protective relays such used on the system get actuated to isolate the faulty portion from the network. Because of this isolation, the cascade tripping on the system is avoided and system stability is obtained easily. Actually the isolation of electrical power from the network causes the change of electrical characteristics (Rise of current, Dip of voltage etc.) on the rest of the network, according to the load demands of the consumers.

5.3.13.a. Fault on the Sub-transmission ties

For the case of the fault on the sub-transmission tie, the directional relays used on either side of the tie, get actuated to isolate the faulty portion from the network. But supply to any distribution load centers (sub-station) does not get hampered. Because other ties connected in the system, provide the required loads to the load centers. Moreover multi-feeding sources (Bulk supplies) easily take the care of any system deficiency or surplus.

5.3.13.b. Faults on Sub-Station Bus (HT Side)

For this case, the bus zone relay if provided on the sub station actuates and all the connected feeders to the bus trip to isolate the fault. For the case of non-provision of this relay, the protection is taken care by the directional relays present on the remote end of the connected ties.

For the condition of bus fault also, the other adjacent substations easily meet the area loads through primary feeder ties.

5.3.13.c. Fault on the HT incoming feeder of S/S transformer:

For this case, the directional relays used on the feeder only actuates and trips its own breaker as well as the LT side breaker in inter trip facility. So the faulty portion gets isolated from the network. The other transformer/transformers such connected in the system takes/take the area load of the faulty transformer.

Note: For this fault the *transformer protection relays if such provided take care to isolate transformer from the supply.

*Transformer protection – 1. Differential relay 2. REF etc…

5.3.13.d. Fault on the LT incoming of S/S transformer

For this case, the non-directional relays such used on the feeder actuates and trips the breaker to isolate the faulty portion. For this fault the *transformer protection relays if such provided also take care to isolate transformer from the supply

5.3.13.e. Fault on outgoing primary feeder

The non-directional relay on the corresponding feeder only actuates to isolate the faulty feeder from the circuit.

5.3.13.f. Fault on Sub-Station Bus (LT Side)

Occurrence of bus fault is very rare. If this happens then the entire feeders connected to this bus will be affected. So, the load areas depending upon the outgoing feeders will be suffered with outage of power supply this difficult cannot be easily overcome by the procedure as described in the network.

By the use of bus- sectionaliser, the faulty portion of the bus can be isolated to extend the power supply through healthy part of the bus. The use of multi-bus system can also solve this type of problem. This spare bus is utilized to extend the power through out going feeders to the consumers.

NOTE; *Author has only expressed the concepts of the scheme. However the detail design and implication in realty need to be considered by the calculation of all the electrical parameters like Fault MVA study, SC level Study, Feasibility reports etc..*

5.4.Power generation control

The practical case of a Hydel Station has been considered for the study named Burla Power, situated in the Sambalpur district, Western side of Odisha. This station has the installed capacity of 275.5 MW with 7 units in the system. The network connectivity to this station is from different grids for successful evacuation of the generated power from the station. This station controls the power flow to the Western Odisha Command area load being interconnected with few vital links as follows.

1. 132 KV DC line with 220/132/33 B.Padar Grid Sub-Station.

2. 132 KV DC line with Chiplima Power House.
3. 132 KV DC line with ALCO, Hirakud.
4. 132 KV Line with 132/33 KV Sambalpur Grid Sub-Station.
5. 132 KV Line with 220/132/33 KV Katapali Grid Sub-Station.

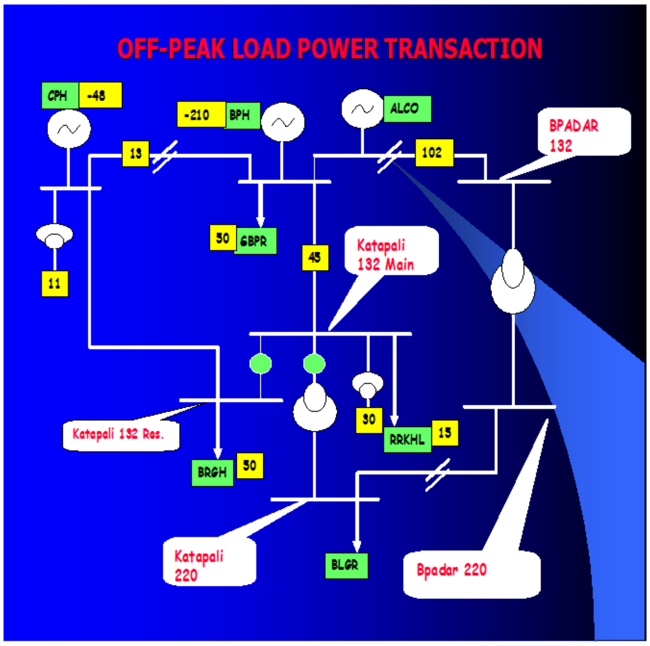


Fig -09

Sometimes disturbance in the system and subsequent mismatch of the Supply and Demand had been observed with outage of all generators in the system total and black out of the Burla Power house. In this paper the detail study of these incidences have been analyzed and possible solutions by considering the relay co-ordinations with the use of few numerical relays in the system have also been focused.

This study has been taken for the highest generation condition being 210 MW for both peak and off peak load condition and observed with variation of load flow in the 132 KV DC flexible links being 62 MW to 102 MW. During Peak Load condition outage of any one line of this link, manages the load with available link, resulting no disturbance. But during OFF- Peak Load condition, outage causes the over loading on the healthy link and results the tripping of the link and disconnection. This load through of 102 MW causes the disturbance on the system with black out of the POWER HOUSE.

5.4.1. Practical Study and Solution

Different cases on which the system disturbances to result have been described with this concept of LADR and association of fundamental principle of relaying concepts. Refer Table no 02.

5.5. *Network System stability during disturbance:*

The practical example has been taken for power hub named 220/132/33 KV Budhipadar Grid sub-station. This is one of the biggest Grid, situated in the Jharsuguda district, Western side of Odisha. This grid has 25(Twenty Five) nos 220 KV bays, 17(Seventeen) Nos of 132 KV bays with MVA capacity of 320 MVA. The generators to the system are from thermal units (IB Thermal, Starelite system, Bhusan System) and hydel units from Burla P.H. This Grid controls the power flow to the Western Odisha

Table No -02 Different Situation for Generating Station BURLA

Sl	SITUATIONS	SCHEMES
1.	Over loading Situation of 132 KV Burla- B.Padar DC line.	1. Numerical Relay at Burla PH end on each B.padar line will provide ALARM from load limit of 75 MW (375 Amp) for ramping down of the machines till to the resetting limit of this relay. **2.** Relay will issue trip command after 4 minutes for the load of 80 MW (400 Amp) and above. **3.** The numerical Relay will trip Bpadar end after 5 Minutes as Back up.
2.	Over loading Situation of 132 KV Burla- Katapali line	Relay at KATAPALI end will trip the AUTO TRANSFORMER after 75 MW and cause extra load flow to the allowable limit through BPADAR lines from BPH NOTE – 1. If 132Kv ALCO draws load from BPH above 40 MW then this scheme will be disabled at KATAPALI end for system stability.

Command area load and interconnected WESTERN region load through Korba system. Sometimes disturbance in the system and subsequent mismatch of the Supply and Demand has been observed with total black out of the Budhipadar command area with outage of all inter-connected generators in the system. For designing of the application of LADR in the system, the connected links at the stations have been categorised as LOAD LINK, GENERATOR LINK and FLEXIBLE LINK. The power flow on the flexible links during the abnormality condition has been studied. Refer Figure no 10.

In this study the relay called LADR monitors the change of electrical parameters on the system and the relay is also set with certain pre-decided programmes as per the critical study of the load flow during abnormal condition. So during such condition, the pre-defined target

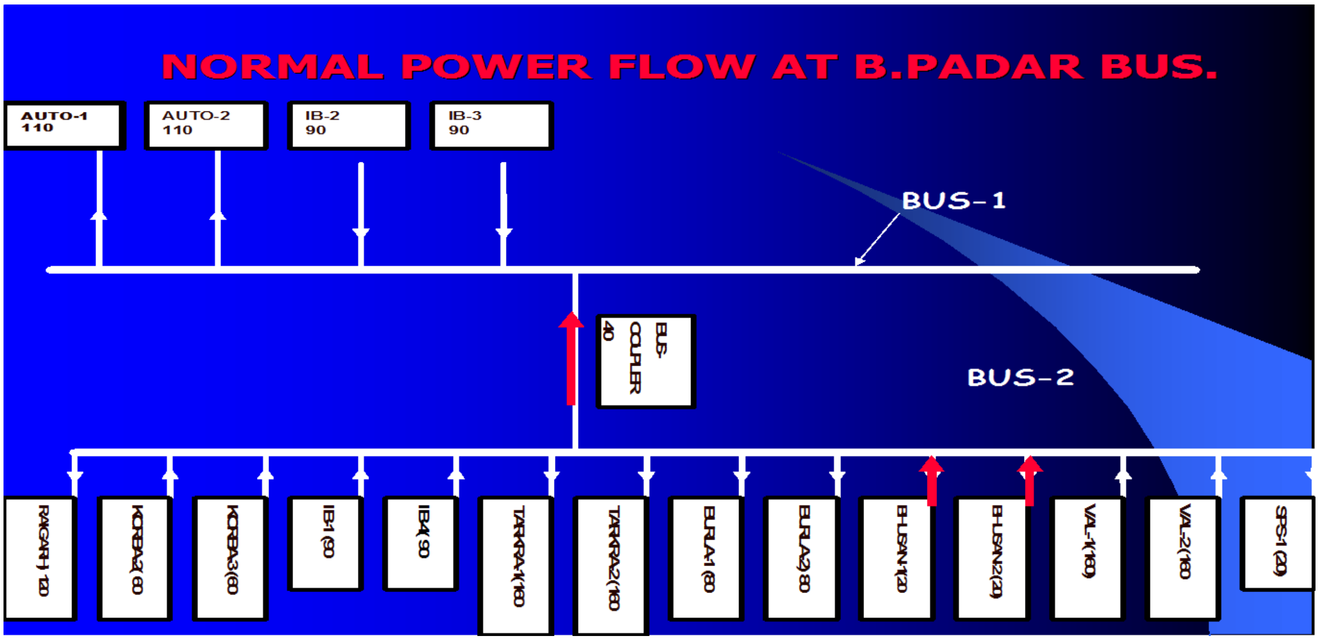


Figure 10

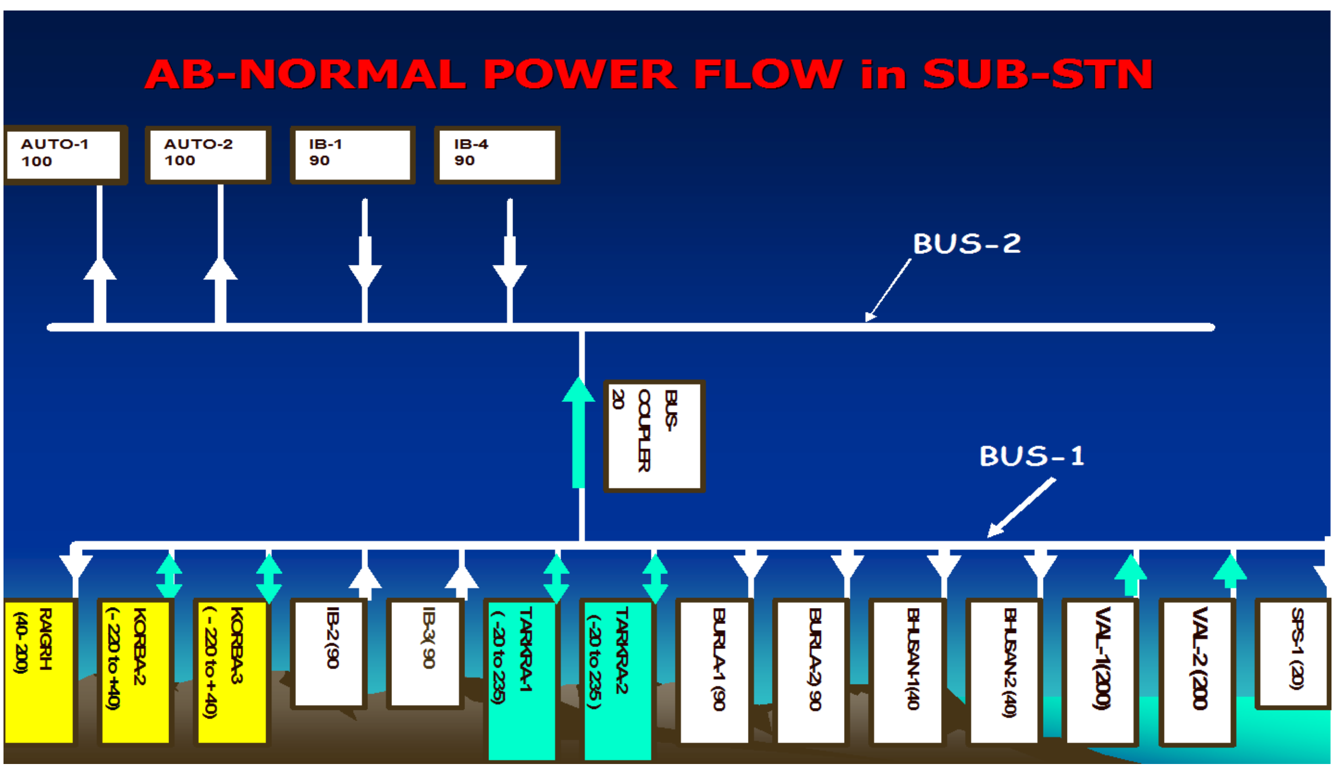


Fig- 11

loads or generators are cut down accordingly to result the balancing of the demand and supply, for which the possible situation disturbance gets avoided. The following conditions could be depicted for this article.

5.5.1. Outage important/ major Load Links:-

For this condition, the generators become surplus and cause over voltage and over frequency situation and tripping out of those generators if the setting value reaches the limit, resulting further disturbance. Now LADR relay as per the change of the electrical parameters decides and activates the pre-defined programme for ramping down the available generators in the system in proportionate according to their share to the network and avoids the system disturbance due to match of supply and demand.

Table No-03 Different situation at the Grid Sub-Station Budhi Padar

Situations	Links	Normal Power Flow	Abnormal Power Flow	Remarks
1. Forced Power Flow from Korba Links	Korba 2,3	- 120 MW	-300 MW	If Tarkera line trips, then system disturbance may result.
	Tarkera 1,2	+ 320 MW	+480 MW	
	Raigarh	+120MW	+140 MW	
2. Fault Outage of Tarkera Lines	Korba 2,3	- 120 MW	+100 MW	If Raigarh trips then system disturbance may result.
	Tarkera 1,2	+ 320 MW	0 MW	
	Raigarh	+120MW	+220 MW	

5.5.2. Outage important/ major Generator Links:-

For this condition, the Loads become surplus and cause under voltage and under frequency situation and tripping out of other healthy generators if the setting value reaches the limit, resulting further disturbance. Now LADR relay as per the change of the electrical parameters decides and activates the pre-defined programme for tripping/ shading of the target loads from the system in proportionate according to the requirement of the network and avoids the system disturbance due to match of supply and demand.

5.5.3. Disturbance of the adjacent System Network:-

Sometime the flexible links participate in the abnormal power flow due to the system disturbance of the adjacent Network. So the values of electrical parameters also change. For this situation also LADR relay plays the role of adjustment of Supply and Demand to avoid the possible incidence of system disturbance.

5.5.4. PRACTICAL EXAMPLE (Refer Table No 03)

5.5.4.1. Situations of Extra Generation Flow from Vedanta and Bhusan.

Normally the generation flow from Vedanta remains of 320 MW and Bhusan of 40 MW. But during the situation like either extra generation at Vedanta/ Bhusan or outage of loads at these units may cause the generation flow to B.Padar Bus. During this condition, the extra loads try to flow in the Flexible links. It has been seen that 220 KV Tarkera feeders carry the extra flow with reduction of Generation flow from Korba system. So 220 KV Tarkera lines get over loaded and outage of this network may cause the system disturbance.

5.5.4.2. Situations of Load flow to Vedanta System.

For the abnormal condition like outage of the generator units of Vedanta and requirement of area load of this system may cause flow of load from B.Padar Bus, instead of normal condition of Generation flow to the Bus. During such situation, the extra load tries to flow from Korba system with load reduction on 220 KV Tarkera and Raigarh feeders. Similarly during this condition if these overloaded feeders trip, then the system disturbance may result.

5.5.4.3. Other situations of abnormal Power flow

The different conditions that result the situation of abnormal power flow on the flexible links are listed below. The detail of the power flow has been provided in the table no-3

5.5.4.4. Analysis of the Power Flow study

From the above study, during different situations at B.Padar Grid Sub-Station, it can be concluded that the flexible links manage the load in the system. The availability of Tarkera, Korba and Raigarh Links adjust the load and avoid the possible situation of system disturbance. But further failure of the overloaded lines would have resulted in the system disturbance due to change in the electrical parameters. So the planning and control of this situation should have to be attempted for matching of the available Load and Demand in the system. The concept of LADR plays the role of either shedding of target feeders or ramping of proportionate generators from the system. For better and confirmed control LADR concept can be embedded with the use of Islanding scheme and the detail is explained below.

5.5.5. Solution by use of LADR and Islanding Scheme at B.Padar.

Example-1.(Tripping of flexible feeder)

Suppose Tarkera 1,2 tripped due to fault in the system, suddenly 320 MW will be thrown and flexible feeder Korba ties will take care the extra to certain limit. During this limited allowable time and load available in Bus Coupler, LADR will act as per the monitoring of dI/dt from the target loads and generators and accordingly send command for shedding of the generators or forced outage of the pre-decided scheme.

Example-2.(Tripping of Generator Link)
Similarly for withdraw of generators, suddenly load will be deficit in the system. The flexible feeders will try to take care of the situation up to allowable time. This time also LADR will act according to the dI/dt and available load in Bus Coupler and send command for shedding the loads on 132 KV side as per the demand

Example-3 (Abnormality in system parameters) :
Suppose abnormality in electrical parameters demands the islanding of the generators, then all the target generators will be isolated as per the gradation of the parameters except IB system. So IB system will remain with the radial available loads at B.Padar Bus and system will be survived from abnormality
The use of LADR and Islanding Scheme is tabulated in Table-04

Table No 04 Settings to be adopted in Special Relay

Parameter	Settings	Remarks
(f+df/dt), tf > f< - f>	-6 to 1Hz/S, 1S 48.5 - 51 Hz	**Load Shedding# Generator Shedding $**
V<, tv>	198 Kv , 5S	90 % voltage, 5.0 sec (Alarm).
V<, tv>	195 Kv, 5 s	87.5 % (Island)./ **Load shedding#**
V>, tv>	245 Kv , 5 s	111.3 % voltage, 5.0 sec (Alarm).
V>, tv>	258 Kv, 5 s	120 % (Island)./ **Gen. Shedding$**
f<, tf>	48.5 Hz, 5s	96% frequency, Alarm
f<, tf>	48 Hz, 3s	95.5% Island)./ **Load shedding#**
f>, tf>	52 Hz, 3s	**Alarm**
f>, tf>	52 Hz, 5s	**Gen. Shedding$**

1. Tarkera 160MW (E) or Korba 2,3 (100 MW) (I) for **Load shedding** # to 132 KV side
2. Tarkera 180MW (E) or Korba 2,3 (140 MW) (I) for **generator shedding $** to Vedanta + IB Thermal (Band 1)
3. Tarkera 200 MW (E) or Korba 2,3 (150 MW) (I) for **forced Generator shedding $** to Vedanta + IB Thermal (Band 2) without any frequency condition.

Note: - 1.Tarkera 160MW (E), for outage of Tarkera, LADR ready with logic for forced tripping of Vedanta system.
2. Korba 2,3 (100MW) (I), for outage of Korba, LADR ready with logic for forced tripping of Raigarh.
3.. Korba 2,3 (150MW) (I), for outage of Korba, LADR ready with logic for forced tripping of Raigarh + Katapali.Note1.

5.5.6. Special Review of BLACK OUT Incident on 30th and 31st July 2012.

During the end days of July 2012 i.e. on 30-31st, there had been a severe Power System disturbance in India. On 30th at 02.33 hrs, the Northern Region was collapsed with a disturbance of load of around 36,000 MW. On 31st July, the disturbance was rather severe and on this day Northern, Eastern and North-Eastern regional grids were collapsed with a disturbance of load of about 48,000 MW. On both of the days, few pockets were only survived from black out due to successful functioning of islanding schemes.

5.5.6.a. Analysis of the Incident.

With detail study and analysis of the system disturbance, it can be concluded with the fact that the initiation/origin of the disturbance starts from the root level of the system mismatch between DEMAND and SUPPLY at the local power hubs. The recommendation of the committee also concludes with suggestion to strengthen the Special Protection Scheme (SPS) for the management of local issues. So it needs to study the power flow during the exigency condition on the available feeders, generators and ties at the power stations. In this article an innovative concept has been described, which has been introduced in the form a controlling relay called LOAD ACCESSED DIRECTIONAL RELAY (LADR). For designing of the application of LADR in the system, the connected links at the stations have been categorised as LOAD LINK, GENERATOR LINK and FLEXIBLE LINK. The power flow on the flexible links during the abnormality condition has been studied.

5.5.6.b. Remarks on the System Disturbance

With detail study and analysis of the system disturbance for both of the days, it can be concluded with the fact that the initiation/origin of the disturbance starts from the root level of the system mismatch between DEMAND and SUPPLY at the local power hubs. The load on the important links becomes above the allowable margin due to major outage of the inter-connected links, over drawal of command area load at the inter-connected Grid Sub-Stations or rise of the generation (Supply System).

On 30th July, load on the important links was high due to outage of the major inter-connected links and the condition again deteriorated due to extra load drawal by the inter-connected Grid Sub-Stations at 400 KV Agra Power Hub. The 400 KV Bina –Gwalior line tripped on Zone 3 (Load encroachment Condition) with subsequent major disturbance of the system. ***The root cause of extra load drawal is due to the imbalance/mismatch of the LOAD and DEMAND at the Power Hubs.***

Similarly on 31st July, the depleted condition was prevailing in the system due to outage of major links. But over load tripping of 220 KV links between Badod-Modak and Badod–Kota, resulted the load rise on the 400KV Gwalior-Bina line. Subsequent tripping of 400KV line initiates the cascade tripping and final collapse of the three regions. ***In this condition the root cause is again the imbalance/mismatch of the LOAD and DEMAND at the Power Hubs like 220 KV Badod, Modak and Kota***

5.5.6.c. Possible Solutions By LADR

LADR monitors the change of electrical parameters on the system, specially the dI/dt factor with corresponding response of voltage and frequency factor. Accordingly the relay is set with certain pre-decided programmes as per the critical study of the load flow during abnormal condition. So during such condition, the pre-defined target loads or generators are cut down accordingly to result the balancing of the demand and supply, for which the possible situation of system disturbance gets avoided. This control of LOAD and SUPPLY gets managed at the local power centers and avoids the cascade effect on inter- regional stations. The effect of 30th and 31st July-12 in India could have been avoided if the major power hubs would have been installed with LADR for controlling the difference between SUPPLY and DEMAND. In this article the overall study of these incidences has been reflected with possible solutions of the use of LADR, which has also been described to develop the awareness among power engineers.

5.6. Advance embedded Concept with WAMs.

By the concept of LADR at the local Power hubs, the matching of SUPPLY and DEMAND could be achieved for which the subsequent tripping of the inter-connected lines could be avoided. This concept controls at the root level of Power transaction and for instances if required the same could also be embedded with SPS (Special Protection Scheme) and islanding system to develop the feasible and workable logic according to the practical need of the system.

But sometimes the disturbance/ outage of inter-regional networks play the role of angular deviation between two inter-connected systems. The PMU (Phasor Monitoring Unit), installed on these systems decide the quantum of Loads/Demands and Generators/Supplies, need to be controlled. These PMUs are monitored by satellite links and decision of DEMAND or SUPPLY cut-off at large practice from the regions could be taken by NLDC with subsequent command to the respective RLDC for necessary action. This system is called WAMs (Wide Area Monitoring System). LADR could also be communicated at root level to the central PMU for corrective action at large.

6. CONCLUSION:-

The detail scheme by the use of innovative concept called LADR could be utilized in the presently used Numerical relays by considering the system load flow during and after the occurrence of disturbance in the system. But for special case like regional load flow control this logic could be synchronised to the WAMS (Wide Area Monitoring System)

7. Recommendations:

We strongly feel that our recommendations will go a long way in improving the standards on the performance of Protection scheme in Power System Network. This concept is simple and easily programmable in presently used numerical relays.
OPTCL has already adopted some of its applications and successfully managing stable and reliable Power system on its network.

NAME :-**PRASANTA KUMAR PATTANAIK**
Deputy General Manager (Electrical)

ORGANISATION :-**ODISHA POWER TRANSMISSION CORPORATION LTD. (OPTCL)**

CONTACT NO. **09438907492**
Email :- ele.pkpattanaik@optcl.co.in
ppk110.pp@gmail.com

Dy. General MANAGER (ELECTRICAL)
E&MR Division, Bhubaneswar
OPTCL Hqr Office
P.O. BHOI NAGAR
BHUBANESWAR-751022

Brief Bio-data

Er Prasanta Kumar Pattanaik: - is presently working with OPTCL as Dy. General Manager (Elect) in E & MR Division, Bhubaneswar, Odisha and associated with the Protection and Control schemes of Electrical systems.

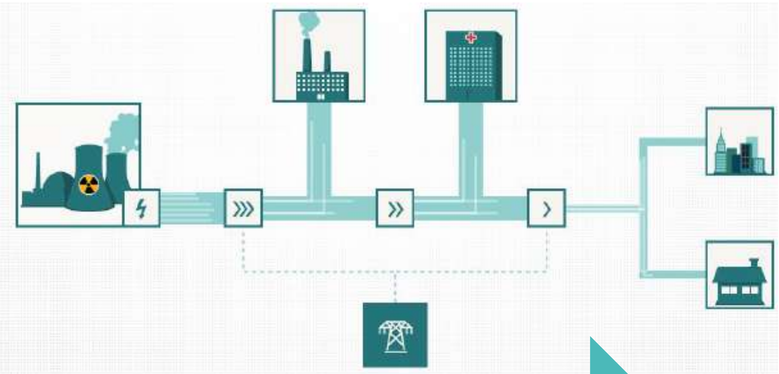
He is having 27 years of technical experience in Designing, Testing and Commissioning of Protection Control and Operational Schemes, Project Implementation, Co-ordination, Operations & Maintenance of Electrical Equipments at various LT/ HT/ EHT level Grid Sub- Stations. He has published around 80 technical papers in different National/International conferences /journals. He is also the author of many Technical books on electrical technology particularly meant for practice Engineers. He has also been awarded in many national and international forums.

Synchronous Rotating Equipment as Backbone for Renewables

Central Electricity Authority, Ministry of Power, New Delhi, Dec 2017

Renewables Growth
Impact on transmission system

Traditional Grid



Unidirectional energy flow

Trends

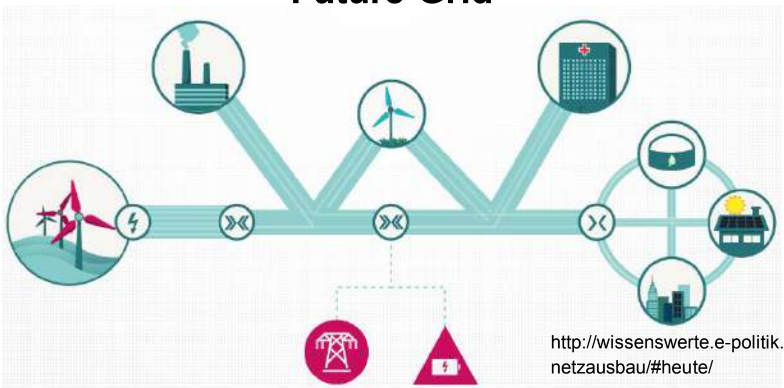
- High share of non-synchronous generation: wind farms & photovoltaic
- Growing HVDC Network
- Need for energy storage elements
- Decommissioning of conventional power plants

Today →

Consequences

- Remaining fossils highly cycled
- Increased weather & time dependency
- Short circuit power reduced
- Less system inertia

Future Grid

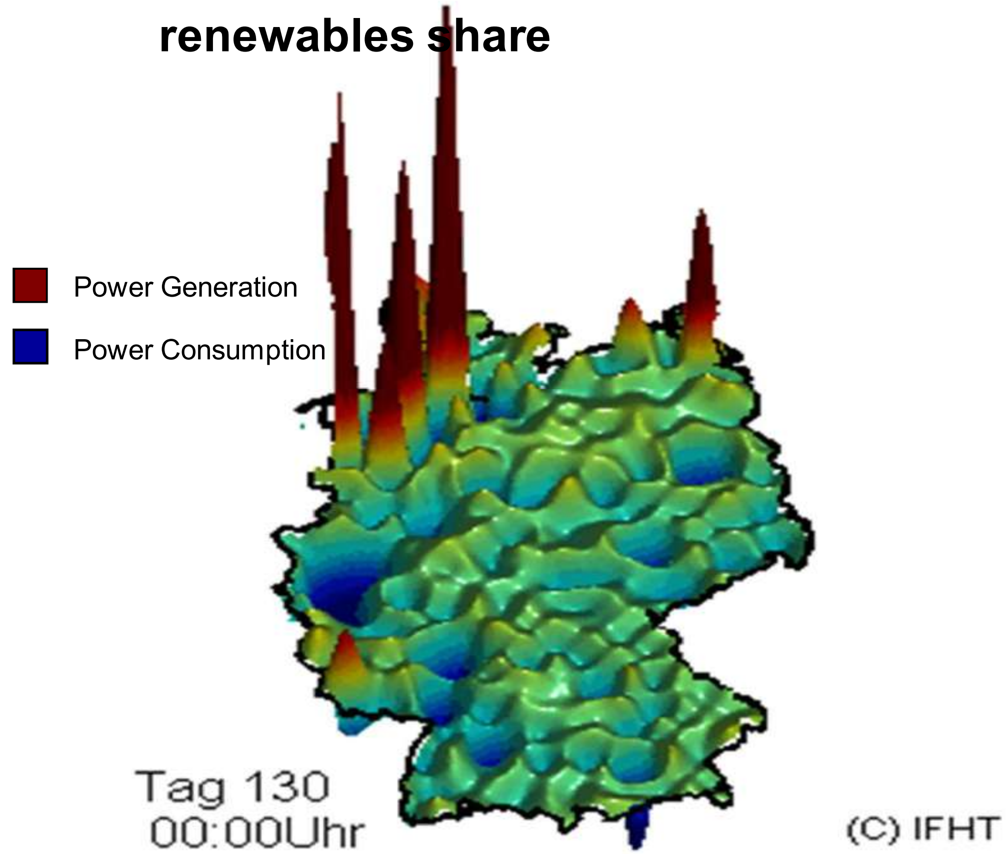


Multidirectional energy flow

Increased share of renewables requires new grid control and stabilization equipment

Renewables Growth
Impact on transmission system

Simulation Germany with 80% renewables share



Complex energy flow in the transmission system due to renewables dependencies on:

- Weather
- Day time
- Climate consideration - renewables location

General transmission system requirements in the converter dominated system are still the same:

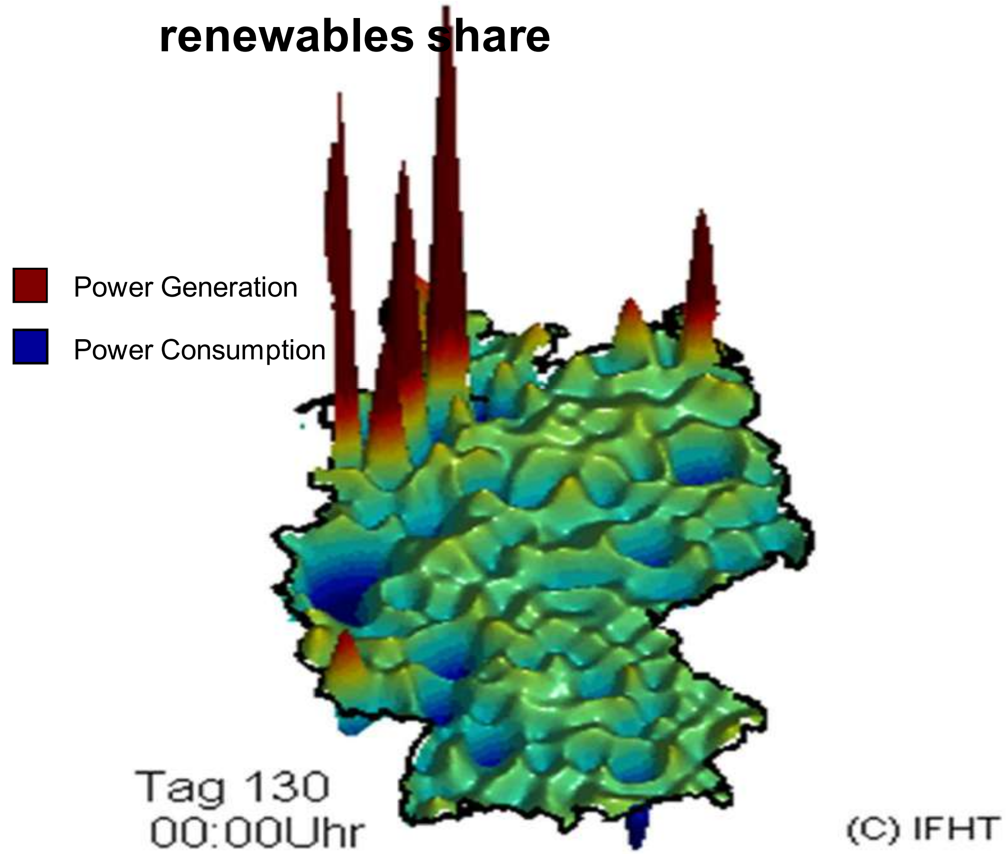
- Active power and frequency control
- Reactive power and voltage control
- Capability to ride through disturbances

HVDC and FACTS technology are developing at astonishing pace to ensure safe operation of the grid system

Synchronous power generation equipment is still essential to ensure grid stability

Renewables Growth
Impact on transmission system

Simulation Germany with 80% renewables share



Synchronous generators provide unique capabilities compared to power electronics based technologies:

- Short circuit power enhancement in weak grids
- Synchronous system inertia
- Fault ride through capability
- Short term overload capability as defined per generator standards IEEE C50.13-2014 und IEC 60034-3 (150% I_N for 30 sec)
- Grid re-build capability after blackout (with GT or ST)
- Back-up power supply (with GT or ST)
- Don’t produce harmonics

Synchronous Generators are simple and reliable grid stabilizers with unique capabilities

Synchronous Generators in Renewables Dominated Grids

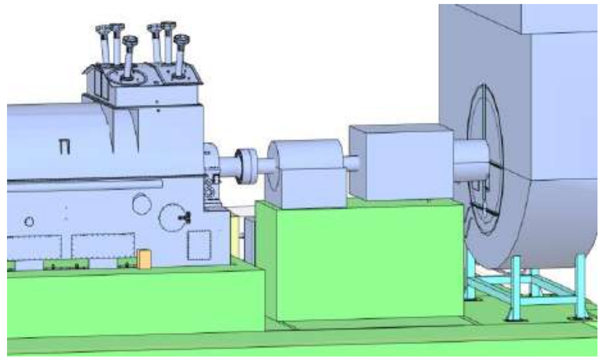
Grid Stabilization Options - Modular Flexibility

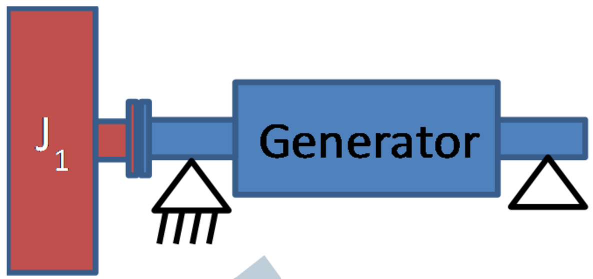
SIEMENS
Ingenuity for life

Configuration	Operational Concept & Benefits
Grid stabilizer 2.0 H^+ G SSS clutch M GT *New: Under development*	**Uninterrupted Synchronous Condenser operation** ✓ GT start-up by shaft integrated drive, synchronized within 5 min **Desynchronization and run-down only GT or together with generator**
Grid stabilizer 1.0 H^+ G SSS clutch GT *Reference: e.g.Escom South Africa*	**GT start-up requires desynchronization and run-down of the generator from syncon mode** ✓ Frequency stabilization and active power reserve ✓ Capability to rebuild grid after area-wide blackout - power island operation (fully self-sustaining))
Synchronous condenser H^+ G Option: Flywheel for Increased Inertia *Reference: several with different generator products*	**Turning and start-up by SFC, synchronization during run down from over-speed** ✓ Voltage stabilization by reactive power supply ✓ Short circuit power enhancement (Sn" ≥ 3 x Sn) ✓ Dynamic frequency stabilization by kinetic energy storage and release (inertia)

Highest flexibility with switch-over time 0 sec

SSS clutch option to enable syncon operation





Synchronous Rotating Equipment as Backbone for Renewables
Indian Market

Market situation

- Currently low share of non-synchronous generation (wind & PV) – no need for rotating stabilizers
- Several old thermal power plants already considered for de-commissioning
- Plan to install 100 GW solar and 75 GW wind capacity until 2022 will create **an urgent demand for grid stabilizers**
- First motivation to convert old plants to synchronous condenser applications based on NTPC feedback
  To consider:
  - Operational cost
  - Remaining life time and reliability of the old equipment
  - Location in the transmission system
  - Equipment characteristics as Xd'', Uk, H constant, ceiling voltage,….

Synchronous Rotating Equipment as Backbone for Renewables
Indian Market

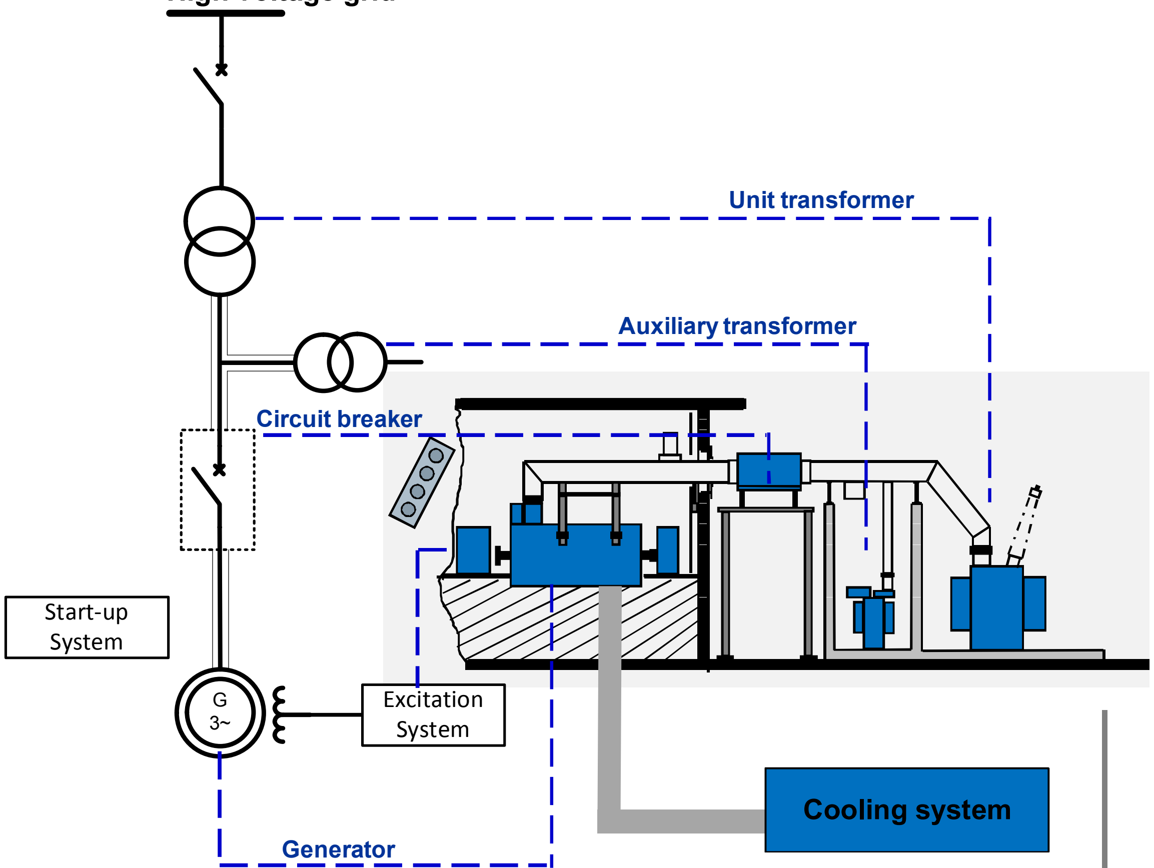
SIEMENS
Ingenuity for life

Recommendations and options for the renewables turnaround (Indian Energiewende)

- Based on experience from Europe Siemens can contribute to grid simulations with the targeted share of renewables – future grid stability
- Only the right mix of static and rotating equipment contributes perfectly to the grid stability
- Ensure clear responsibility for installation and operation of rotating grid stabilization equipment (Transition System Operators or Power Producers)
- Consider policy framework for:
  - Conversion of old thermal plants into synchronous condensers, optionally with additional inertia
  - Installation of new rotating grid stabilization equipment, customized solution with low OPEX
- Consider the importance of reliability of the stabilization equipment

Synchronous Generators in Renewables Dominated Grids
Synchronous Condenser

Configuration



Synchronous Generators in Renewables Dominated Grids
Synchronous Condenser

SIEMENS
Ingenuity for life

Function

Stable AC voltage source with real system inertia
Capability to improve the strength of the system

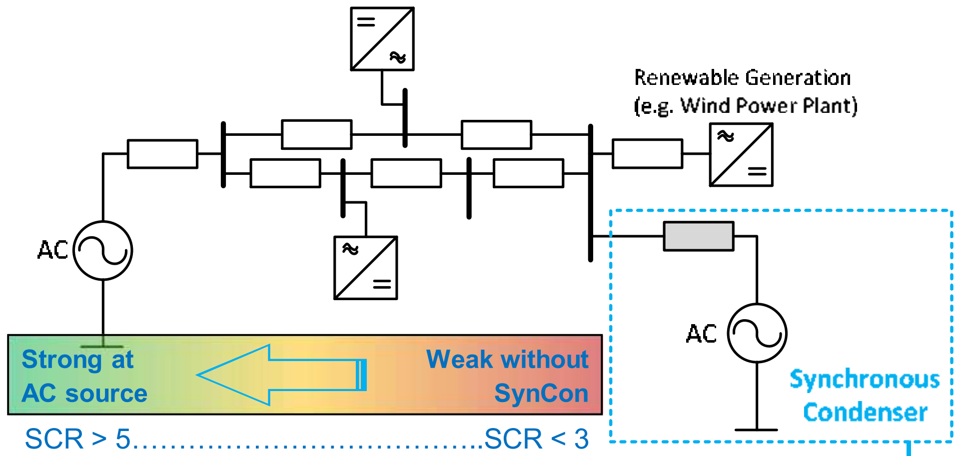
Key buying factors

Technical specification

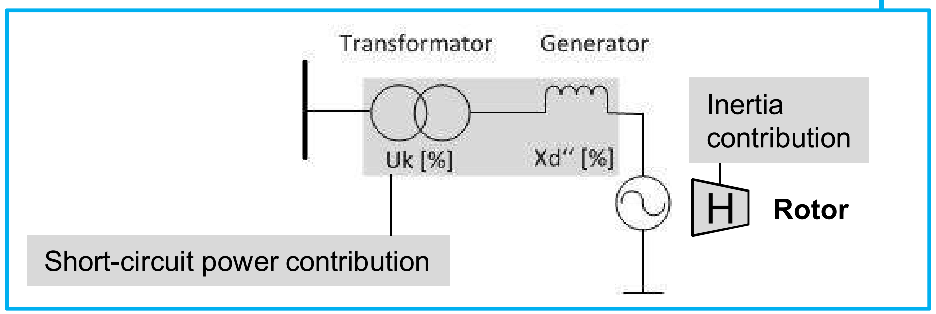
- Short circuit power contribution with low x_d“
- Reactive power output range in MVAr
- Inertia increase by rotor; H = approx. 2 sec

Cost position

- Losses with very high evaluation in €/kW
- Operational cost – unstaffed operation and almost maintenance free
- CAPEX and footprint



Short Circuit Ratio (SCR) = $\frac{S_{Grid}}{P_N}$



Synchronous Generators in Renewables Dominated Grids
Synchronous Condenser with Flywheel

Function

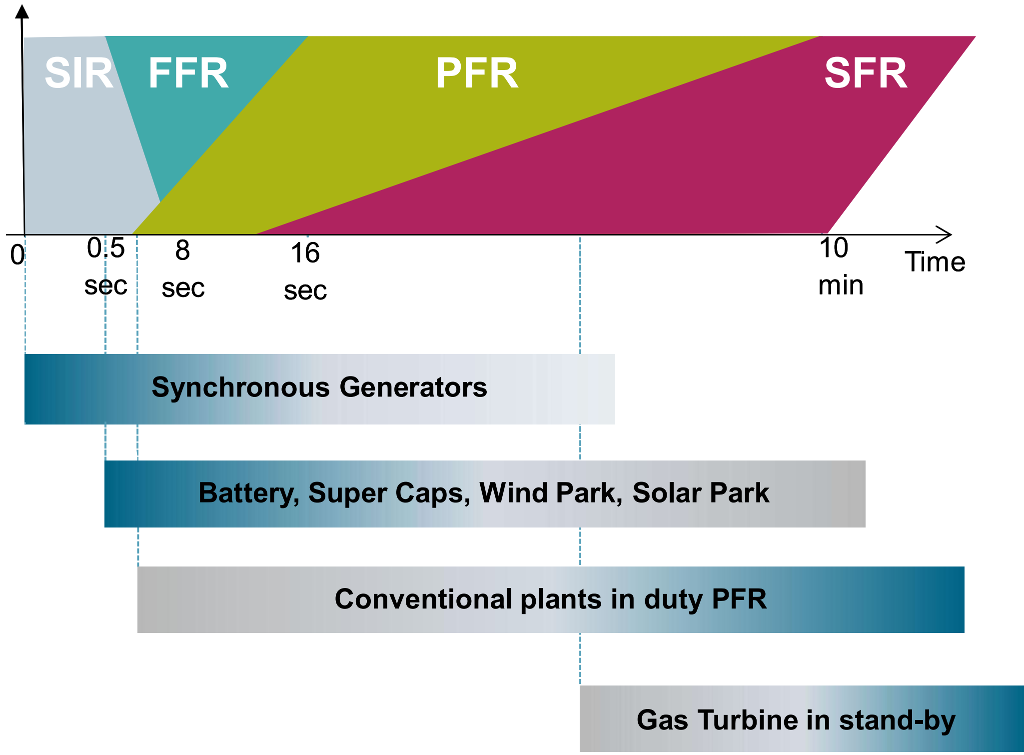
Increase inertia in system to avoid high RoCoF events and system collapse

Frequency stability

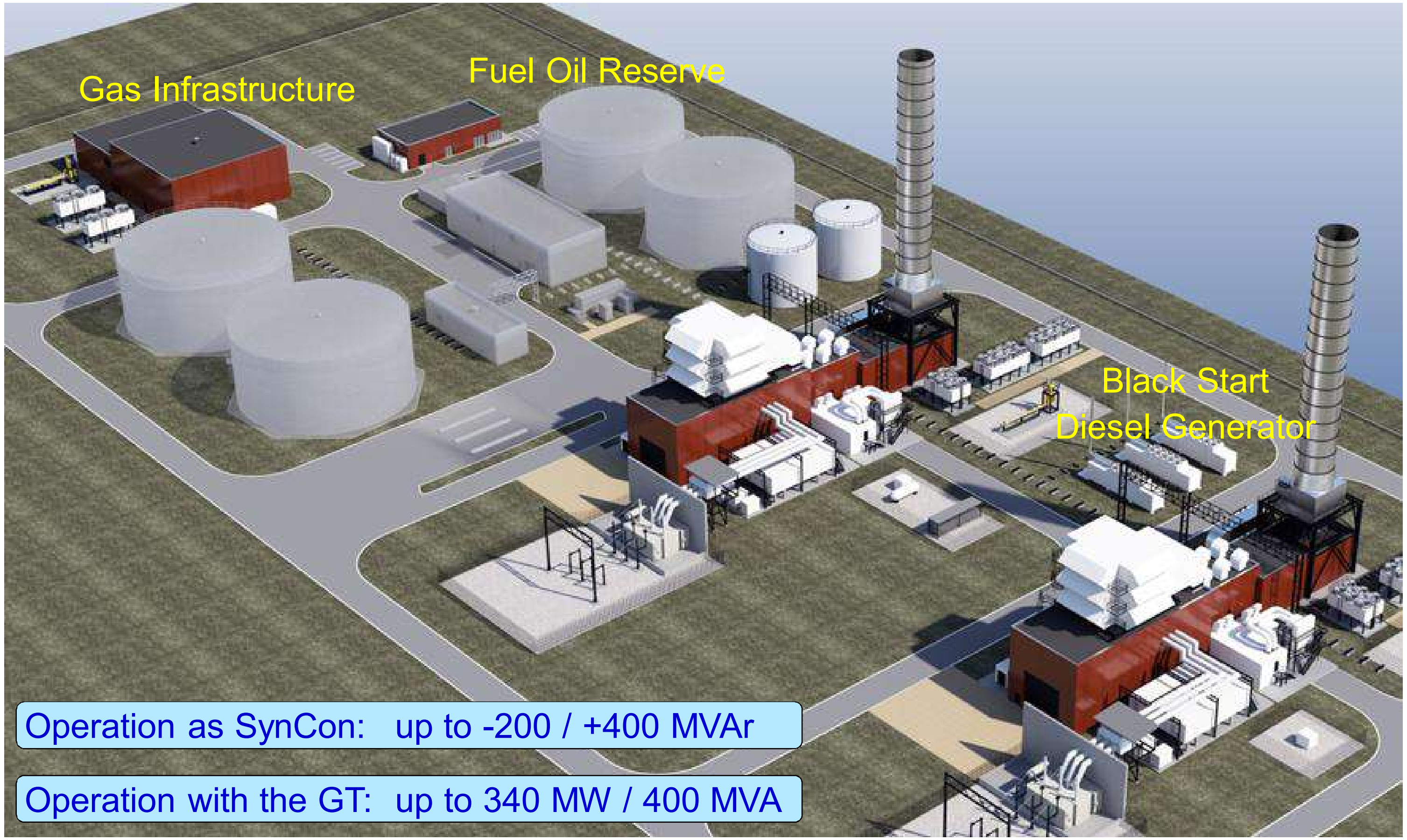
- Balancing generation and load
- Control frequency within permissible range
- Power plants with synchronous generators naturally contribute to inertia and participate in frequency control

Frequency response services:

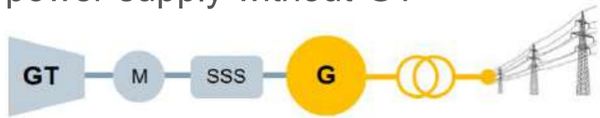
- Synchronous Inertial Response (SIR)
- Fast Frequency Response (FFR)
- Primary Frequency Response (PFR)
- Secondary Frequency Response (SFR)



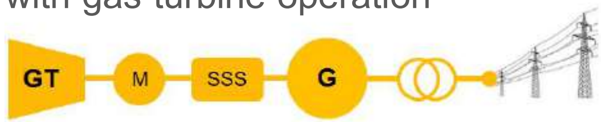
Synchronous Generators in Renewables Dominated Grids
Grid Stabilizer 2.0



1. **Voltage Stabilization**
   Inertia Increase
   Short Circuit power
   Quick start of reactive power supply without GT



2. **Grid Power Balance**
   Quick start of active and reactive power supply with gas turbine operation



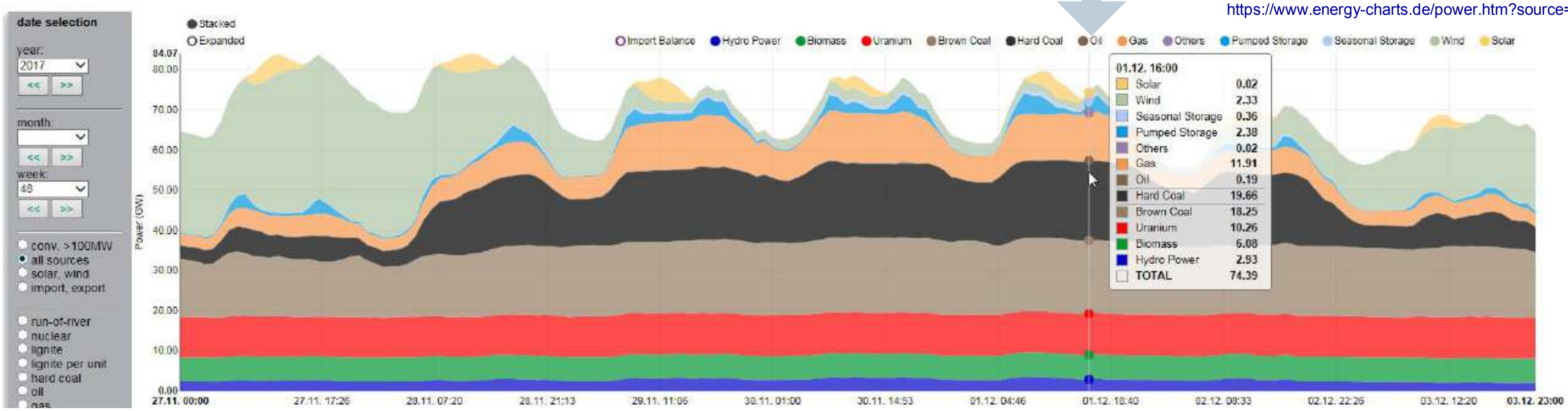
3. **Grid Restoration**
   Gas turbine start with black-start diesel into island operation with fuel oil

Synchronous Generators in Renewables Dominated Grids
European Market

- Comprehensive grid simulations determine demand on synchronous rotating equipment in the transmission systems
- TSO's decide to install synchronous condensers in the weak parts of the grid with less conventional power plants and many renewables connected via converter
- Several retirements of conventional plants trigger requests to convert the old or install a new equipment to achieve the same MVAr, inertia and short circuit power
- Flatness of wind in the evening, while solar not generating is a future challenge

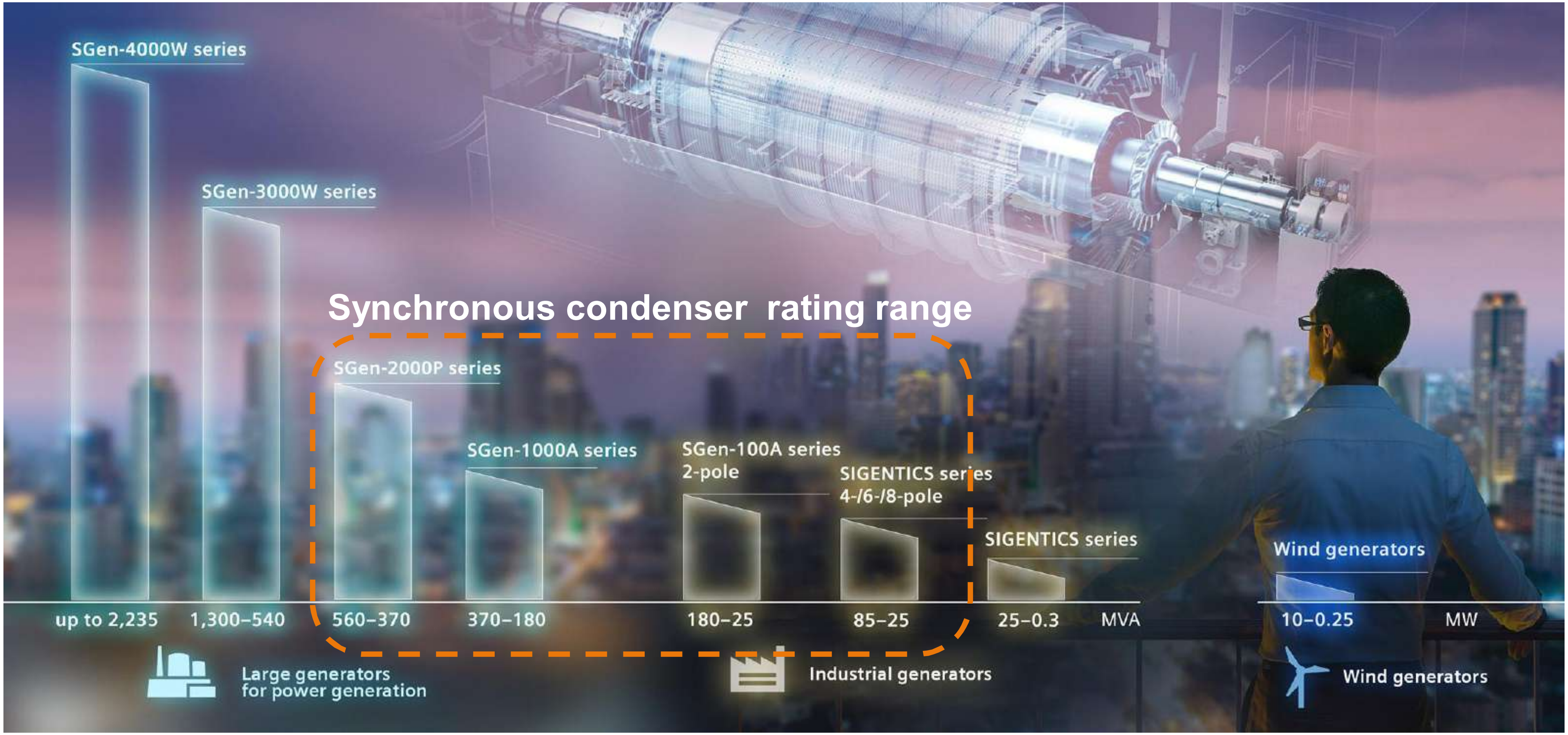
Electricity production in Germany in week 48 2017

Source:
https://www.energy-charts.de/power.htm?source=all-sources&week=48&year=2017



Germany	First 3 large synchronous condenser projects assigned (300 MVAr range), 1,2 GW back-up GT units in planning
Italy	Plan to install synchronous condensers with fly wheels, total MVAr capacity of 7000 MVAr, 28 units with specified inertia constant H > 7 sec
Denmark	High share of wind power with a 50% target in 2020, 7 synchronous condensers in approx. 200 MVAr range

Grid stabilization with dynamic synchronous condenser
Product Overview



Grid stabilization with dynamic synchronous condenser

Robust air cooled generator products

All products optionally extendable with flywheels or SSS-clutch connected drives

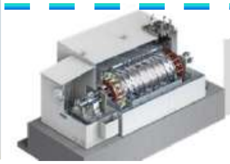
- Highest rating with air cooling up to -250..+400 MVAr per single unit (exported reactive power)
- Efficiency optimized configuration for synchronous condenser operation – flexible pressurization
- Highest flexibility with unlimited MW & MVAr cycling capability
- Wide range of voltage control

Air / H_2O

Air Pressurized

370-560 MVA

Air



25-370 MVA

- Unstaffed remote control operation
- Maintenance free GVPI stators
- No rotor disassembly over entire lifetime
- Cost optimized condition based maintenance
- Plug & Play site installation concept

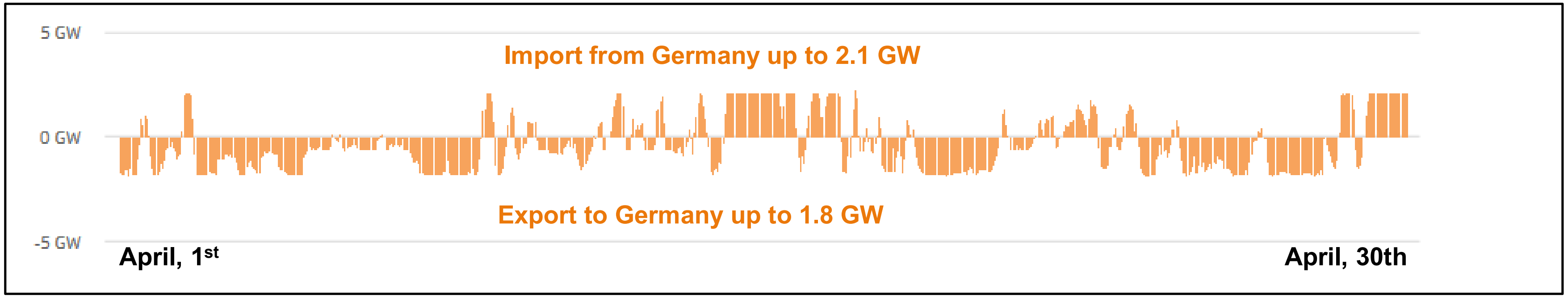
- Highest robustness
- Compact foot print with minimum auxiliaries
- Air cooling options: open or closed cycle ventilation

Synchronous Rotating Equipment as Backbone for Renewables
Denmark Target: 50% Wind in 2020

SIEMENS
Ingenuity for life

Danish energy market boundaries:

- Denmark: 5.7 million citizens, electricity consumption of ca. 34 TWh, production 3.5 GW average
- Shut down of Danish Central Power Plants due to low earnings and preferred treatment of wind
- Strong dependency on European grid interlinks, particularly with Germany (energy import/export up to 50% of total consumption) – see example April 2017



- Highest end user energy price in Europe
- Wind turbines not capable to provide necessary short circuit power and inertia to the power system
- **Decision to install 7 synchronous condensers, connected to 400 kV transmission system as simple grid stabilizers**

Synchronous Rotating Equipment as Backbone for Renewables
Denmark Target: 50% Wind in 2020

Boundaries for synchronous condensers installed in Danish grid:

- Right distribution and location at or close to HVDC converter stations
- Short circuit power 800 - 1000 MVA per unit
- Reactive power compensation range: approx.-150 Mvar - +215 Mvar
- Inertia increase only by generator rotor (H approx. 2 sec), no additional fly wheel
- 2-3 thermal plants to be in operation in the Western and Eastern part of the Danish power system

The transmission system is build on the physical properties of the synchronous generators and still requires the "invisible services" in regards to voltage & frequency stability provided by central thermal power plants and **synchronous condensers**

Optimal Generation Mix to Meet the INDC Targets

Himanshu Upadhyay	P.E.Kamala	Ammi R Toppo	Praveen Gupta
Assistant Director	Deputy Director	Director	Chief Engineer
Central Electricity Authority (CEA)	CEA	CEA	CEA

Abstract:

Government of India is committed to achieve Energy Autonomy and provide Clean, Affordable, Reliable and Sustainable Power for All. Government of India has also made international commitment (INDC) to have about 40 percent cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030 and to reduce the emissions intensity of its GDP by 33% to 35% by 2030 from 2005 level. To achieve this Government of India has set a target of 175 GW of Renewable Installed Capacity by 2021-22. Generation Expansion Planning studies were carried out by CEA for the preparation of National Electricity Plan to meet the demand of electricity as per the 19th Electric Power survey for the year 2021-22 and 2026-27 considering the 175 GW RE installed capacity by 2022. It was found that the coal-based capacities will be underutilized and the coal based capacity addition till 2027 will slow down. Therefore, this paper work out the Renewable Energy Sources Capacity Requirement to meet INDC target of 40% installed capacity from non-fossil fuel by 2030.

1. Introduction

Generation capacity augmentation is the most vital component amongst various modes adopted for meeting the ever-increasing demand of power to achieve the targeted growth rate. Coal is the major source for power generation in our country however, since Low Carbon Growth Strategy has to be followed, other generation options also need to be harnessed in the optimum manner. Optimum Generation mix is an optimization problem, in which the objective function is to minimize 1) the costs associated with operation of the existing and committed generating stations 2) the annualized/ levelised capital cost and operating cost of new generating stations and 3) Cost of energy not served in such a way to satisfy the different constraints in the system such as Renewable capacity addition targets fixed by Government, Must Run Status for Renewable Energy Sources like Solar, Wind etc., LOLP (Loss of Load Probability), ENS (Energy Not Served), International commitments by India (Paris Agreement) etc.

2. Installed Capacity at the end of 12th Five Year Plan ie 31.03.2017

Total Installed Capacity as on 31.03.2017 i.e. at the end of 12th Five Year Plan was 326.84 GW, which comprise of 44.47 GW from Hydro, 218.328 GW from Thermal, 57.26 GW from R.E.S and 6.78 GW from Nuclear. The installed capacity of thermal power is about 67 %, however, the generation from these sources is around 80%.

3. Optimal Capacity Mix studies

i. Generation expansion planning studies has been carried out for the year 2021-22 and 2026-27 to find out the optimal capacity mix based on the Electricity demand assessed by the 19th Electric Power Survey (EPS) Report and keeping in view GOI initiatives of 175 GW of RES capacity Target by 2022.

The studies have revealed the following:

a. For period 2017-22, committed capacity addition of Hydro 6,823 MW, Gas 406 MW, Nuclear 3,300 MW, RES 1,17,756 MW (Total RES capacity by 2022 to be 175 GW) and with a retirement of coal based capacity of 22,716 MW (of old and inefficient units and due to Environment norms) and Demand as per the 19th EPS (225 GW of peak demand and 1566 BU of energy requirement) has been considered. It was found that only 6,445 MW additional coal based capacity would be required during 2017-22 to meet the peak demand and energy requirement in the year 2021-22. However, coal based capacity of 47,855 MW is at various stages of construction which is likely to be commissioned during 2017-22. The overall PLF during 2021-22 of coal-based capacity (including 47,855MW) is likely to be 56.5%.

b. For the period 2022-27, committed capacity addition of Nuclear- 6,800 MW, Hydro-12,000 MW and RES 1,00,000 MW during the year 2022-27 has been considered. The study has also taken into account the Coal based capacity of 47,855 MW already under construction for benefits during 2017-22, and with likely retirement of coal based capacity of 22,716 MW and 25,572 MW during 2017-22 and 2022-27 respectively, and demand projections as per the 19th EPS (Peak demand of 298.7 GW and Energy requirement of 2047 BU for the year 2026-27). Study for the period 2022-27 reveals that a coal based capacity addition of 46,420 MW is required.

c. The likely installed capacity from different fuel types at the end of 2021-22 in base case, works out to be 4,79,419 MW including 47,855 MW of Coal based capacity currently under construction and likely to yield benefits during 2017-22 and retiring a capacity of 22,716

MW. The projected installed capacity at the end of 2026-27 works out to be 6,19,066 MW. The details are given in **Table 3** and **Exhibit 3**.

Table 3
Projected Installed capacity by the end of 2021-22 and 2022-27

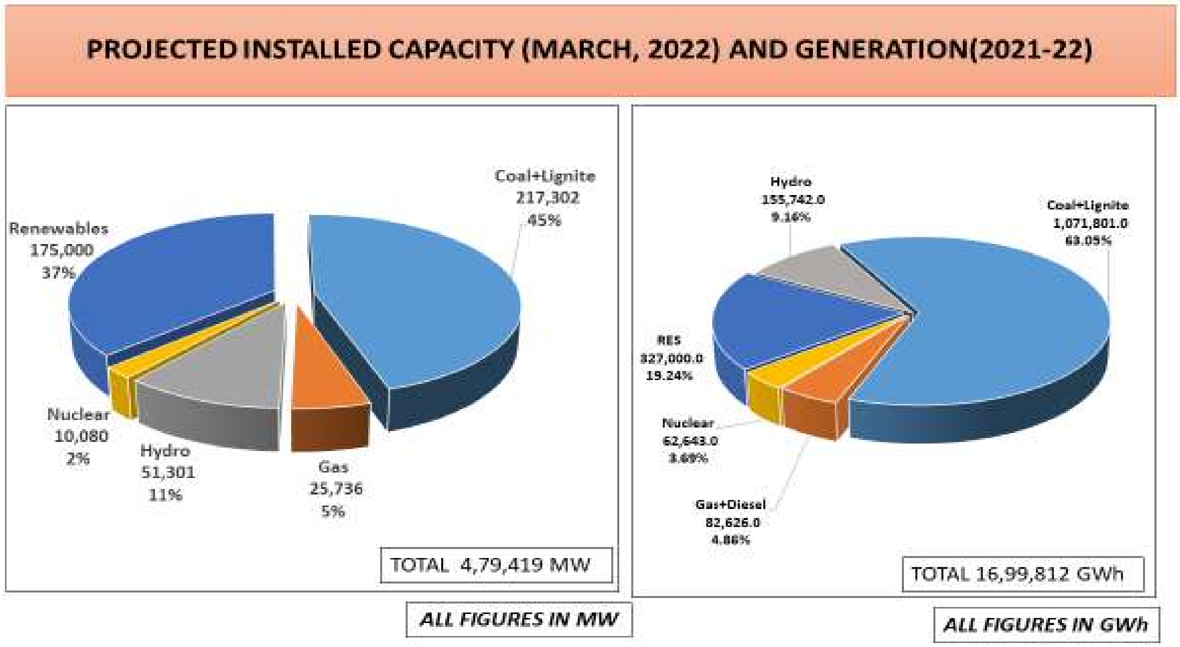
(FIGURES IN MW)

	IC in 2021-22		**IC in 2022-27**	
Fuel Type	**Capacity (MW) in 2021-22**	**%**	**Capacity (MW) in 2022-27**	**%**
Hydro	51,301	10.7	63,301	10.2
Coal + Lignite	2,17,302	45.3	2,38,150	38.5
Gas	25,736	5.4	25,735	4.2
Nuclear	10,080	2.1	16,880	2.7
Total Conventional Capacity *	**3,04,419**	**63.5**	**3,44,066**	**55.6**
Total Renewable Capacity	**1,75,000**	**36.5**	**2,75,000**	**44.4**
Total Installed Capacity	**4,79,419**	**100.0**	**6,19,066**	**100.0**

*Including 47,855 MW of Coal based capacity addition currently under construction, retirement of 22,716 MW and likely to yield benefits in 2017-22 and an additional 46,420 MW coal based capacity addition required during 2022-27. Also retirement of coal based capacity of 22,716 MW and 25,572 MW during 2017-22 and 2022-27 respectively has been taken into consideration.

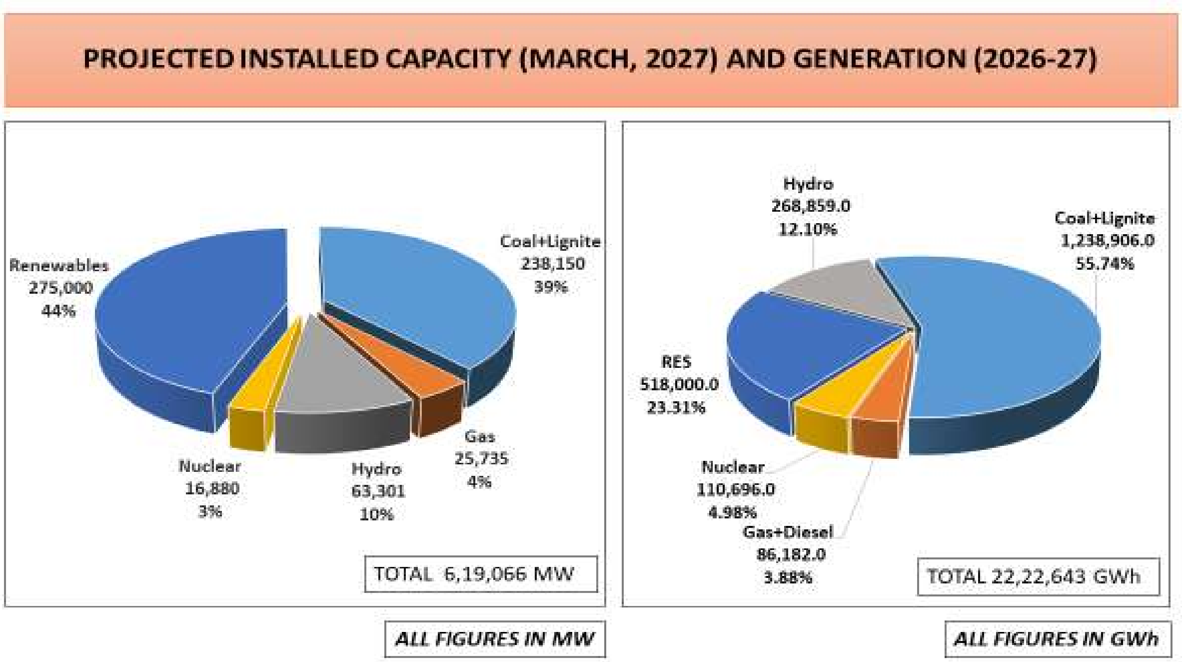
The Projected Generation (BU) during the year 2021-2022 would be 1,699 BU, which comprise of 1,071.80 BU from Thermal (Coal and Lignite), 327 BU from RES, 155.74 BU from Hydro, 62.64 BU from Nuclear and 82.62 BU from Gas and Diesel.

Exhibit 3



The Projected Generation (MU) during 2026-27 would be 22,22,643 MU, which comprise of 1,238,906 MU from Thermal (Coal and Lignite), 518,000 MU from RES, 268,859 MU from Hydro, 110,696 MU from Nuclear and 86,182 MU from Gas and Diesel.

Exhibit 4



The share of installed capacity from Renewable energy is expected to dominate share of installed capacity in the year 2021-22 and 2026-27. Also in terms of generation mix, RES generation is going to contribute around 21% of the total generation expected to come in the year 2021-22 and around 25.3 % in the year 2026-27. **International Commitment - INDC Targets**

India had submitted its Intended Nationally Determined Contribution (INDC) to UNFCCC. The key elements are:

- To reduce the emissions intensity of its GDP by 33% to 35 % by 2030 from 2005 level.
- To achieve about 40 percent cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030, with the help of transfer of technology and low cost international finance including from Green Climate Fund (GCF).
- To create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030.

4. Projected Achievements of INDCs

a. Installed capacity and share of non-fossil fuel

In March 2016, Percentage of Non- Fossil fuel in Installed Capacity was 33.20 %. It is found by the studies that it is likely to increase to 49.31% in March 2022 and 57.37 % in March 2027. However, as per INDC Target, the percentage of Non- Fossil Fuel in Installed Capacity is to be 40% by 2030. **Table 4** below give the percentage of non-fossil installed capacity by the end of 2022 and 2027.

Table 4

(FIGURES IN MW)

Year	Installed Capacity (MW)	Installed Capacity of Fossil fuel (MW)	Installed Capacity of Non-Fossil** fuel (MW)	%of Non-fossil fuel in Installed Capacity
March,2016	3,26,833	2,18,330	1,08,503	33.20%
March,2022	4,79,419	2,43,038	2,36,381	49.31%
March,2027	6,19,066	2,63,885	3,55,181	57.37%

** Non Fossil Fuel – Hydro, Nuclear and Renewable Energy Sources

Note:

1. Including 47,855 MW of Coal based capacity addition currently under construction and likely to yield benefits in 2017-22 and an additional 46,420 MW coal based capacity addition required during 2022-27 & a coal based capacity considered for retirement being 22,716 MW during 2017-22 and 25,572 MW during 2022-27.

2. The actual % may change to the extent of thermal capacity materialising and actual retirement taking place during 2017-22 and 2022-27.

b. CO_2 emissions Intensity from Power Sector

In INDC target, India has committed to reduce the emissions intensity of its GDP by 33% to 35 % by 2030 from 2005 level. In Generation Expansion planning studies, it was found that percentage reduction of emission intensity with respect to base year 2005 is to be 53.65%, which is way ahead than the INDC Target (**Table5)**.

Table 5

	Years		
	2005	**2022**	**2027**
Emission intensity kg/₹ GDP	0.015548	0.009249	0.007207
% Reduction in emission intensity base 2005		40.51	53.65

5. Renewable Energy Sources Capacity Requirement to meet INDC target of 40% installed capacity from non-fossil fuel by 2030

a. As seen from the above from **Table 4** that with the RES capacity target of 175GW by 2022 and proposed capacity from Hydro and Nuclear, share of Non- Fossil fuel in Installed Capacity which is currently at 33.20 %, is likely to increase to 49.31% by March 2022 and 57.37% by the end of year 2026-27 .

A study was carried out to assess the capacity addition requirement from RES to meet the INDC targets of 40% of the installed capacity from Non-fossil fuels by the year 2030. As the data available is upto the year 2027, the study was aimed to achieve INDC targets by the year 2027.

Taking into account the coal based capacity of 47,855 MW already under construction for likely benefit up to March 2022, additional coal based capacity with possible capacity from Renewable energy sources have been assessed to fulfill the INDC target by 2027. Also, it is assumed that only present level of domestic gas will be available for gas based plants upto 2026-27 (i.e present PLF of 22% for gas based power plants)

It is seen from the studies that to meet the peak and energy requirement for the year 2026-27 and to fulfill the INDC commitment of 40% non fossil fuel generation capacity by 2027, a Renewable Installed capacity of 125 GW by the end of 2026-27 is required. Along with a capacity addition of 10,100 MW Nuclear (3,300 MW from 2017-22 and 6,800 MW from 2022-27), 11,823 MW Hydro (6,823 MW from 2017-22 and 5,000 MW from 2022-27) and 75,460 MW of coal based capacity during 2022-27. This coal based capacity addition is over and above 47,855 MW of coal based capacity already under construction for benefits during 2017-22.

The breakup of projected Installed capacity by 2026-27 is given below in **Table 6** :

Table 6

Total Installed capacity by 2026-27

(FIGURES IN MW)

Sector	Installed Capacity
Coal	2,67,192 MW
Gas	25,727 MW
Hydro	56,301 MW
Nuclear	16,880 MW
RES	1,25,000 MW
Total	4,91,100 MW
% of Non-fossil fuels in IC	**40%**

b. CO_2 emissions Intensity from Power Sector in year 2027

India has committed to reduce the emissions intensity of its GDP by 33% to 35 % by 2030 from 2005 level as per the INDC. It is seen from the studies that with a Renewable Installed capacity of 125 GW by year 2027 and the proposed addition of 10,100 MW Nuclear (3,300 MW from 2017-22 and 6,800 MW from 2022-27) and 11,823 MW Hydro (6,823 MW from 2017-22 and 5,000 MW from 2022-27), emission intensity from power sector will reduce to 42.90 % in 2027. However, the net reduction of CO2 emissions will be less as emissions from thermal power stations will increase due to frequent cycling and ramping of the plants than during steady state operation.

Table 7

	Years		
	2005	**2022**	**2027**
Emission intensity kg/₹ GDP	0.015548	0.010286	0.008878
% Reduction in emission intensity base 2005		33.84	42.90

It is estimated that heat rate of subcritical machines (proposed for flexible operation due to integration of renewable energy) will increased by 1.5 % due to part load operation, it is estimated that CO_2 emissions also will increase by 1.5%.

6. Conclusion

In the view of Government of India's ambitious Target from Renewable Energy Sources Capacity Addition of 175 GW by 2022 and the coal based capacity of 47,855 MW already at advance stages of construction and likely benefit up to March 2022 the scope of optimal generation mix is very limited in near future. It is seen from the studies that to meet the peak and energy requirement for the year 2026-27 and to fulfill the INDC commitment of 40% non-fossil fuel generation capacity by 2027, a Renewable Installed capacity of 125 GW by the end of 2026-27 is enough. Along with a capacity addition of 10,100 MW Nuclear (3,300 MW from 2017-22 and 6,800 MW from 2022-27), 11,823 MW Hydro (6,823 MW from 2017-22 and 5,000 MW from 2022-27) and 75,460 MW of coal based capacity during 2022-27. This coal based capacity addition is over and above 47,855 MW of coal-based capacity already under construction for benefits during 2017-22. With RE capacity of 125 GW by 2026-27, the reduction in emission intensity from the power sector is also likely to reduce by 42%.

The issues of balancing and ramping requirement will also reduce with 125 GW of RE as compared to 175 GW and also the PLF of coal based power plants will increase and coal based plants will be financial viable in future.

REFERENCES

1. **CEA Website (www.cea.nic.in)**
2. **Draft National Electricity Plan (Generation, Volume-1) of Central Electricity Authority, published on 07.12.2016.**
3. **India INDC to UNFCCC.pdf**

Views Expressed in the paper belong to authors and not necessarily are the views of organization they represent.

DAY 2: 21ST FEB 2018

SESSION 3:

DISTRIBUTION

New Natural Ester-based Transformer Fluid Development - Evaluation of Technical Benefits in the present Indian context

By Dr C.S.NARASIMHAN, Head – R&D, Savita Oil Technologies Ltd.

ABSTRACT:

The paper describes interesting research carried out at our R&D centre of Savita Oil Technologies Limited on a new ester fluid for use in power and distribution transformers. The new fluid is a natural ester, based on Soybean Oil, which is a renewable raw material. The product & process have been scaled up in pilot plant and validated further in our plant. The product was also tested for all dielectric, chemical & physical properties as per national & international standards in accredited laboratories in India & abroad. The new fluid has edge over conventional mineral oil-based transformer oils with respect to fire-safety, biodegradability and efficiency of performance. Due to these benefits, our product is already being used in both power and distribution transformers in India and outside India. The new development is expected to substitute partly the conventional mineral oil fluid wherever the potential benefits mentioned above are required by Utilities.

Introduction:

Mineral Oils are the work-horses of the transformer industry for more than a century now and it will perhaps continue to be so in the long term in terms of quantities used. The major reason for their popularity is the cost. Besides cost, it also fulfils several functional requirements for use as an insulation fluid in a transformer. It has excellent dielectric properties. It saturates the paper insulation fast due to its low viscosity. Its low viscosity also facilitates good heat transfer which helps in its efficient cooling function.

Reasons for exploring alternative fluids:

While the mineral oil is well established due to the reasons mentioned above, there are a few disadvantages as well. They are not biodegradable. This will mean that if there is a spill, especially in environmentally sensitive places like a transformer located on ships or close to water bodies, the clean-up costs will be very high. This is especially so in countries where the regulations are strong and the polluter bears the cost of clean-up. A second disadvantage of mineral oils is their low flash and fire points. This is related to issues of safety during the operation of a transformer. The fire point of mineral oil is in the range of 160 to 170^{0}C which means it can catch fire above that temperature and can even result in explosion. Several fire accidents resulting in damage to life and property have been reported in the past in mineral oil filled transformers. Besides the above disadvantages, mineral oils also suffer from a few performance issues which will be highlighted in the subsequent sections.

The Therefore the major drivers for developing alternative fluids are: Fire-safety, environmental-friendliness and better efficiency. In the present Indian context, fire-safety of transformers perhaps is the immediate driver for using our new natural ester fluid.

Rationale for choosing to develop Natural Ester- based transformer Fluid as our R&D project?

Historically, the search for alternative fluids has led to several alternatives. The first one to appear on the scene was the infamous PCBs (Polychlorinated Biphenyls). This fluid was introduced due to its non-flammable nature. However, soon it came to light that these are carcinogenic and so had to be withdrawn.

The second class of fluids that appeared as an alternative was Silicones. These are still in use due to their high thermal and oxidative stability and very high thermal class (K class) with a high fire point of >350^{0}C. However, the fluid has one negative feature, namely, lack of biodegradability. Hence it doesn’t find favour in majority of applications. Its major use is limited to traction motors and distribution transformers.

The search for alternative fluids continued and eventually another class of chemical known as esters made their presence. The reasons are not far to seek. Esters are biodegradable, have high flash and fire points (>300^{0}C) and indeed are found to have certain performance advantages as well which we will see in the subsequent sections.

Essentially, two types of esters are potential candidates for fulfilling the objectives of biodegradability, fire-safety and performance advantages. They are: Synthetic ester and Natural ester. We chose to work on Natural ester because they are based on renewable raw materials, biodegradable and have very high fire point and relatively cheaper compared to synthetic ester. Synthetic esters have two disadvantages compared to Natural esters – they are based on petrochemical raw materials and hence carbon foot print is higher than that of a natural ester which is based on renewable raw materials like vegetable oils. Secondly, synthetic esters are far more expensive than natural esters. In the sections that follow, we will discuss our research work carried out on Natural esters for use as transformer fluids.

Natural Ester Process Development:

A. Laboratory Scale:

Our research work involved the following stages.

1. Selection & Modification of Vegetable Oils: Selection of vegetable oils is very important to ensure a good transformer fluid is finally prepared. Modification of the selected oil was necessary to make the structure of vegetable oils more stable thermally & oxidatively.

2. Refining the vegetable oil: This was an important step to remove polar impurities from the oil. The impurities are known to affect dielectric properties of the oil adversely. The process involves use of special physical & chemical steps using advanced adsorbents.

3. Development of additive packages: The additives are needed for imparting thermal and oxidative stability of the fluids. Additives are also needed for improving low temperature properties of the oil. Good flow and viscosity are important for a transformer fluid operating during winter times when the ambient temperatures are rather low.

4. Final processing involves vacuum dehydration to bring moisture levels very low to ensure high dielectric strength.

We carried out the above process development steps in the laboratory scale and the product that was made in the lab scale (about 5kgs) was tested for properties. Once the properties were found acceptable, we went for the second stage of development, namely, pilot scale studies, which is described in the following section.

B. Pilot scale studies & Validation:

The above process steps were then scaled up in a pilot scale facility to make 150kg of the product. The product produced in the pilot scale was also characterized for basic properties as well as dielectric behaviour.

C. Plant Scale Validation:

A plant to produce 400KL of fluid per month was built in the first phase using in-house engineering & project experience. The plant process and product were also validated by studying the product characteristics. Subsequently, the plant capacities were further ramped up.

D. Our Natural Ester (Biotransol HF)properties:

In this section we put together the properties of the fluid. The properties were measured as per IEC & IEEE standards for all parameters shown in table 1. The product properties were validated in accredited laboratories in India as well as abroad.

Table 1 List of all properties as per IEC standards for Mineral Oil and Natural Ester

Property	Limits As per Standard IEC methods	
	Mineral oil as per IEC 60296:2012	**Natural Esters as per IEC 62770**
1 – Function		
Viscosity at 40 °C	Max. 12 mm^2/s	≤ 50 mm^2/s
Viscosity at –20 °C	-	-
Viscosity at –30 °C	Max. 1 800 mm^2/s	-
Viscosity at –40 °C	-	-
Viscosity at 100^0C	-	≤ 15 mm^2/s
Pour point	Max -40^0C	≤ -10^0C
Water content	Max 30 mg/kg[c]/40 mg/kg[d]	≤ 200 mg/kg
Breakdown voltage	Min. 30 kV / 70 kV [e]	≥35 kV
Density at 20 °C	Max. 0.895 g/ml	≤ 1.0 g/cm^3
DDF at 90 °C	Max. 0.005	≤ 0.05
DC Resistivity at 90^0C	-	-
Particle content	No general requirement	-
Crystallization	-	-
2 – Refining/stability		
Colour	-	-
Appearance	Clear, free from sediment and suspended matter	Clear, free from water and suspended matter and sediment
Acidity	Max. 0.01 mg KOH/g	≤ 0.06 mg KOH/g
Interfacial tension	No general requirement	-
Total sulphur content	No general requirement	-
Corrosive sulphur	Not corrosive	-
Potentially corrosive Sulphur	Not corrosive	Not corrosive
DBDS	Not detectable (< 5 mg/kg)	-
Inhibitors of IEC 60666	(U) Uninhibited oil: not detectable (< 0.01%) (T) trace inhibited oil: < 0.08 % (I) inhibited oils: 0.08 % – 0.40 % (see 3.6 to 3.8)	-
Metal passivator additives of IEC 60666	Not detectable (< 5mg/kg), or as agreed upon with the purchaser	-
Other additives	See [g]	-
2-Furfural and related compounds content	Not detectable (< 0.05 mg/kg) for each individual compound	-
Stray gassing	No general requirement	-
3 – Performance		
Oxidation stability - Total acidity - Sludge - DDF at 90 °C - Viscosity at 40^0C	 Max. 1.2 mg KOH/g Max. 0.8 % Max. 0.500 -	 ≤ 0.6 mg KOH/g - ≤ 0.5 ≤ 30% over initial
Gassing tendency	No general requirement	-
ECT	No general requirement	-
4 – Health, safety and environment (HSE)		
Flash point	Min. 135 °C	>250^0C
Fire Point	-	≥300^0C
PCA content	Max. 3 %	-
PCB content	Not detectable (< 2 mg/kg)	Free from PCB
Bio0radation	-	Readily biodegradable

c For bulk supply.
d For delivery in drums and IBC.
e After laboratory treatment (see 6.4).
g The supplier shall declare the generic type of all additives, and their concentrations in the case of antioxidant additives.

One can clearly see that our product meets all the requirements as per the standard and it's superiority over mineral oils with respect to fire point (360^{0}C for the ester versus 170^{0}C for mineral oil) and biodegradability.

The most important property, namely, dielectric strength, of the ester is comparable to mineral oil. There can be no compromise on this property for good performance as a dielectric fluid.

E. Properties of our Natural Ester (Biotransol HF) related to its performance as a transformer fluid:

This section describes properties of our natural ester related to its performance in a transformer.

1. Biodegradability & Aquatic Toxicity:
   Biodegradability was carried out by OECD 301B while aquatic toxicity to fish was carried out by OECD 203 test protocol at accredited laboratories of Intertek India Pvt. Ltd.
   The conclusions confirm that our natural ester is non toxic to fish as well as completely and readily biodegradable as per OECD classification.
2. Variation of Viscosity with temperature:

Temperature (^{0}C)	Kinematic Viscosity (cSt)
40	32.1
50	23.8
60	18.0
70	14.0
80	11.3
90	9.2
100	7.7

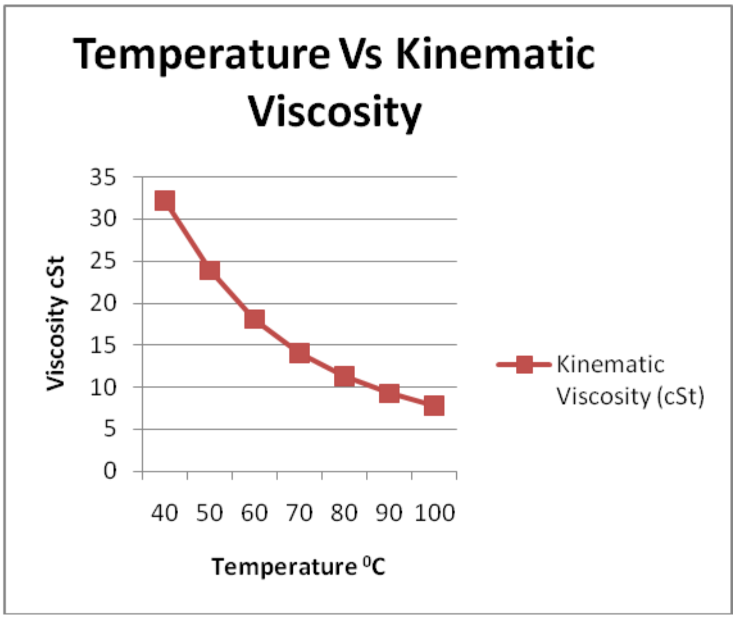


Fig 1 Data of Temperature Vs Viscosity for Natural Ester

Viscosity versus temperature is an important parameter to understand its cooling capability in a transformer. The figure 1 compares a conventional mineral oil and our new product natural ester Biotransol HF. It may be seen that even though the viscosity at 40^{0}C is higher for ester, the viscosity at the operating temperatures of a transformer are comparable (say @100^{0}C) to mineral oil.

3. Moisture tolerance & performance benefits over mineral oil :

Time (min)	Moisture in oil (ppm)	
	Paper Saturated with Moisture (Natural Ester)	Paper Saturated with Moisture (Mineral Oil)
0	87	3
30	1520	87
45	1550	105
60	1572	115
75	1580	137
90	1590	149
105	1610	151
120	1630	160
135	1650	162
150	1680	157

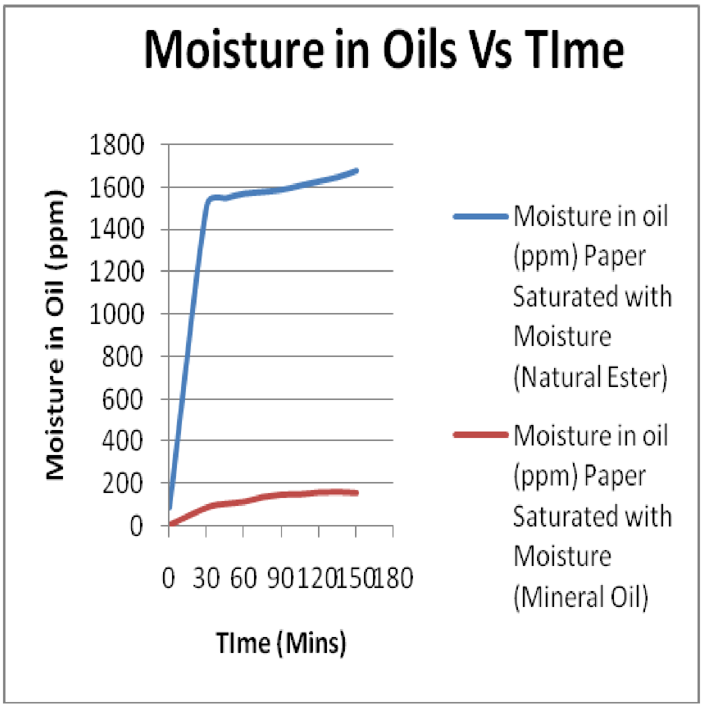


Fig 2 Comparison data of Paper saturation with moisture in Mineral oil & Natural Ester.

The figure 2 gives moisture tolerance of our natural ester. The figure describes the ability of the fluid to extract moisture from a wet paper. This property ensures the insulation paper remains dry and hence translates to longer life of paper compared to a case where mineral oil is used.

It is important to note that the dielectric strength of the new fluid remains unaffected even up to 400 ppm of moisture. This is shown in the figure 3. This is in contrast to a mineral oil which shows deterioration in dielectric strength even when moisture content goes above 50 ppm in oil.

Natural Ester Moisture (ppm)	BDV (kV)
77	68
110	66
148	65
208	64
270	62
346	57
485	46
525	40
587	31
690	27
810	24
937	22

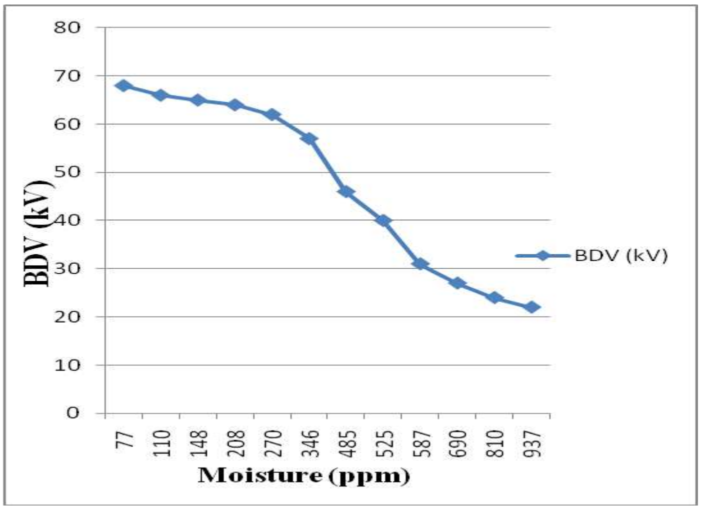


Fig 3 Data of Moisture Vs BDV for Natural Ester

This property also allows the transformer to operate at higher temperatures than a mineral oil filled transformer and hence allows it to operate at higher loads.

4. Thermal aging studies:

This is very important to understand what happens to the fluid when exposed to heat and exposed to atmospheric air. The test was carried out as per IS 12177-1987 test protocol at 115^{0}C in a beaker containing our natural ester fluid. The beaker was kept open to atmospheric air. The properties of the oil are recorded. The table 2 below gives results. The results indicate the fluid is quite sturdy and thermally stable.

Table 2 Thermal aging studies as per IS 12177 –1987 for Natural Ester

TEST	Natural Ester initial value (Before aging)	Natural Ester without Copper catalyst	Natural Ester with Copper catalyst
Viscosity @ 40^{0}C cSt	32.14	33.09	32.51
Specific resistance@30^{0}C (Resistivity) ohm-cm	6.95X10^{12}	21.5X10^{12}	8.85X10^{12}
Specific resistance@90^{0}C (Resistivity) ohm-cm	1.4X10^{12}	2.8X10^{12}	1.51X10^{12}
Dielectrical Dissipation Factor @90^{0}C (Tan delta)	0.0116	0.00605	0.013
Total Acid Number	0.003	0.0066	0.0074

5. Fire Behaviour of our Natural ester

In the following paragraphs, we will compare the fire properties of all two materials (mineral oils and Natural Ester oil).

Table 3 compares the Fire point, Specific heat, Heat of Combustion and thermal class- Mineral oil, & Natural ester. The table also gives the total heat energy required to take the fluid to its fire point.

Fluid	Mass of 1000 liters	Fire point (^{0}C)	Specific Heat capacity (J/Kg^{0}C)	Temperature change (^{0}C)	Energy to raise to fire point (MJ)	Net Calorific Value (MJ/Kg)	Thermal Class
Mineral Oil	880 Kg	170	1860	80	130.94	46	O
Natural ester	920 Kg	360	1908	270	473.95	39	K

Note – 1. Transformer operating temperature is considered as 90^{0}C. 2. Net calorific values are taken from literature.

One can clearly see that the specific heat is higher for Biotransol compared to Mineral Oil. This implies one needs higher heat to raise the temperature by 1^{0}C. This factor coupled with the fact of high fire point means that one needs to provide a lot more heat energy to Biotransol compared to a mineral oil to take the fluid to its fire point. For instance, Biotransol needs heat energy of 473.95 Mega joules/kg whereas mineral oil needs just 130.94 Mega

joules/kg to take the fluid to its fire point. This essentially means that the time to ignition will be longer for our natural ester Biotransol HF compared to a conventional mineral oil.
The table also compares the heat of combustion of mineral oil and Biotransol. Clearly, Biotransol generates less heat compared to a mineral oil during combustion (46 MJ/Kg for mineral oil versus 39 MJ/Kg for Biotransol). As a result of lower heat of combustion, the oil will not support the fire to the same extent as a mineral oil. In other words, Biotransol has a self-extinguishing property while mineral oil does not possess this property.

Pictures shown below show the differences in burning behaviour between a mineral oil and Biotransol HF when the fluids are exposed to oxyacetylene flame. In the picture 'a' below, one can see that the mineral oil starts giving off fumes within 35 seconds and nothing happens to Biotransol. At approximately 40 seconds (picture b), mineral oil catches fire while still nothing happens to Biotransol. Mineral Oil fire goes on and on till the fuel is consumed. At about 3.2 minutes, Biotransol catches fire as its fire point is reached (picture c). However, the flame height is quite small and in fact it gets extinguished within a few seconds since the fluid does not support the flame (this is not shown in the picture). These facts come out clearly in video film taken.

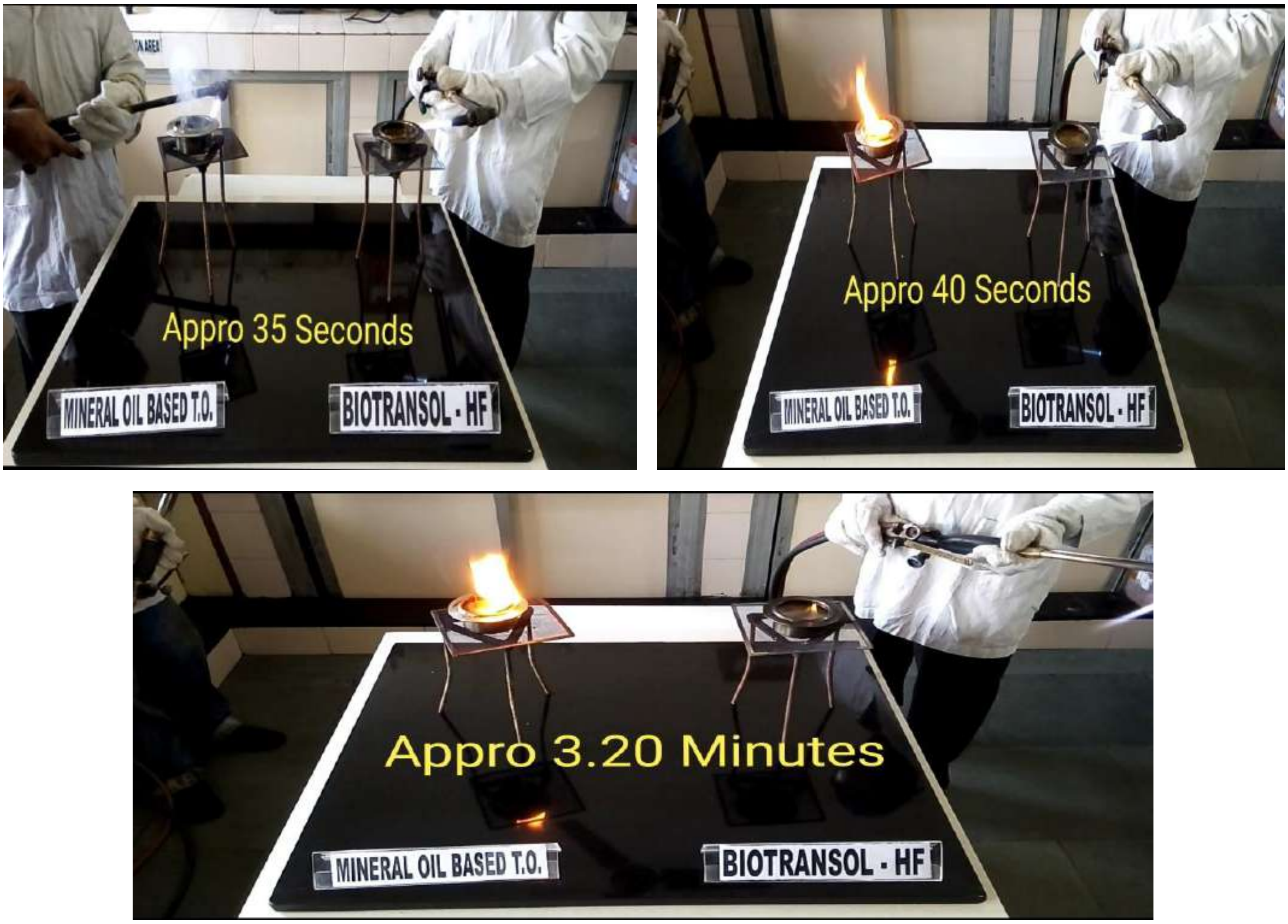


Fig 4 Comparison difference of ignition behaviours between Mineral oil & Natural Ester.

6. Stray Gassing:

This relates to hydrogen and hydrocarbon gases produced when the fluid is subjected to a temperature of 120^{0}C. The fluid is stripped with air before heating to 120^{0}C. This is carried out as per ASTM D 7150 test protocol. The dissolved gases in the oil after the above treatment are measured by the so called DGA technique using a state-of-the-art technology. The equipment used is shown below:

Fig 5 DGA equipment for stray gassing as per ASTM D 7150.

The results of stray gassing are tabulated below in table 4:

Table 4 Stray gassing results for Natural ester as per ASTM D 7150 standard

Natural Ester	N_2 STRIPPING		AIR STRIPPING	
	RT	120°C	RT	120°C
CO_2	174.3	**812.0**	168.6	**1214.0**
O_2	201.0	**209.0**	1247.3	**307.0**
N_2	2426.6	**2108.0**	2195.9	**2238.0**
H_2	19.0	**322**	20	**332**
C_2H_2	BDL	**BDL**	BDL	**BDL**
C_2H_4	BDL	**7.2**	BDL	**8.0**
C_2H_6	BDL	**388**	BDL	**428**
CH_4	13.2	**20.4**	13.7	**21.8**
CO	17.1	**79.0**	22.5	**121.0**

7. Studies on compatibility of transformer components with our natural ester:

This is very important for the material design of a transformer and therefore we carried out a detailed study of compatibility of the new fluid with a variety of components conventionally used in a transformer. The studies were carried out using a ASTM D 3455-11 standard experimental protocol. The results of the study are tabulated in the following tables

Sr.No.	Ingredients	B.N.1	B.N.2	B.N.3	B.N.4
1.	Biotransol HF	187.3 gm	908.75 gm	800 ml	800 ml
2.	Resi Glass tape	1.873 gm	-	-	-
3.	Fibre glass tape	-	9.0875 gm	-	-
4.	Blockodized high tensile hardware	-	-	63.5971 gm	-
5.	Zinc hardware	-	-	-	13.9 gm

A) Analysis results of Biotransol HF- Batch No.1 (Resi glass tape)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.5
2.	Interfacial tension (IFT)	ASTM D 971	24.7	19.7
3.	Acid value	ASTM D974	0.0113	0.0205
4.	Dielectrical strength	ASTM D877	78-80	-
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.0316

B) Analysis results of Biotransol HF- Batch No.2 (Fibre glass tape)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.0
2.	Interfacial tension (IFT)	ASTM D 971	24.7	21.7
3.	Acid value	ASTM D974	0.0113	0.015
4.	Dielectrical strength	ASTM D877	78-80	60
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.0257

C) Analysis results of Biotransol HF- Batch No.3 (Blockodized high tensile hardware)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.5
2.	Interfacial tension (IFT)	ASTM D 971	24.7	21.7
3.	Acid value	ASTM D974	0.0113	0.0419
4.	Dielectrical strength	ASTM D877	78-80	62
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.0248

D) Analysis results of Biotransol HF- Batch No.4 (Zinc hardware)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.0
2.	Interfacial tension (IFT)	ASTM D 971	24.7	22.7
3.	Acid value	ASTM D974	0.0113	0.0201
4.	Dielectrical strength	ASTM D877	78-80	54
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.0446

Test	Initial value (cm)	After 164 hrs value (cm/gm)	% changes
A. Resi glass tape – **1. Dimensional changes (cms)** **a) Length** **b) Width** **c) height** **d) weight (gm)**	75 - - 1.873	75 - - 2.3003	No change - - 22.81
B. Fibre glass tape – **1. Dimensional changes (cms)** **a) Length** **b) Width** **c) height** **d) weight (gm)**	- - - 9.0875	- - - 9.1070	- - - 0.2145
C. Blockodized high tensile hardware **1. Dimensional changes (cms)** **a) Length** **b) Width** **c) height** **d) weight (gm)**	- 3 1.8 63.59	- 3 1.8 63.59	- No change No change No change
D. Zinc hardware **1. Dimensional changes (cms)** **a) Length** **b) Width** **c) height** **d) weight (gm)**	- 1.8 1.1 13.9	- 1.8 1.1 13.9	- No change No change No change

Sr.No.	Ingredients	B.N. 1	B.N. 2	B.N. 3	B.N. 4
1.	Biotransol HF	800 ml	800 ml	800 ml	800 ml
2.	Nitrile gasket	36.1866 gm.	-	-	-
3.	SBRC gasket	-	19.1204 gm.	-	-
4.	Signot belt (High tensile plastic belt)	-	-	5.0512 gm.	-
5.	Pressboard	-	-	-	5.9457 gm.

A) <u>Analysis results of Biotransol HF- Batch No.1</u> (Nitrile gasket)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.5
2.	Interfacial tension (IFT)	ASTM D 971	24.7	21.9
3.	Acid value	ASTM D974	0.0113	0.04
4.	Dielectrical strength	ASTM D877	78-80	57
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.163

B) <u>Analysis results of Biotransol HF- Batch No.2</u> (SBRC gasket)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.5
2.	Interfacial tension (IFT)	ASTM D 971	24.7	21.2
3.	Acid value	ASTM D974	0.0113	0.035
4.	Dielectrical strength	ASTM D877	78-80	54
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.064

C) <u>Analysis results of Biotransol HF- Batch No.3</u> (Signot belt - High tensile plastic belt)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.5
2.	Interfacial tension (IFT)	ASTM D 971	24.7	22.4
3.	Acid value	ASTM D974	0.0113	0.028
4.	Dielectrical strength	ASTM D877	78-80	62
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.039

D) <u>Analysis results of Biotransol HF- Batch No.4</u> (Press board)

Sr. No.	Test Name	Test standard method	Initial value Before experiment	After 164 hrs value
1.	Color	ASTM D1500	1.0	1.5
2.	Interfacial tension (IFT)	ASTM D 971	24.7	29.3
3.	Acid value	ASTM D974	0.0113	0.026
4.	Dielectrical strength	ASTM D877	78-80	73
5.	Dissipation (power factor) @ 90^0C	ASTM D924	0.02	0.0249

2) Physical changes of Compatibility materials –

Test	Initial value (cm)	After 164 hrs value (cm/gm)	% changes
A. Nitrile gasket –			
1. Dimensional changes (cms)			
a) Length	10.696	10.701	0.046
b) Width	1.966	1.94	1.32
c) height	-	-	-
d) weight (gm)	36.1866	36.1945	0.02
B. SBRC gasket –			
1. Dimensional changes (cms)			
a) Length	8.088	7.98	1.33
b) Width	3.164	3.186	0.695
c) height	0.86	0.88	2.325
d) weight (gm)	19.1204	19.0622	0.304
C. Signot belt (High tensile plastic belt)–			
1. Dimensional changes (cms)			
a) Length	15.25	15.252	0.013
b) Width	1.86	1.86	No change
c) height	0.13	0.13	No change
d) weight (gm)	5.0512	5.0517	0.0098
D. Pressboard –			
1. Dimensional changes (cms)			
a) Length	9.218	9.14	0.85
b) Width	4.04	4.08	0.99
c) height	0.194	0.158	18.55
d) weight (gm)	5.9457	6.5688	10.479

F. Field Trials and launching of product:

Based on the favourable performance related data, we carried out field trials successfully. We collected oil samples for over 2 years from distribution transformers which are found satisfactory.

Subsequently, our natural ester, Biotransol HF, fluid has been launched for power as well as distribution transformers.

11. RETROFILL:

This is yet another driver for the use of ester fluids in India. Here, an old mineral oil filled transformer which is nearing its end of life is selected for retrofill. Mineral oil is completely drained off and is replaced by ester fluids. The esters will give the transformer another lease of life by extracting moisture out of the paper insulation. Here, it’s important to understand that the ester will not reverse the condition of an aged paper but will only slow down further aging compared to mineral oil. Thus the major advantage of retrofill is to defer Capital expenditure (Capex).

Here are the important steps and precautions to be followed for retrofill in order to get best results:

1. **De-energization of the unit and grounding of equipment.**
2. **Draining of transformer oil.**
3. **Flushing with heated replacement fluid and draining of residual “flushing” fluid.**
4. **Replacement of aged or damaged seals and gaskets. Then filling of the transformer with new fluid from the bottom under partial vacuum.**

Standing time will have to be allowed to dissipate trapped air bubbles.

Bibliography:

1. IEC 62770, Edition 1.0, 2013-11, Fluids for electrotechnical applications – Unused natural esters for transformers and similar electrical equipment.

2. Experiences in service with new insulating liquids, Work group A2-35, Cigre A2-35, October 2010.

3. C. PERRIER, M. RYADI (Areva T&D, France), Y. BERTRAND, C. TRAN DUY (Edf R&D, France), Comparison between mineral and ester oils, D_102_2010, CIGRE 2010.

4. Dr. J.C. Mendes, A.S.G.Reis, E.C.Nogawa, C.Ferra (ABB, Brazil), A.J.A.L.Martins, A.C.Passos (CEMIG, Brazil), Advanced application of a Natural ester vegetable oil in a HV Power transformer, A2-101, CIGRE 2008

5. R. Girgis, M. Bernsjo (ABB Power Transformer, USA), G.K. Frimpong (ABB TRES, USA) Detailed performance of a 50 MVA transformer filled with a natural ester fluid versus mineral oil, A2_107_2010, CIGRE 2010.

6. T.V. OOMMEN, C.C. CLAIBORNE, ABB Power T&D company Inc. (US), Biodegradable insulating fluid from high oleic vegetable oils, 15-302, session 1998 Cigre.

7. D. Martin, Z.D. Wang, P. Dyer, A.W. Darwin, I.R. James (UK), A comparative study of the Dielectric strength of ester impregnated cellulose for use in large power transformer, 2007 International conference on solid dielectrics, Winchester, UK, July 8-13, 2007.

8. J. Luksich, K. Rapp, “Suitability of Natural Ester Fluids for Retofilling Transformers”, Weidmann 2012 Technical Con-ference, Las Vegas, NV October 18, 2012.

9. C.P. McShane, K.J. Rapp, J.L. Corkran, G.A. Gaug-er, J. Luksich, “Aging of Paper Insulation in Natural Ester Dielectric Fluid”, IEEE/PES Transmission & Distribution Conf., October 28- November 2, 2001, Atlanta, USA

10. K.J. Rapp, C.P. McShane, J. Luksich, “Interaction Mechanisms of Natural Ester Dielectric Fluids and Kraft Paper”, IEEE/DEIS 15th International Conf. on Dielectric Liquids, June 26- July 1, 2005, Coimbra, Portugal

11. Ronny Fritsche, Uwe Rimmele, Frank Trautmann, Michael Schäfer, “Prototype 420 kV Power Trans-former Using Natural Ester Dielectric Fluid”, TjH2b-19th Annual High Voltage Electrical Equip-ment & Management Conf., TechCon North America, Feb. 3-6, 2014, Phoenix, USA

12. IEEE C57.147-2008, ”Guide for Acceptance and Maintenance of Natural Ester Fluids in Transform-ers”, Institute of Electrical and Electronic Engi-neers – Power & Energy Society, July 2008, New York, USA

Evaluation of Natural Ester Filled Distribution Transformer- An Emerging Trend.

Rajaram Shinde
Global Technical Adviser
Cargill Inc.
Rajaram_Shinde@cargill.com

Naveen Jain
Technical Sales Manager
Cargill India Pvt. Ltd.
Naveen_Jain@Cargill.com

Rajib Chaudhary
National Head-Dielectric
Cargill India Pvt. Ltd
Rajib_Chaudhary@cargill.com

Abstract: Dielectrics fluid and Electrical Insulation paper are dedicated to transformer insulation. The transformer is a very essential apparatus in an electric power system and its reliability is of utmost importance as transformer failure results in a very costly and difficult to predict interruption of energy delivery. Transformer's performance depends heavily on its insulation system; therefore, the insulation is perhaps the most critical transformer part. The prime function transformer oil of transformer has always been to insulate and cool the system. In the present times, its role has been expanded far beyond these two important functions. [1]

As Per IEC 60076:2013 Part 14, table C.2 Natural ester dielectric fluid is high thermal class insulation, provides fire safety as well as prevent thermal ageing. It helps to improve the load capacity without changing design of transformer. Today the Natural esters are the most accurate diagnostic media amongst available alternate fluids to monitor and assess the overall health of the transformers IEEE C57.155 (DGA Guide). Aging substation infrastructure, environmental protection, and resource sustainability are other growing issues**.** Ester based alternate fluids are now available in market viz. Natural Esters which take over the limitations of conventional mineral oil in terms of partial biodegradability, low fire point and consequent safety issues with transformer explosions and fires that can cause catastrophic damages.

however, a good number of distribution transformers up to 33 kV have been retro filled with ester liquids. In case of distribution transformers CPFL has taken lead and used natural ester liquids, and CPFL replaced a 112.5 kVA MO transformer with a 45 kVA FR3 fluid-filled transformer.

Keywords: Distribution Transformer, Life assessment, Fire safety, Ester Fluid, Natural Ester.

INTRODUCTION

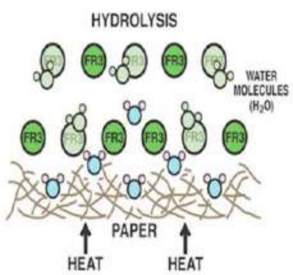
Insulation system plays vital role in the transformer. Its primarily function as di-electric insulating and cooling medium in the transformer. The operational stress inside the equipment in service and chemical reaction cause generation of moisture, acids and gases. Excessive presence of the decay products will lead to accelerated deterioration in the dielectric strength of the fluid apart from damaging the insulation paper (Typically in case of mineral oil).

To resolve all the above problems and improve the life of the transformer natural ester Dielectric fluid is a proven solution. With its unique electrical properties of high thermal Capability, higher fire point & hydrolysis help to improve the life of insulation paper. Natural ester directly enhances the life of insulation system & Transformer.

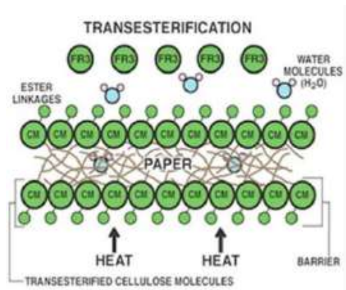
Natural Ester Dielectric Fluid

1. **Slow down Thermal Ageing:**

Typically, operating temperatures for transformers lie between 65°C to 90°C. At these temperatures, the insulation materials undergo slow ageing with concurrent loss in electrical and mechanical properties. The insulation properties can also degrade due to the presence of moisture. Within a transformer when the insulating paper ages, water molecules are released from the insulation which accelerate further degradation of the cellulose due to hydrolysis leads to corrosive reaction in mineral oil. [3] However, with natural ester (FR3) fluid, a hydrolysis reaction occurs whereby a molecule of water is converted to a non-reactive, long chain, free fatty acid thus absorbing the water molecule into the carbonyl structure of the natural ester. These fatty acids have no negative impact on the performance of the fluid or transformer. Also, they are non-corrosive & non-reactive as compared to acids generated with mineral oil shown in fig. (2)



(Figure 1. a)



(Figure 1.b)

Figure 1: Hydrolysis process with Natural ester fluid. Fig. (2.a) Mineral oil Fig (2.b) FR3 fluid.

In figure (1.a.) Shows that in hydrolysis process Natural ester FR3 dielectric fluid consumes water molecules creates fatty acids. In this way, it will remove dissolved water (Moisture).In figure (1.b.) Shows combination natural ester attached to the weak point of the cellulose. During hydrolysis, fatty acids form attached to cellulose and strengthening the insulation paper.

With a FR3 fluid-filled transformer, the water volume (ppm) allowed before reaching saturation and acid counts will be higher. That's not a bad thing – that's normal for FR3 fluid compared to a mineral oil transformer. By being able to absorb the extra water produced as part of the thermal aging process and having a higher water saturation point, FR3 fluid protects the insulation paper (essentially 'self-drying') thus extending the asset life and helping improve the grid reliability. FR3 fluid can extend the insulation life of new transformers or the residual insulation life in a retro-filled transformer.

2. **Fire Safety :**Natural ester dielectric fluid is made up of renewable vegetable oils (USDA Certified Bio based Product). It has been found to meet the specifications since as per IEC 60076 part 14 table C.2, they have high ***fire points (300˚-360˚C***) help to improve thermal capability of insulation paper.it has Underwriters Laboratory (UL) and Factory Mutual (FM) Research Corporation Less Flammable Fluid Certification.It has lower pour points (-10˚C) and have high dielectric breakdown voltage (>50KV). These are in conformity with standards like IEEE C57, IEEE 637, ASTM D6781 and IEC 60296.

3. Impact on transformer life extension

Natural ester (FR3) fluid extends insulation life by a factor of as much as 5-8 times because it has the unique ability to draw out retained moisture and absorb water driven off by aging paper. It also helps prevent paper molecules from severing when exposed to heat. These properties can result in an increase of overloadability and/or longer transformer insulation life, resulting in both lower life cycle cost and delayed asset replacement. In Figure 3. We can find that in seal tube test after 80 years of service life of transformer insulation paper still with working state as compare to mineral oil. Conclude that natural ester fluid accelerate the life of asset by improving the life of insulation system.

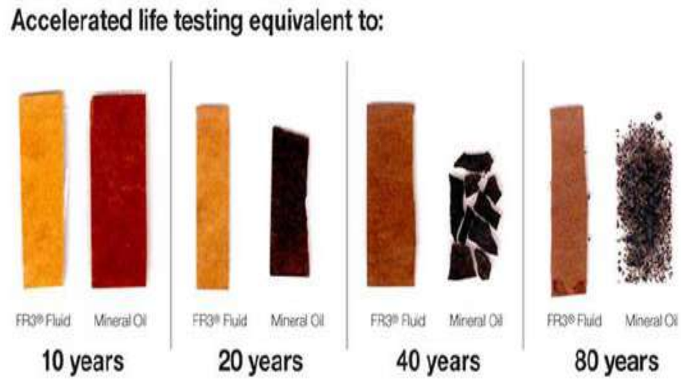


Figure 3. Seal tube test

4. Biodegradable Natural Ester fluid:

is incombustible and possess non-toxic attributes, which has boosted its Increasing popularity and use in transformers. The advantages offered by natural ester over mineral oil are as follows:

- Offer higher flash/fire points.
- Biodegradation of esters is much better compare to mineral oil or silicone liquid shown in (figure 4).

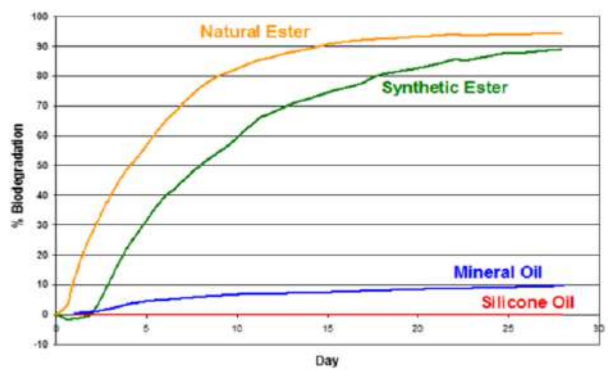


Figure 4: shows the good biodegradability of ester based insulating fluids (CIGRE SC A2 reports

CASE STUDY:

CPFL: Research, development and hands-on experience:

In 2003, CPFL Energia, a Brazilian utility, initiated investigations for high temperature compact distribution transformer, using Natural Ester liquids. Based on a 45 kVA transformer, a final rated capacity of 88 kVA has been reached after modifications in the cooling ducts and radiators. Two prototypes were installed at a heavily loaded network point, replacing mineral oil filled transformers of 112.5 kVA. After 12 years of continuous operation, one of the prototypes was removed for the study, while the other remains in service. The transformer was still in perfect operational conditions, submitted to an average loading along the 12 years of 82 kVA and peak loading reaching 123 kVA (273.3% of the original 45 kVA rating). A complete teardown was performed and samples of main insulating materials were assessed by two different laboratories, one in Brazil and one in USA. The visible wearing of the external painting is the main indication of the years, while the core and coil, when un-tanked, gave the impression of handling a brand-new transformer.

Application concepts: downsizing the transformer:

The typical loading profile of most of distribution utilities around the world includes one or two peak loading periods per day, having duration of 1 or 2 h, and a relatively low loading level for the rest of the 24 h cycle. In mineral oil transformers, the main limitation for transformer selection is exactly the peak load, since the overloading is limited by the top oil temperature, which should not be higher than 115°C (long- and short-term emergency loading limit, according to loading guides).

Table 2. Loading factor of the prototype transformer

Year	Loading factor, %	Maximum winding temperature (hotspot), °C
2003	0.68	115
2004	0.75	121
2005	0.71	118
2006	0.72	119
2007	0.72	119
2008	0.75	122
2009	0.73	120
2010	0.75	122
2011	0.76	126
2012	0.74	125
2013	0.72	119
2014	0.71	117
2015	0.72	118

The network point selected was known as a heavy loading region, requiring a mineral oil transformer of 112.5 kVA. Alternatively, the decision was to install the 88-kVA natural ester immersed transformer. The loading at this point is shown in Table 2. The column 'loading factor' indicates the percent average loading based on a nominal power of 112.5 kVA. The result is an average loading for the total 12-year period of 82 kVA (72.8% of 112.5 kVA). The column 'maximum winding temperature' shows the hotspot temperature during peak loading, not at the indicated loading factor (average). The location is a residential/commercial profile, having a loading peak daily between 5 pm and 8 pm, reaching up to 123 kVA, representing 140% of the 88-kVA rating and 273% of the original rating.

Fig. 5

Fig. 5

Fig. 7

Fig. 5 shows the transformer as removed from the pole, after 12 years of continuous loading. It can be seen the wearing of the painting, but no signals of any leakage. Fig.6 shows the inside of the transformer at the time of cover removal.

As typical in distribution transformers in Brazil, the transformer has a headspace for absorbing the volumetric expansion of the dielectric liquid due to temperature variation. This headspace is not filled with any inert gas, it was ambient air when the transformer was closed, kept confined along the years. The natural ester liquid is clean and transparent, still holding its original green colour.

No film is seen on top of the liquid or on the tank walls or internal portions of the bushings. It is also remarkable the absence of any indication of corrosion commonly seen when removing the cover of distribution transformers. The dry-out effect of natural ester, responsible by keeping the insulating paper dry, has also kept the air cushion free of moisture, preventing the formation of corrosion spots. No visible signs of degradation can be identified to the transformer or its components in this top view.

Fig. 7 shows the internal part of the tank after removal of core and coils and drained of dielectric liquid. At the bottom a small volume of natural ester may be identified, as the draining was performed by a suction system (no drain valve available). Also remarkable is the absence of sludge at the bottom. A mineral oil transformer loaded similarly would be expected to have a relevant amount of solid material at tank bottom. The absence of any type of wax or gel at tank bottom also confirms the oxidation stability natural ester liquid. Fig. 8 shows the core/coil assembly, having the appearance of a brand-new unit.

Fig. 8. Core and coil assembly immediately after un-tanking.

As per laboratory test, During the regular loading of a transformer, there will be thermal degradation of the solid insulation, resulting in reduction of the DP. This is mainly accelerated by the factors:

- oxygen: an oxygen rich liquid increases paper degradation rate by a factor between 2.5 [11] and 10 [12], and is prevented by the use of oil preservation system;
- water: after oxygen, this is the main factor for paper degradation [10];
- acid number: depends on the corrosiveness of the acids (short chain versus long chain).

Table 4 Degree of polymerisation of Kraft paper samples

Id.	Paper sample location	DP
1	HV1 layer 1 (near LV)	949.1
2	HV1 last layer	915.1
3	HV2 layer 1 (near LV)	832.6
4	HV2 last layer	946.8
5	HV3 layer 1 (near LV)	941.1
6	HV3 last layer	908.8
	average	915.6

In a mineral oil transformer, it would be expected a reduction of the DP around 50% after 12 years in service (half-life). Assuming an initial value of 1100 and 200 as end of life, the expected range of DP for a regular loaded transformer would around 650. As the transformer of this test has been severely loaded, reaching hotspot temperatures higher than the currently accepted values of nominal life for the Kraft paper immersed in natural ester, it would be reasonable to find valued closer to the 650 or even lower. All paper samples taken from the transformer were analysed in Brazil and in United States, two independent and qualified laboratories. The average value of all measurements, taking the lowest measured values of each sample as valid, showed an average residual DP of 915.6. Values for each sample are presented in Table 4.

CONCLUSION

Tests performed by ‘real-life conditions’ are very often less accurate than laboratorial ones. In this study, some important information was lost due to the decision of keeping the process as close as possible to that of a regular transformer. This ‘real life’ transformer test as installed on the grid at high loading/overloading conditions for 12 years shows favorable results. The results of the materials analysis show that the materials remained in very good condition. The 25 years life expectation for mineral oil immersed transformers is often not achieved due to the high incidence of lightning impulses in the region and the common loading peaks beyond nameplate rating, which result in overloading and overstressing the transformer. For natural ester immersed transformers, designed to the higher temperature rise limits as per [7], the national regulation agency (ANEEL) has already increase the life to 27 years, based on the performance of the installed transformers.

The concept applied for this test is not corresponding to the current ‘green transformers’ of this customer, but it may represent a new paradigm for distribution transformers selection. The capacity of holding much higher values of overloading improves the range of application of the transformers, potentially allowing an increase in average loading to better use the capability of the asset. It appears that higher peak loads will not affect the reliability of the network for natural ester immersed transformers, allowing the transformer selection to consider average loading instead of the peak. A significant reduction in cellulose ageing of insulating paper impregnated with natural ester is confirmed in a real-world application. The behavior of all applied materials surpassed expectations. As a result, this may represent effective opportunities for the utilities to achieve real financial savings in their distribution and power grids.

Bibliography:

[1] Bingenheimer, D., Franchini, L., Del Fiacco, E., et al.: 'Sustainable electrical energy using natural ester technology'. CIRED Frankfurt – 21st Int. Conf. on Electricity Distribution, paper 1148, June 2011

[2] McShane, C. P., Gauger, G. A., Luksich, J.: 'Fire resistant natural ester dielectric fluid and novel insulation system for its use'. IEEE/PS Transmission & Distribution Conf., New Orleans, USA, April 12–16, 1999

[3] McShane, C. P., Rapp, K. J., Corkran, J. L., et al.: 'Aging of paper insulation in natural ester dielectric fluid'. IEEE/PS Transmission & Distribution Conf., Atlanta, USA, October 28–November 2, 2001

[4] McShane, C. P., Rapp, K. J., Corkran, J. L., et al.: 'Aging of plain Kraft in natural ester dielectric fluid'. IEEE/DEIS 14th Int. Conf. on Dielectric Liquids, Graz, Austria, July 7–12, 2002

[5] IEEE Standard C57.154: 'IEEE standard for the design, testing, and application of liquid-immersed distribution, power, and regulating transformers using high-temperature insulation systems and operating at elevated temperatures', October 2012

[6] IEC 60076-14: 'IEC standard liquid-immersed power transformers using high-temperature insulation materials', September 2013

[7] ABNT NBR 5440: 'ABNT standard overhead distribution transformers – requirements', April 2014

[8] IEEE Standard C57.147: 'IEEE guide for acceptance and. Maintenance of natural ester fluids in. Transformers', July 2008

[9] Rapp, K. J., McShane, C. P., Luksich, J.: 'Interaction mechanisms of natural ester dielectric fluid and Kraft paper'. IEEE/DEIS 15th Int. Conf. on Dielectric Liquids, Portugal, June 2005.

[10] ABNT NBR 5416: 'ABNT standard load application on power transformer – procedure', July 1997 (Confirmed in August 2013)

[11] Fabre, J., Pichon, A.: 'Deteriorating processes and products of paper in oil. Application to transformers'. CIGRE Conf. on Large High Voltage Electric Systems, Paper 137, Paris, 1960

[12] Lampe, W., Spicar, E.: 'The oxygen-free transformer.

Title:-PQ issues in CESC’s Distribution System

Name: RAJIB KUMAR DAS

Organisation: CESC Limited, Kolkata

Introduction:-

Power Quality (PQ) related issues are becoming a major concern now days.

CESC Limited, a 120 years old electricity distribution utility, serves 3 million consumers spread in 567 sq km around the city of Kolkata.

Power supply in CESC area is 24x7. So, outage of supply is not a concern in the area of CESC’s supply. Other common Power Quality (PQ) issues are:-

- Reactive Power Demand
- Harmonic Distortion
- Voltage Sag /Swell and Flicker
- Voltage unbalance

In CESC, PQ measurement are being carried out in different sections of the network. With increased penetration of Solar PV power plant, the measurement are done more frequently.

PQ issues as stated above and its management is reported herein below:-

PQ issues:-

Reactive Power Demand

CESC’s EHV and HV network is almost 100% underground. At low voltage level, 60% of the network is underground. Underground cables are itself a source of reactive power. However, to meet the requirement of reactive power by consumers and minimise reactive power flow through the network, capacitors are being installed at all voltage levels – 132kV, 33kV, 11kV, 6kV and LV. All the capacitors are switchable to get the maximum benefit. CESC is installing Automatic Power Factor Controllers (APFC) at LV side of distribution transformers for accurate reactive power flow control. With proper reactive power control, voltage level is maintained very much within the limits specified by the Regulator.

Voltage Regulation Limits:-

Voltage Level	Higher Side	Lower Side
EHV	10%	12.5%
HV	6%	9%
LV	6%	6%

It is to be noted that there is high power factor rebate and surcharge on power factor, for HT consumers. Consumer can avail rebate of 5 to 8% on energy charge by maintaining power factor 0.99 and above. It is observed that majority of HT consumers avail high rebate by maintaining good power factor. However, as of now, there are no such provisions for LT consumers.

Harmonics

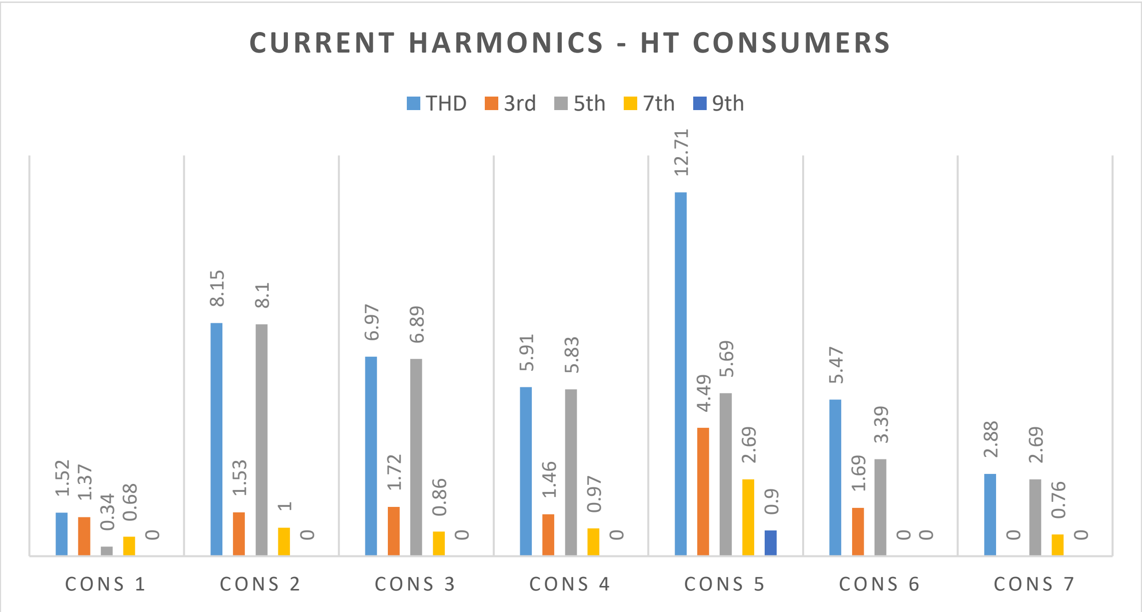
There is a saying :"***The utility owns the voltage, and the end-user owns the current***"-meaning that the utility is responsible for the generation , distribution , and regulation of the voltage at an end user's meter, but the end users load is what characterizes the shape of the electrical current. Whenever the current waveform is distorted to an extent, the supply voltage may get distorted. One of the main reason of current distortion is loads which are non-linear and generate harmonics e.g. UPS, Arc furnaces, Speed drives, Rectifiers / Inverters etc.

Consequences of high harmonics are many, some of which are listed below:-

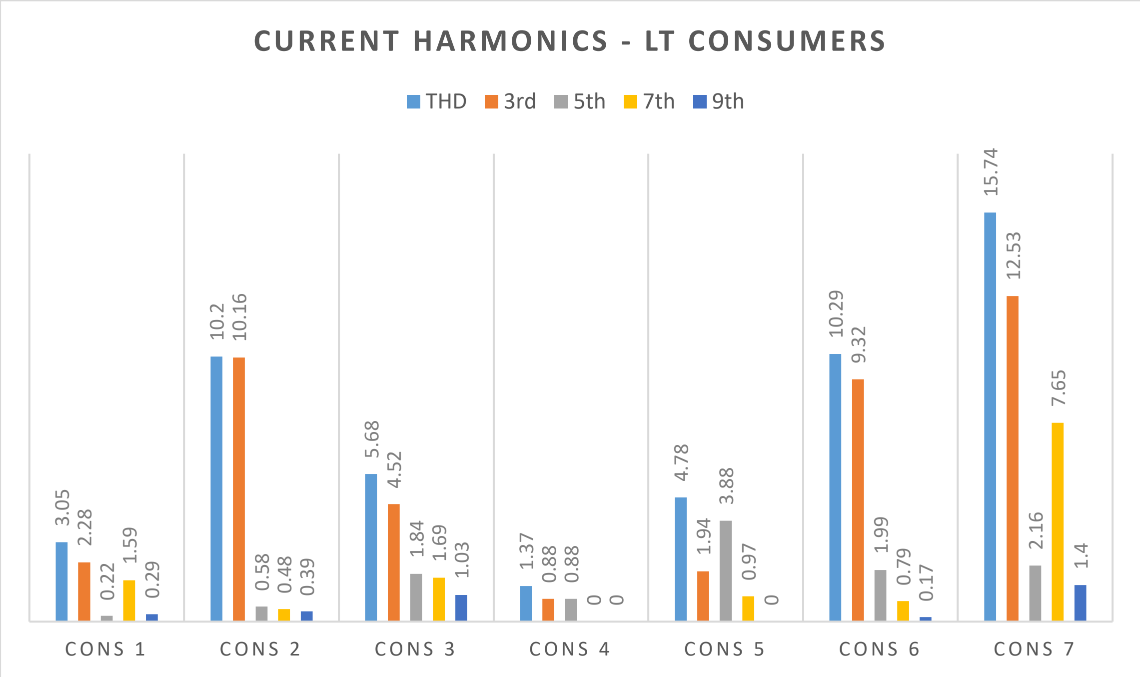
- Overloading and overheating of Transformers/Cables/CBs
- Overloading of capacitors and fusing
- Increase in losses
- Errors in measuring energy
- Malfunction of control equipment
- Loss of efficiency of motors

It is observed that Total Harmonic Distortion (THD) in current at the point of supply for High Tension (HT) consumers is varying widely in the range of 2% to 13%. Often it is higher with respect to others in case of Steel & Rolling Mills, Commercial establishments and Hospitals.

The following diagrams shows harmonics (THD, 3rd, 5th, 7th and 9th) in current drawal order for few consumers (CONS 1 to CONS 6):-



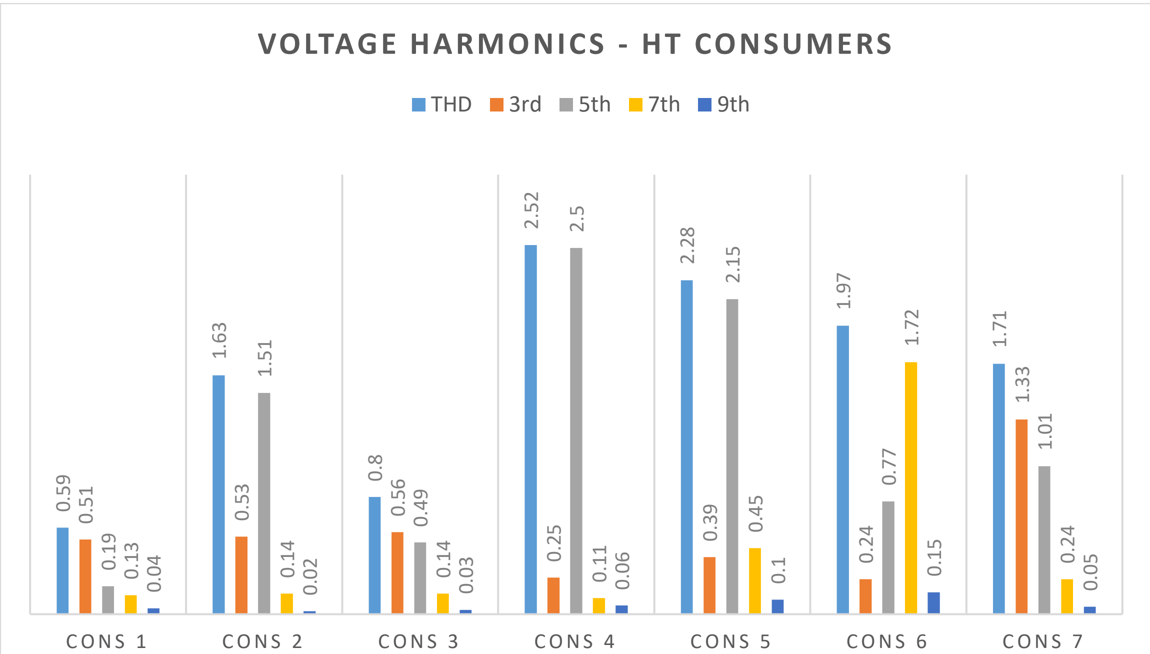
For Low Tension (LT) consumers, THD in current ranges from 1 to 15%. Generally, it is high for commercial establishments.

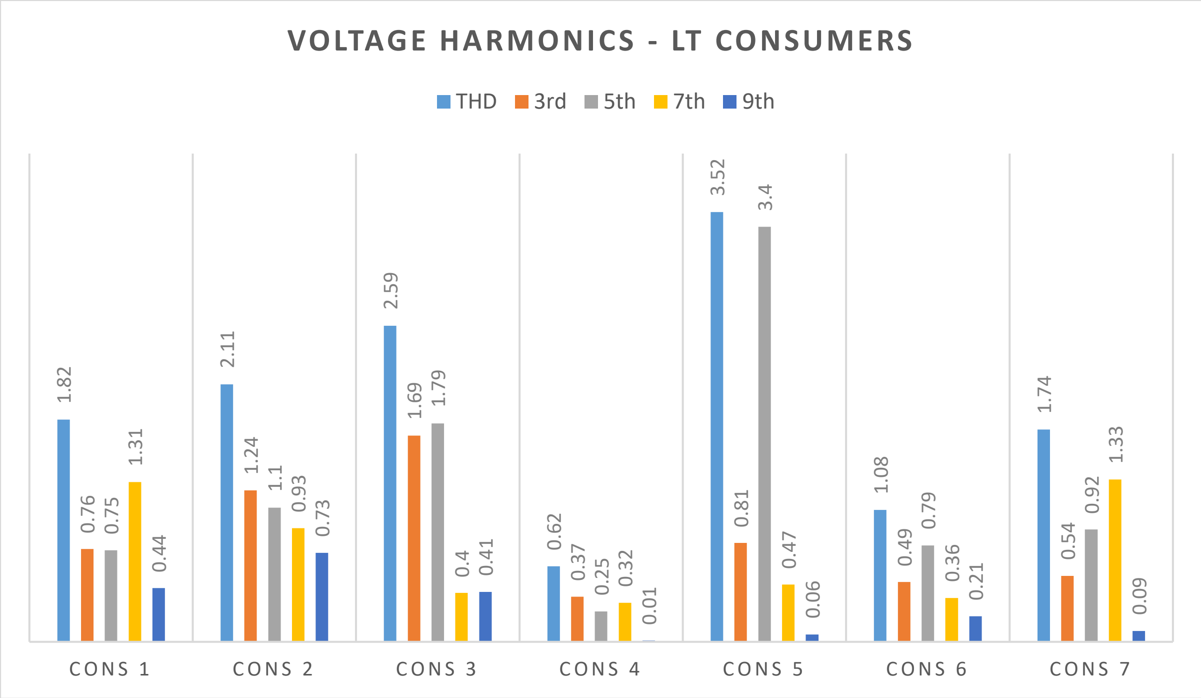


As we know, Voltage distortion depends on Short Circuit Ratio **(I_{SC} / I_L)** of the system. Short Circuit Ratio of CESC System is high at all voltage levels due to higher capacity of transformers and parallel operation at high voltage levels in many cases.

During measurement, it is observed Total Harmonic Distortion (THD) in voltage within the range of 0.60 to 2.50% for HT consumers. However, for LT consumers it is little higher 1.8% to 3.5%.

The following diagrams shows harmonics (THD, 3rd, 5th, 7th and 9th) in supply voltage:-





Measurements and observations on Harmonics for consumers with Solar PV Plant:-

Harmonic distortion are also measured at consumers where Solar PV Plant is installed. With generation from Solar PV Plant, there is an increase in current harmonics. The following measurement was done for one HT industry which has installed 750kWp Solar PV Plant at his premises.

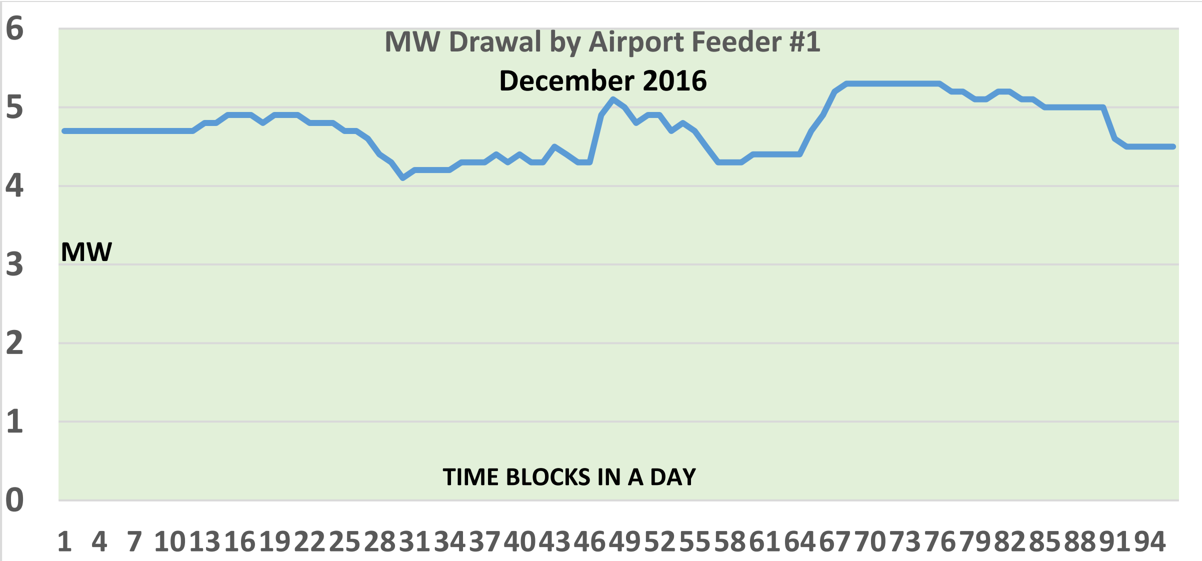
	Solar Generation Off		**Solar Generation On**	
Phase	% THD Current	% THD Voltage	% THD Current	% THD Voltage
R	3.1	1.6	5.1	1.6
Y	2.8	1	4.7	1
B	2.9	1.4	4.8	1.3

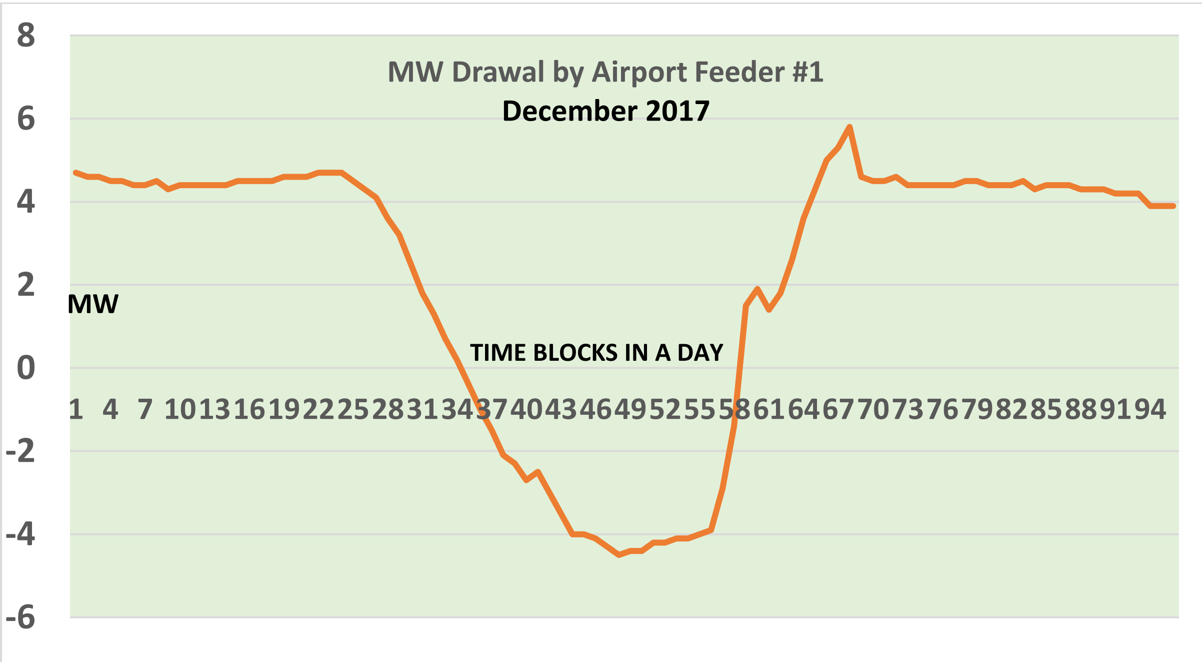
Observations made in case of a LT consumer having Solar PV Plant of 35 kWp is given below:-

	Solar Generation Off		**Solar Generation On**	
Phase	% THD Current	% THD Voltage	% THD Current	% THD Voltage
R	6.1	1.6	17	1.8
Y	5.5	1.3	14.6	1.2
B	3.8	1.5	16.5	1.5

In a case for a LT consumer having 5kWp Solar PV Power Plant, harmonic content current observed, was very high (>20%) and the meter reading was found to be erratic. The case was referred to the meter manufacturer and following changes in software, the matter has been settled.

Recently, Kolkata Airport has commissioned a 15 MWp Solar PV Power Plant. Airport is getting supply by 2 separate 33kV feeders. The said 15MWp plant has been interconnected with the Airport 33kV feeder No.1. The following graphs show MW power flow from CESC's system to Airport via 33kV feeder No.1.





During daytime, when the Solar PV power plant is operational, there is injection of power to CESC system. Reactive power flow was also checked during same period under study. It was observed that the reactive power flow was well controlled by Airport. However, with Solar, during daytime there was some amount of reactive power drawal, from CESC system.

Harmonics for LED lights:-

Another major concern for harmonic sources, is LED lights. There are LED lights in the market from various manufacturers. Harmonics was measured with LED lights from 3 different makes and the results are given below:-

RATED WATT	**5W**	**5W**	**8W**
VOLTAGE (%THD)	1.4	1.5	1.4
CURRENT (%THD)	17.3	13.3	14.8

Voltage Sags / Swells and Flicker

Reasons of Sags / Swells are large motor starting, Transformer energisation, Faults, SLG fault, Bulk load throw-off, Capacitor switching on. Voltage flicker are caused by Arc furnaces, Arc welders. Generally, the reasons are beyond control of licensee.

Unbalance

CESC network is small. So, impedance difference in phases may not have much effect. In CESC System, the loads at HT level are normally balanced. Unbalanced loads are observed at LT level. Often, network is reconfigured for load balancing. In CESC System, 100% DTRs are metered and readings are available online at remote. By studying DTR metered data, exercises are taken up for physical changes in network isolation, to make the network balanced.

Challenges:-

Major challenge towards addressing issues are:-

- Creating awareness amongst consumers about consequences of poor power quality
- Creating awareness amongst consumers about contribution towards power quality by the equipment / appliances being used by them.
- Measurement of power quality parameters – reactive power/power factor, harmonics
- Assessing impact of power quality on plant & equipment and/or appliances
- Regulatory measures for mitigating power quality issues
- Recommendation of evaluation techniques (SAIFI, SAIDI, Harmonics)
- Cost benefit analysis in terms of pay-back period, Internal Rate of Return (IRR) towards investment for mitigating PQ issues
    - Applicable for Utilities as well as consumers

Way forward:-

Reactive power compensation is always desirable at load points. Thus, it is best suited when compensation is made by the consumers. As mentioned hereinabove, there is a strong commercial signal for HT consumers towards power factor improvement and consumers automatically choose for reactive compensation. Appropriate provision should be made for LT consumers as well. Utilities should also arrange for measurement. This will lead to win-win situation both for utilities and consumers.

Consumers should be made aware about the consequences of harmonics through various media. Utilities should provide suitable metering equipment for measuring harmonics. Thereafter, additional surcharges or rebate should be made for consumers dumping harmonics in the system. With appropriate commercial signals, consumers shall provide adequate harmonic suppression units to avoid dumping of harmonics into Licensee's distribution system.

Central Electricity Authority and appropriate Regulatory Commissions should take measures to include provisions relating to PQ issues including Harmonics in line with BIS, IEC or any other Standards of International repute (IEEE Standard) in Regulations (Standards of Performances of Licensees Relating to Consumer Services / Supply Code / Distribution Code etc.). Such provisions should be harmonious with applicable Regulations / Orders of the appropriate authority.

Conclusion:-

The availability of electric power with high quality is becoming crucial day by day. There would be huge losses due to PQ problems unless addressed properly. Duty of a distribution licensee is "*to develop and maintain an efficient, co-ordinated and economical distribution system in his area of supply*". CESC always endeavour its best to supply high-quality power to its consumers; there are concerns which would be improved by partnering consumers with appropriate regulatory guideline.

How do Supply Side Constraints Affect the Rural Residential Feeder Parameters?

Sneha Swami[1], Ganesh Hegde[1], Anand B. Rao[*1, 2] and Satish B. Agnihotri[1, 3]

[1] Centre for Technology Alternatives for Rural Areas (CTARA),
[2]IDP in Climate Studies, [3]Centre for Policy Studies (CPS),
Indian Institute of Technology Bombay, Mumbai – 400 076, India

[*]Anand B. Rao. Tel: (+91) 22 25767877, Fax: (+91) 22 25767874, E-mail: a.b.rao@iitb.ac.in

Abstract: *Government of India (GoI) has a target to provide 24*7 electricity supply to all residential consumers by March 2019. Apart from electrification of all the households, load shedding is being removed in many states for residential consumers. It is important to understand the effect of supply availability on the feeder parameters due to availability of electricity for longer hours. This study undertakes the analysis of rural residential feeders under 3 substations of Kalyan region (where load shedding is removed from June 2015), where feeder parameters such as electricity consumption, all types of interruptions (duration and frequency), aggregated technical and commercial (AT&C) losses and bill collection efficiency are analyzed. The effect of reduction in load shedding on the availability of electricity supply and consumption pattern is analyzed. Statistical tests were conducted to see the changes in AT&C losses, mean consumption and bill collection efficiency for the periods with and without load shedding. This study intends to reflect upon the impacts of reliable electricity supply and its effects on feeder parameters. It is observed that both seasonality and availability of supply have effect on residential electricity consumption, while variation in AT&C losses and bill collection efficiency are region (substation) specific.*

Keywords: Rural electricity access, residential electricity consumption, availability and reliability of electricity supply, feeder analysis, electricity and development.

1. Introduction

Energy is an important driver to improve the quality of life both at the individual and the community level. Electricity, in particular, is one of the most convenient energy carrier and a vital input to the development of any region. Mere access to electricity would not ensure the development of the region, whereas the actual consumption could be a measure for the quality of life (or Human Development Index). Often, per capita electricity consumption is considered as a proxy for the wellbeing of a society or a household [1, 2]. Residential consumption of electricity rises with the increase in the economic status (or *vice versa*) [3], with the increased affordability to buy new appliances or usage for more number of hours. Limited availability and unreliable supply could limit the use of appliances and in turn hinder income generating activities [4, 5]. Macro level analysis of electricity and related development would mask its effects on the village or the households (HHs). It is important to study the impacts of electricity access, availability and consumption by the consumer in order to understand the respective development activities. It is also important to analyze the effect of unreliable and inadequate supply on the consumption pattern and related feeder parameters. Such understanding would help in exploring the potential development activities for various stakeholders and also in formulating appropriate policies and programs at the regional level [6]. It is observed that load shedding is the main cause of poor electricity supply availability. Hence, the present study aims to understand the effects of improved supply hours on the consumption pattern and selected feeder parameters for the rural residential feeders.

Residential electricity consumption contributes to about a quarter of total electricity consumption in India. Due to increasing income levels, rapid electrification and technology development, residential electricity consumption is likely to increase significantly in near future. End use of electricity in rural households is mainly for lighting, fans, television, mobile charging and a few mechanical applications such as grinding and water pumping etc [7]. The availability of electricity when it is required and the reliable supply is essential for maximizing its utilization. This also enables (or enhances) economic and productive activities which would increase the livelihood opportunities and contribute to the quality of life [8]. In order to improve the access of electricity in rural India, numerous policy initiatives have been implemented over the years [9]. However, most of these programs focused on connecting the un-electrified areas to the existing electricity grid, where availability, reliability and quality of supply were not addressed adequately [10]. To increase the availability of electricity supply, Government of India has set an ambitious target of providing 24*7 electricity to all consumers by March 2019 under the scheme, 24*7 Power for All [11].

The present study analyses the scenario of electricity availability in the rural areas of Maharashtra, with and without load shedding. The rural residential feeders of Kalyan circle, where improved availability of supply (~ 24 hours per day) has been operationalized since June 2015, have been selected for the study. An effort is made to understand the implications of improved availability of supply on feeder parameters such as electricity consumption, losses and bill collection efficiency. The study gives insights on feeder parameters due to reduced load shedding. The major objectives of the present study are:

- To analyze the trends and patterns in electricity consumption, interruptions and availability of electricity supply at the feeder level
- To assess the effect of improved availability of supply on the electricity consumption, bill collection efficiency, losses incurred by the rural residential feeders and reliability index of feeder

2. Data and Method

There are 4 distribution companies presently serving in Maharashtra, of which, 3 distribution companies are working only in Mumbai and Mumbai suburban area. Maharashtra State Electricity Distribution Company Limited (MSEDCL) covers more than 90% of consumer base including rural residential consumers across the state. Substation is the smallest operating unit in the network of MSEDCL, which is a part of sub-division. Substations also called as, switching stations studied are of 33/11kV and have rural residential feeders connected to it. Substations maintain a daily data sheet which contains hourly voltage and current readings, reading of energy meter, interruption details such as duration, time of occurrence and reasons of interruption. All these readings are maintained manually and the data is not yet available in the digitized format.

For the present study, feeder level monthly interruptions and consumption data was collected from 3 substations (Khardi, Kudawali and Mhasa) for rural residential feeders (Fig. 1). This monthly data is available from Jan-2013 to Dec-2016. Table 1 gives the information about 8 feeders under Murbad and Shahapur subdivisions. Distribution Commercial Losses (DCL) is calculated by considering non-technical, technical losses and bill collection efficiency on respective feeder. DCL groups are divided in A (0 to 18%), B (18 to 26%), C (26 to 34%), D (34 to 42%), E (43 to 50%), F (50 to 55%), G1 (55 to 60%), G2 (60 to 65%) and G3 (Above 65%) groups. Load shedding hours on the feeder are decided according to the DCL group of that feeder. Higher the DCL losses, more are the load shedding hours. DCL data was collected from subdivision for the period of April 2014 to September 2016. However, all these feeders have almost no load shedding since June 2015.

Table 1: Feeder information

Feeder name*	Subdivision	DCL Group	No. of villages	Expected hours of load shedding (hours/day)
Pawale	Murbad, Kalyan	E	5	6.15
Shirgaon		G2	7	7.45
Agashi		F	7	7
Narivali		E	6	6.15
Sasne		E	10	6.15
Kasara	Shahapur, Kalyan	D	3	5.3
Bhatsa		F	3	7
Vaitarna		E	12	6.15

*All are rural residential feeders

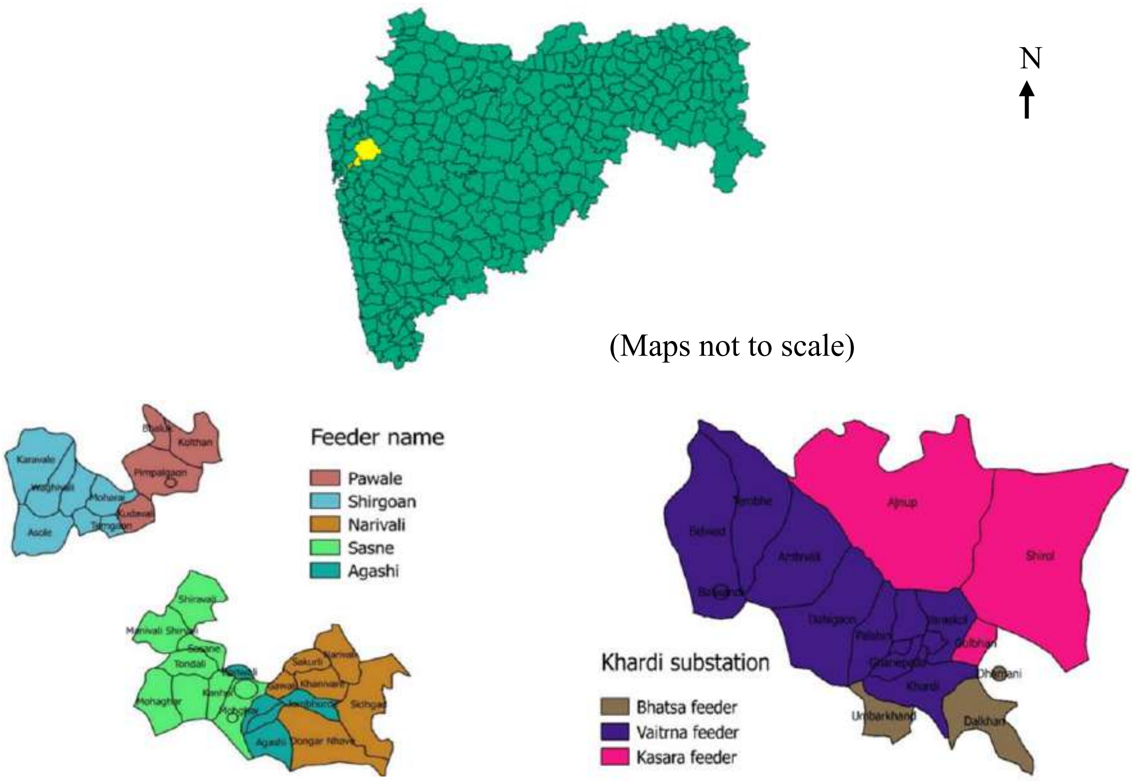


Fig. 1 Study area - villages under studied feeders

Number of interruptions and their durations are represented to understand the change in trend of electricity supply availability. This shows the change in load shedding in the studied period. T-statistics test is used to analyze whether the changes in bill collection efficiency, losses and consumption of the feeder between LS (load shedding) and NLS (non-load shedding) periods are statistically significant. Dynamics of electricity consumption on feeders are analyzed to see the change in load pattern over the period.

3. Insights from Feeder Analysis

The study observes significant increase in availability of electricity in the rural areas due to reduced load shedding. Fig. 2 shows monthly frequency and duration (hours/month) of interruptions divided in load shedding and other interruptions of Agashi feeder. Other interruptions include breakdown, shut down and tripping. One can clearly observe that, the frequency and the duration of LS have been substantially reduced from June 2015. All the studied feeders in Murbad and Shahapur subdivision show the similar pattern. It is seen that duration of load shedding hours is as high as 4 times compared to the other interruptions in a month. We can, therefore, infer that, availability of supply gets affected largely due to load shedding than any other interruption.

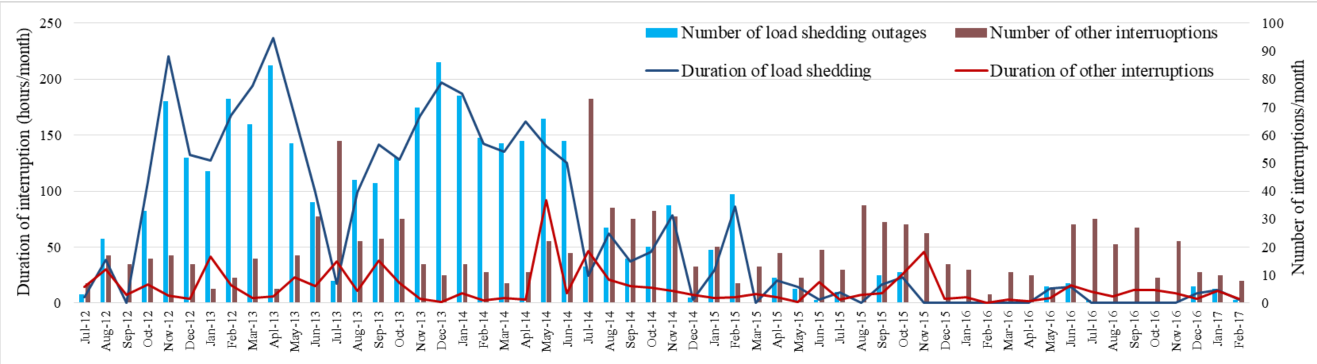


Fig. 2 Frequency and duration of interruptions in Agashi feeder

3.1 Trends of Electricity Consumption

We analyze next, the relation between availability of supply and the electricity consumption in the region. Consumption of electricity is a function of availability and the ability of consumer to utilize the electricity i.e., connected load and hours of usage. With the frequent outages and long hours of load shedding, the consumption gets restricted by utility. The load shedding in Murbad and Shahapur has been significantly reduced since June 2015. It allows the consumers to use electricity according to the needs and end uses. The increased availability of electricity supply is expected to change the overall load pattern and the energy consumption. Hence, study analyses the relation between availability of supply and the electricity consumption in the region. Fig. 3 clearly substantiates the increased consumption with the increased availability of supply on feeder. We can also infer that, the reduced LS is the major reason in improved consumption compared to the other interruptions. Further, it is observed that the increased effect of reduced LS on consumption in different seasons. Figures 4, 5 and 6 show the effect of availability on consumption in non-summer and summer (March - May) months, respectively. One can clearly see that, agreement between availability and consumption increases with the inclusion of seasonal effects.

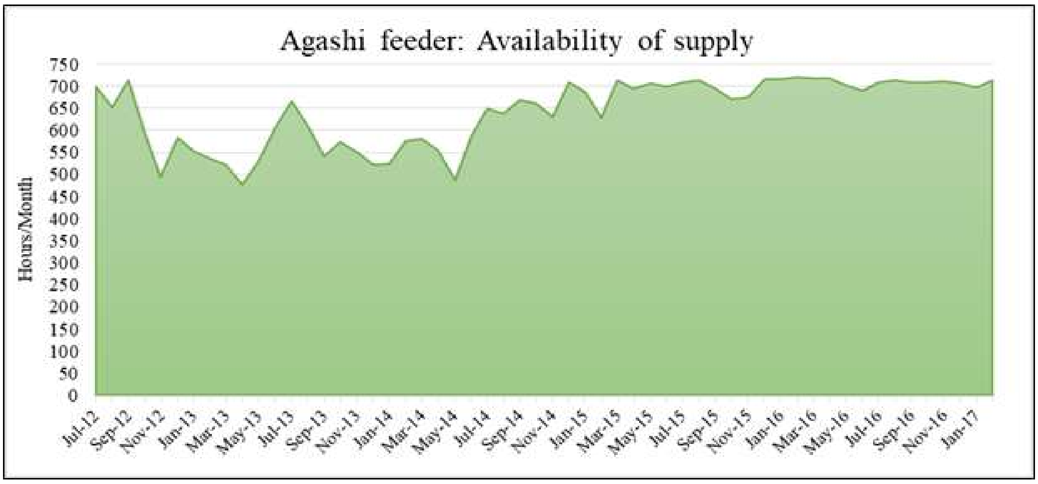


Fig. 3 Availability of supply on Agashi feeder

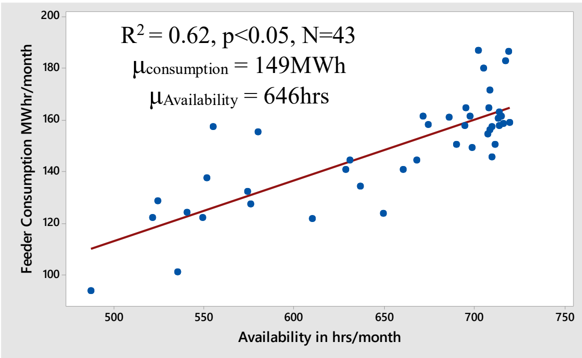


Fig. 4 Electricity supply availability and consumption for Agashi feeder

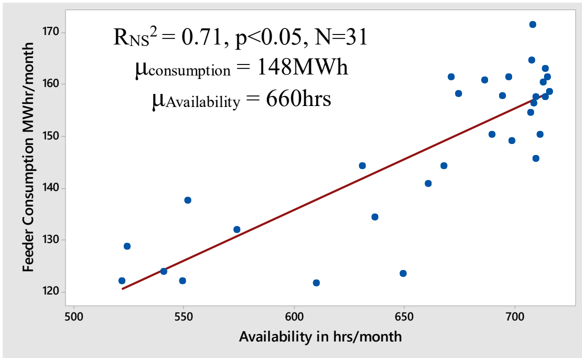


Fig. 5 Electricity availability and consumption for Agashi feeder (Non-summer months)

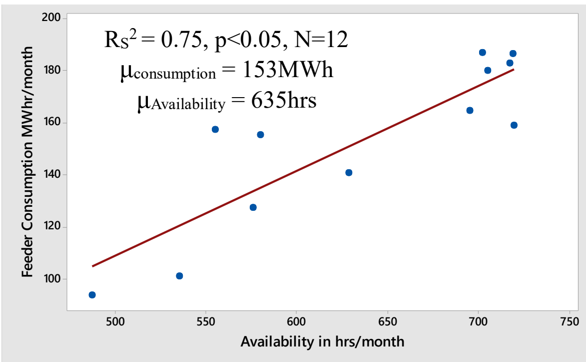


Fig. 6 Electricity availability and consumption for Agashi feeder (Summer months)

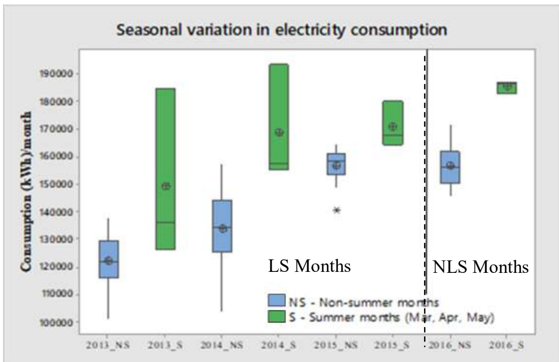


Fig. 7 Electricity consumption seasonal variation: Agashi feeder

Similar pattern is observed in Narivali feeder while the Bhatsa and Sasne feeders show R-squared less than 0.5. However, Kasara and Vaitarna feeders may not seem to follow the trend which needs further investigation. Though total interruption hours are known, timings of these interruptions and load connected in system at that time is still unknown. Thus actual loss of load due to interruption remains unknown which would help the distribution companies (DISCOMs) to optimize the load shedding and implement demand side management (DSM) techniques.

In order to understand the electricity consumption pattern and the effect of improved availability of supply, feeders are studied across the summer and non-summer months (Fig. 7). Months are divided as summer months (S) i.e. March, April, May and rest as non-summer (NS) months. Following are the major observations;

- Mean electricity consumption is increasing over the years. However, one has to account for the load growth factor in the region. The growth in consumption could also be due to the increased economic development of the households or the region. More micro level study is needed to understand the factors that contribute to the increased electricity consumption and load growth.
- Range of consumption as well as mean value of the consumption in summer months is always higher than consumption in non-summer months. Which tells that similar hours of availability may have different electricity consumption due to changing needs of consumers. The load shedding policy of DISCOMs need to consider load pattern on the feeder rather than the losses or collection efficiency.
- As the availability of supply increased in 2016, range of electricity consumption is lesser compared to the previous years. Higher value of mean consumption in summer months in spite of relatively same supply hours, shows that, the electricity consumption is dependent on the appliance ownership, ability of the consumer to utilize the electricity and the seasonal effect apart from the availability of the electricity supply.
- More usage of fans, coolers and refrigerators may have reflected in increased feeder consumption during summer months.

3.2 Effect on Feeder Parameters

We thus see that, improved availability of supply leads to increase in consumption. Further, to verify the change in mean consumption of electricity for pre and post LS periods in the rural residential feeders, T-test was carried out. Fig. 8 shows the difference in mean electricity consumption for pre and post-LS periods for the feeders under 2 different substations. Eq. 1 is used to estimate the difference in mean monthly consumption. We can observe here that, increase in consumption of feeders under Mhasa substation ranges from 20 to 30 MWh/month. Similarly, the difference is as high as 70 MWh/month in the Vaitarana feeder of Khardi substation. Nevertheless, all the feeders showed increase in electricity consumption due to the reduction in load shedding. Load growth factor needs to be considered to estimate the increase in electricity consumption only due to reduced LS. However, for a rural residential feeder, it is difficult to get the actual load growth data, as historical consumption data beyond 3-4 years is not available.

$$\mu = \mu_{NLS} - \mu_{LS} \qquad (1)$$

where, μ – computed difference, μ_{NLS} – mean of non-load shedding months, μ_{LS} – mean of load shedding months.

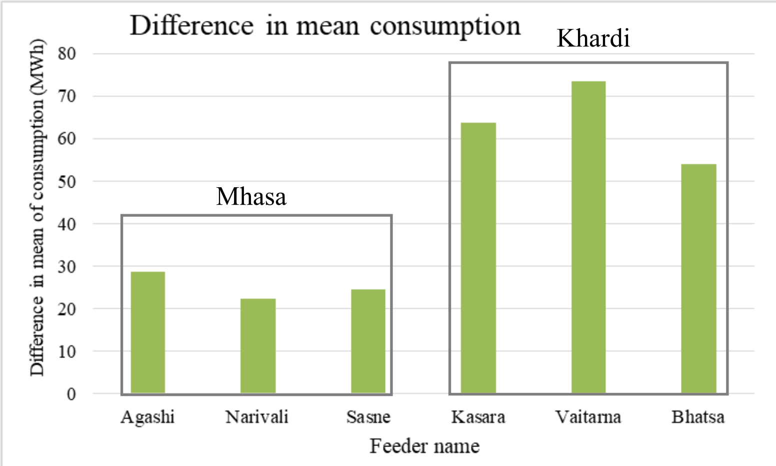
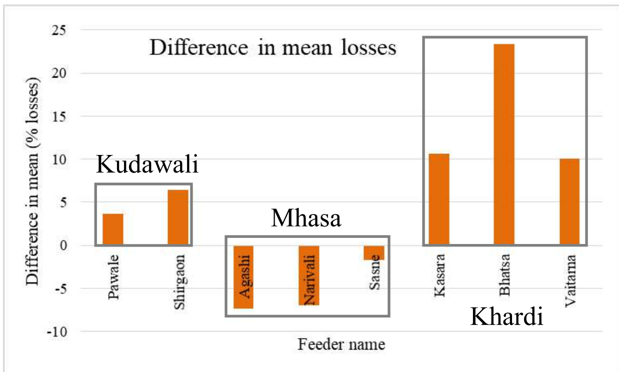


Fig. 8 Difference in mean consumption

Difference between LT sale and LT input is considered as AT&C losses on the feeder. Load shedding on a particular feeder was decided on the basis of DCL, which is a function of bill collection efficiency, technical and non-technical/commercial losses (AT&C). Higher the DCL, more would be the load shedding, before June 2015. Irrespective of losses on the feeder, ~24 hours of supply shall be available after June 2015 as per DISCOM policy. Thus, to capture the effect of reduced LS on AT&C losses, T-test was conducted for the study period. Fig. 8 gives the difference between mean losses (%) pre and post-load shedding. AT&C losses on the feeders of Khardi substation have increased by about 15% after load shedding is reduced. Feeders under Kudawali substation also show 5% increase in losses. This could be attributed to increased un-metered consumption after reduction in load shedding. On the other hand feeders under Mhasa substation show reduced losses.



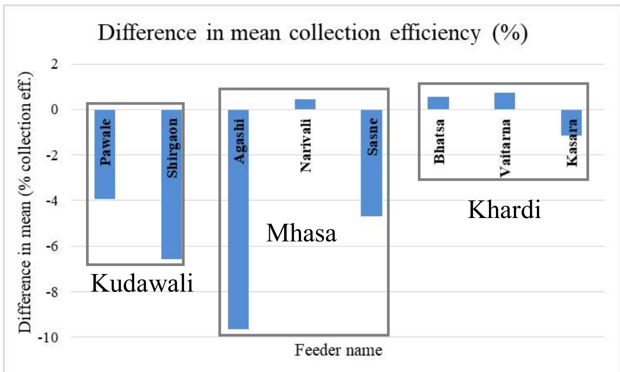


Fig. 9 Difference in mean losses (%)

Fig. 10 Difference in mean collection efficiency

Bill collection efficiency is effectiveness of revenue generated after the sale of electricity for a utility, region or a feeder. It is also a measure of paying ability of the consumers which intern affects the economic health of the DISCOM. The analysis shows the effect on collection efficiency due to the uninterrupted supply in the region. T-test is used to see the mean difference between collection efficiency for LS and NLS months. Collection efficiency on the feeders of Mhasa and Kudawali substation has reduced as shown in Fig. 9. Reduced collection efficiency might be the implication of paying ability of consumers have not changed though consumption has increased as the availability increased. Marginal change in collection efficiency for feeders under Khardi substation is observed, as the collection efficiency was close to 95%. This has significant implications on the policy and the pattern needs to be analyzed across a larger number of feeders.

3.3 Reliability index

Reliable power supply is necessary to run income generating activities. Refrigerators in shops, cold storage for drugs, hospital and schools, flour mill, water (drinking) pumps and other electricity dependent income generation activities need to know about power outages so that they can effectively plan their back up and/or end use. There are various reliability indices used by DISCOMs to show region wise performance of reliability of power supply. Reliability indices are calculated based on number of consumers, connected load, duration and frequency of interruptions. These indices are defined by international standards known as IEEE 1366 [12]. An interruption of greater than 5 minutes is generally considered a supply reliability issue. The most common supply distribution indices are System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), System Average Interruption Frequency Index (SAIFI), Momentary Average Interruption Frequency Index (MAIFI), Customer Average Interruption Frequency Index (CAIFI), Customers Interrupted per Interruption Index (CIII), and the Average Service Availability Index (ASAI).

SAIDI is commonly used for reliability due to sustained interruptions. It measures the total interruption duration for the average customer for given period (Eq. 2).

$$SAIDI = \frac{\sum Customer\ interruption\ duration}{Total\ number\ of\ customers\ served} \qquad (2)$$

Feeder interruptions are the minimum number of interruptions faced by the consumer. Thus for calculation of SAIDI, customer interruption is calculated using interruptions on feeder and its respective number of consumers. Load shedding outages are also considered while calculating the reliability index.

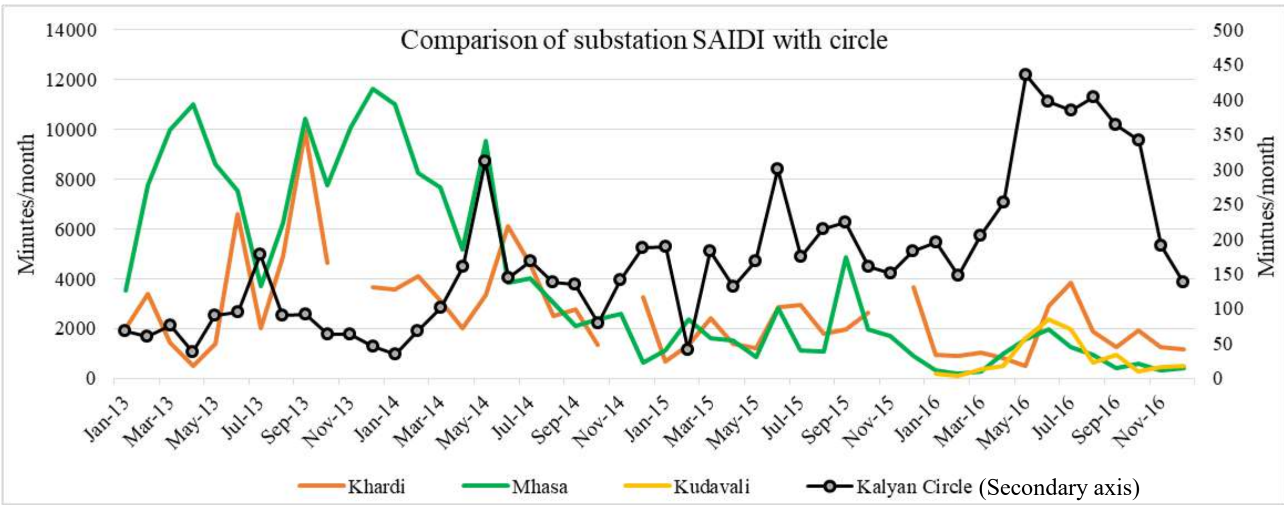


Fig. 11 SAIDI of substations and Kalyan circle

Total number of consumers is limited to substation's consumers. Substation SAIDI is then compared with SAIDI of entire Kalyan circle as shown in Fig. 11. Following are the observation comparing substation reliability with the Kalyan circle:

- Reliability of rural residential feeders under all substations has improved after June 2015, as load shedding has been almost removed.
- Even after the removal of load shedding SAIDI of rural substation remains 5 times higher than Kalyan circle SAIDI.
- We can clearly observe that substation's SAIDI is far less than SAIDI of Kalyan circle before removal of load shedding.
- In the year 2016, SAIDI of Kalyan circle seems to follow same trend as SAIDI of rural substations.
- Difference between the SAIDI of circle and rural substation shows us urban and rural divide for reliable power supply.

4. Discussion and Conclusion

The present study shows the variation in electricity consumption by considering the effect of seasonality and reduced load shedding on the rural residential feeder.

- It is observed that during summer months, the variation in consumption is significantly high during load shedding period and it is lesser when the LS is removed. Wide range of consumption during summer months compared to the other seasons shows the effect of variability in supply availability during those months and the increased end uses.
- However, with reduction in load shedding, not only electricity consumption during summer increased significantly, the range reduced, showing similar consumption level throughout the season. Intuitively, one can say that, with the increase in electricity availability and increased consumption, AT&C losses are expected to increase (without technical efforts improve T&D losses).
- The present study shows that, though improved electricity availability might increase the losses, the case of Mhasa substation in the present study, shows the possibility to reduce losses. Nevertheless, absolute figures of losses of all the feeders are extremely high (ranging from 21.1% on Kasara to 61.2% on Narivali), which seeks immediate attention of policy makers and DISCOMs.
- Bill collection efficiency, also seem to have reduced during no LS period (for Kudawali substation from 95% to 85%). It is important to pay attention here on the policy initiative; though the DISCOMs try to break the vicious circle (low bill payment from consumers due to unreliable supply and lesser supply because of lower collection efficiency), through removing LS, has not improved the bill collection efficiency during the studied period (about 1 year). This is an important insight for policy makers to tackle the issue of lower bill collection efficiency in the early stage which would otherwise lead to mounting of unpaid electricity consumption, faster than before.
- After the removal of load shedding, reliability of supply has improved on rural residential feeders but it still has far more SAIDI when compared to the SAIDI of same circle.

As the study was undertaken for the feeders under 3 substation of Kalyan region, all the results are case specific. Generalizing the results is beyond the scope of the present research. It is observed that the electricity consumption of rural residential feeders is affected by seasonality and availability of supply. The effect of the improved supply on collection efficiency and losses varied for different substations.

5. Policy Recommendations

The Government of India has launched the Ujwal DISCOM Assurance Yojana (UDAY) in 2015, which aims to improve the financial health of DISCOMs in the country. On the other hand 24*7 Power for All has ambitious target of providing 24 hours supply to all consumers by March 2019. However, it is important to assess whether rural consumers can afford this availability of supply. If rural consumers are not able to pay for their consumption, DISCOMs won't be able to generate sufficient revenue returns. This will hamper the targets of UDAY scheme. Thus, the study recommends evidence based policy solution to address the financial status of DISCOMs and giving better quality of supply to consumers at the same time. There is a need of comprehensive approach in policy making, so as to enable the economic development and livelihood opportunities with the better access and reliable electricity supply.

Electricity access is only measured in terms of having an electricity connection in the household. To have a meaningful electrification program this measure needs to go beyond just giving electricity connection and should measure the supply availability and reliability for those connections. Overall performance indicator of any region overlaps poor supply availability and reliability on rural feeders. Thus these performance indicators needs to be measured separately to see the actual development of rural electrification programs.

The present study can be extended with the availability of hourly load data and timings of interruptions. This would help in analyzing the effect of availability on loading pattern and to estimate the cost of lost load. This would also give insights on change in loading pattern with the change in load shedding. The scope of the study can be extended to substations and/or other feeders of different regions of the state to have the deeper understanding and develop the patterns of availability-consumption trends. Further, through a micro level analysis in future, one can link the change in reliability and availability of electricity supply with the impact on development and livelihood activities of region.

Acknowledgments

The authors are thankful to the Maharashtra State Electricity Distribution Company Limited officials for providing the necessary data and to the staffs of Kudawali, Mhasa and Khardi substations for the cooperation during data collection and field visits. We would like to thank Centre for Technology Alternatives for Rural Areas (CTARA), Indian Institute of Technology Bombay for the support during this research.

References

[1] Rao N.D. (2013). Does (better) electricity supply increase household enterprise income in India?, *Energy Policy*, 57, pp. 532–541.

[2] Khandker S.R., Barnes D.F. and Samad H.A. (2010) Energy poverty in rural and urban India: are the energy poor also income poor?, *Policy Research Working Paper Series 5463*. Washington, D.C., World Bank.

[3] TERI, (2015). Analyzing Rural Energy Transitions and Inequities, *TERI-NFA Project Report,* The Energy and Resources Institute

[4] Jain A., Ray S., Ganesan K., Aklin M., Cheng C.Y., and Urpelainen J. (2015) Access to Clean Cooking Energy and Electricity: Survey of States, *CEEW Report* - September 2015.

[5] Yemane W.R. (2006) Electricity consumption and economic growth: a time series experience for 17 African countries, *Energy Policy*, 34(10), pp. 1106–1114.

[6] Pachauri S. and Jiang L. (2008) The household energy transition in India and China, *Energy Policy*, 36, pp. 4022-4035.

[7] Chaurey A, Ranganathan M. and Mohanty P. (2004) Electricity access for geographically disadvantaged rural communities-technology and policy insights *Energy Policy*, 32(15), pp. 1693–1705.

[8] World Bank (2000). *Energy and Development Report: Energy Services for the World's Poor*. World Bank Report 2000, Washinton D.C.

[9] Bhattacharyya S.C. (2010) Energy access problem of the poor in India: Is rural electrification a remedy? *Energy Policy*, 34, pp. 3387-3397.

[10] Ramji A., Soni A., Sehjpal R., Das S. and Singh R. (2012) Rural energy access and inequalities: An analysis of NSS data from 1999-00 to 2009-10, *TERI-NFA Working Paper No. 4*, The Energy and Resources Institute.

[11] Power for All Maharashtra (2014), A Joint Initiative of Government of India (GoI) and Government of Maharashtra, http://powermin.nic.in/en/content/power-all (accessed on 10th January 2018)

[12] IEEE Standard 1366-2012 (Revision of IEEE Std 1366-2003) - IEEE Guide for Electric Power Distribution Reliability Indices

PROSPECTS OF DC MICROGRID IN TIRUVANNAMALAI DISTRICT, TAMILNADU

V.Saravanan[1], M. Aravindan[2], V. Balaji[3], M. Arumugam[4]

[1,4] Department of Electrical & Electronics Engineering, Arunai Engineering College, Tiruvannamalai 606 603, Tamilnadu, India
[2]Research Scholar, SCSVMV University, Kancheepuram, & Assistant Executive Engineer / O & M / Mambakkam, Tamilnadu Generation and Distribution Corporation, Tamilnadu, India
[3]School of Electrical Engineering, Bahir Dar University, Ethiopia
[1,4]Phone: 04175 255101, +91 9994062645, [1,4]Fax: 04175 237789
Email: [1]vsaranaec@yahoo.co.in,[2] puduaravindam@gmail.com [4]drmarumugam@yahoo.com

ABSTRACT: A well planned DC microgrid (DC MG's) is expected to provide various functionalities like stability, power quality, coordinated control, grid support capability. Moreover, a DC MG's with proper integration of renewable energy sources should have features like redundancy, flexibility and scalability from architecture point of view. In this work, a DC microgrid project is suggested to rural part in Tiruvannamalai district with hybrid energy systems

Key words: DC microgrid, solar, wind, Hydel, Co generation, architecture, control strategies, protection

1. INTRODUCTION

Energy is one of the key infrastructural requirements needed to realize high economic, sustained and inclusive growth of a country. The key objective is to meet the growing demand of energy in an efficient, economically viable, and environmentally sustainable manner. Distributed generation (DG) systems based on renewable energy resources play an important role in electric power systems for addressing energy security needs and sustainable development. Renewables contribute around 18.18% to the total grid power installed capacity in the country as on November 2017. The estimated share of these resources in electrical networks will increase significantly in the near future by providing different benefits like cost reduction, reliability of main grid, and emission reduction.[1]

Ministry of New and Renewable Energy (MNRE), Government of India had issued a draft policy for mini and micro grids for the country in June 2016. This policy aims to increase microgrid capacity to 500 MW in the next five years in the private sector. This includes the deployment of roughly 10,000 renewable energy based mini and micro scale projects averaging 50 kW across the country. Some highlights of the policy include: 1) regulated price determination for mini grid projects (with tariff determination flexibility provided to operators), 2) the provision of single-window clearances for seeking right of way and regulatory approvals, and the availability of information on taxes, 3) local village committee creation to ensure payment collection, customer adoption, and easier dispute resolution, 4) grid connection provision to enable the sale of power to utilities, 5) renewable purchase obligation multiplier to make interconnections enabling attractive options for distribution companies, the specification of standards, performance, and quality. The following are the voltage and power levels for the DC micro grids mentioned in the policy: 1)24-Vdc systems up to 1 kWp capacity, 2) 72-Vdc systems for more than 1 kWp and up to 10 kWp capacity. Most of the successfully implemented microgrid projects employ mini hydro, solar PV, biomass and wind as source of power generation.[2]

The concept of microgrid is established in India with micro hydroelectric (hydel) power generation commissioned in 1897 at Darjeeling. The main benefits of using dc power distribution are: 1) significant energy savings because of a reduced number of energy conversion (ac to dc and vice versa) processes. 2) savings of between 20 and 50% of electricity with dc electrical loads, such as light-emitting diode (LED) lights, fans with brushless dc motors, and other dc-powered electronics, compared to ac powered appliances, such as compact fluorescent lamp (CFL) lighting and induction motors connected with ac adapters. Few solar-powered 48-Vdc power distribution system/ dc microgrid has been implemented in school/rooftop apartments in India [3]-[6]

2. DC MICROGRID: FEATURES, TYPES AND STRUCTURES

Microgrid has the attributes like higher reliability, improved power quality, reduced emissions, reduced network congestion/power losses, increased energy efficiency, natural interface with renewable energy sources (RESs), electronic loads and energy storage systems (ESSs). Microgrids can also eliminate investments on additional generation and transmission facilities to supply remote loads. Moreover, microgrids islanding capability in the event of faults or disturbances in upstream networks would enhance grid and customers' reliability and resilience. [7, 8]

Microgrids can be categorized into different groups based on the type (such as campus, military, residential, commercial, and industrial), the size (such as small, medium, and large scales), the application (such as premium power, resilience-oriented, and loss reduction), and the connectivity (remote and grid-connected). Based on the voltages and currents adopted in a microgrid, however, three microgrid types can be identified: 1) ac; 2) dc; and 3) hybrid. In ac micro grids, all distributed energy resources (DERs) and loads are connected to a common ac bus. DC generating units as well as energy storage will be connected to the ac bus via dc-to-ac inverters, and further, ac-to-dc rectifiers are used for supplying dc loads. In dc micro grids, however, the common bus is dc, where ac-to-dc rectifiers are used for connecting ac generating units, and dc-to-ac inverters are used for supplying ac loads. In hybrid micro grids, which could be considered as a combination of ac and dc micro grids, both types of buses exist, where the type of connection to each bus depends on the proximity of the DER/load to the bus.

A general structure of dc micro grids is shown in Fig. 1(a). In dc micro grids, three-phase ac-to-dc rectifiers and transformers are required to connect ac DERs to the common bus, single- and three-phase dc-to-ac inverters are needed for supplying ac loads, and a three-phase dc-to-ac/ac-to-dc converter, a transformer, and a point of common coupling switch are required for connecting the microgrid to the utility grid. The direction of arrows in figure shows the direction of power flow. Also different dc loads require different dc voltage levels, so dc-to-ac converters have to be considered as well in order to change the voltage level of the dc sources to desired levels. A common DC bus can represent one or more loop/radial distribution networks that connect loads and DERs within the microgrid to handle dc voltages and currents. In a DC grid system, the energy sources and power electronic loads can be supplied more effectively and efficiently by choosing a suitable voltage level and thereby avoiding a few conversion stages as shown in Fig. 1(b). Furthermore, the Energy Storage System (ESS) can be directly connected to the main DC bus or connected via a DC-DC converter. [9, 10]

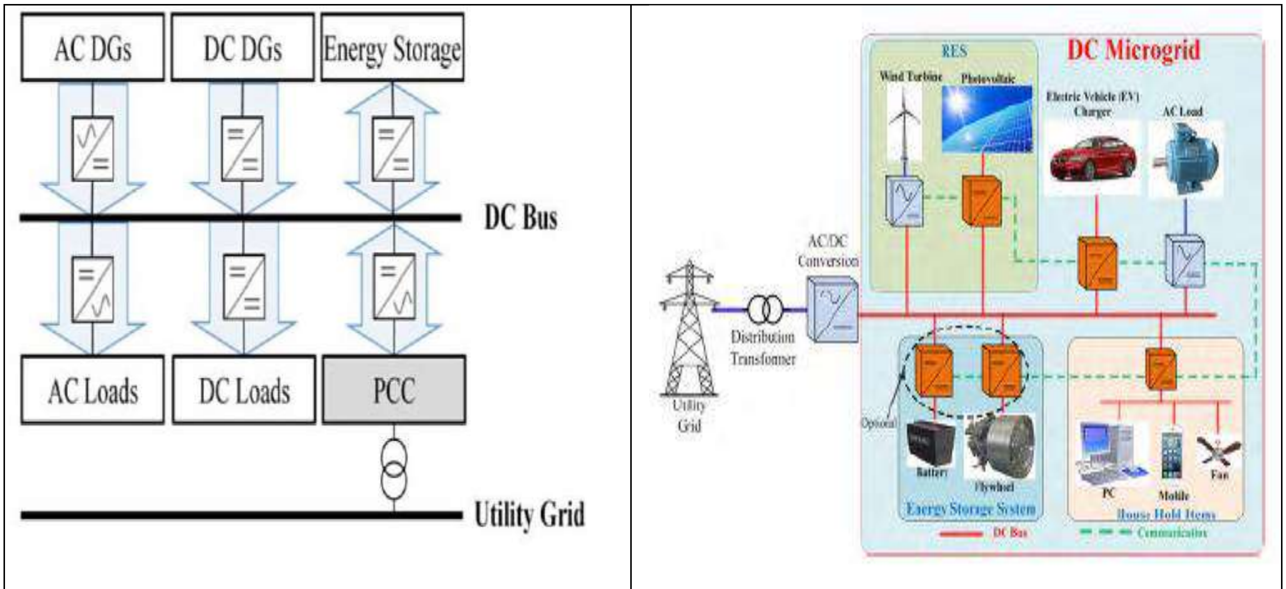


Fig. 1. (a) General structure of dc micro grids. (b) Building block of dc micro grids.

3. DC MICROGRID IN TIRUVANNAMALAI DISTRICT: PROPOSED SYSTEM

Tiruvannamalai district lies between 11° 55' and 13° 15' North latitude and 78° 20' to 79° 50' East longitude. It has 4 municipalities, 18 town panchayat, 10 special panchayat and 860 village panchayat covering an area of about 6188 square km. The average maximum and minimum temperature throughout the year is about 36.7^{o} C and 22.4^{o} C. The following details are obtained from district statistical hand book during the year 2016 – 2017. The power consumption of low tension loads like agriculture, domestic, commercial and public lighting accounts about 1771.93 million units (MU). The instantaneous and sustained peak demand is about 307.13 MW and 274.79 MW respectively.The main source of power generation in Tiruvannamalai district is through hydel power generation from Sathanur dam of capacity 7.5 MW, generating about 9.3644 million units (MU). Private Sugar mills viz Bannari Amman (28.8 MW), Dharani (15MW) have exported 63.87 MU and 28.47 MU to the utility. Private Solar PV system of capacity 30 MW by M/s. Shapooriji Pallonji Solar PV Private limited exported 46.97 MU to the utility. Tiruvannamalai district has three 230/110 kV substations (SS) in Tiruvannamalai, Arni, Echur and nineteen 110/33/22/11 kV SS and forty seven 33/11 kV SS.[11].As per Report on Green Energy Corridors (Transmission Plan for Envisaged Renewable Capacity) by Power Grid Corporation of India Limited, Gurgaon (Vol. 1, July 2012), Tiruvannamalai district is envisaged to have solar power generation upto 175 MW.

The proposed DC microgrid system has hybrid systems consisting of solar, wind, small hydel and co generation from sugar mills. Permanent magnet synchronous generator (PMSG) is selected for extracting wind power considered because it does not require a dc excitation system, also suitable for this geographical location. The Z source converter is used to regulate the DC power obtained from the PV panels. Z source network constitutes the optimally designed inductor and capacitor to ensure better voltage boosting to overcome the fluctuations due to solar - wind resources. The AC power obtained from PMSG is converted into DC power by means of bridge rectifier. The combined DC power is then given to the proposed cascaded Z source H bridge multilevel inverter through a common dc link to obtain sinusoidal AC power, which is then connected to the electric grid. The proposed cascaded Z source H bridge multilevel inverter can be extended with more H bridge cells, needed for future capacity addition. The proposed Z source converter/ inverter ensure wider voltage regulation. It can achieve the distributed maximum power point (MPP) tracking (MPPT) to increase the system efficiency and achieve high voltage/high-power grid tie without a transformer and battery. The schematic diagram of the proposed dc/ac micro grid is shown in the Figure. 2.

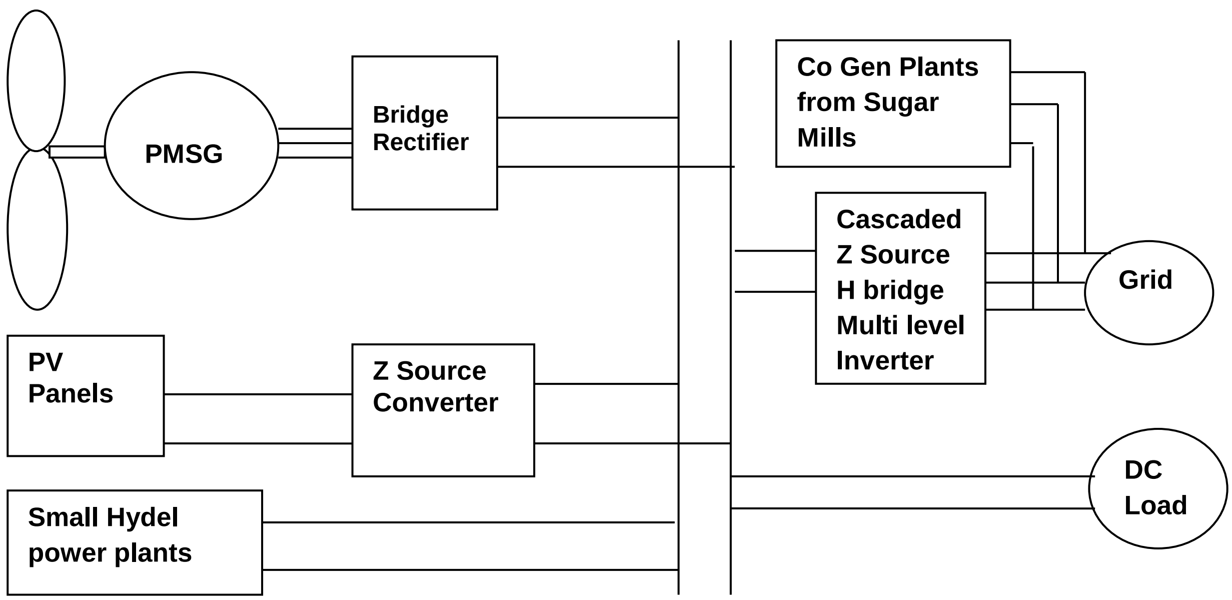


Fig. 2 Proposed architecture of hybrid renewable energy generation system in a DC microgrid.

4. DC MICROGRID: PROTECTION CHALLENGES AND CONTROL AND NETWORK CONFIGURATION ISSUES

A microgrid is well suited to protecting sensitive loads from power outages. High reliability can be obtained by utilizing the power-electronic interfaces of the distributed resources, together with fast protection systems. A LV dc microgrid must be connected to an ac grid through converters with bidirectional power flow and, therefore, a different protection system design is needed. A salient property of the DC microgrid architecture is the distributed control of the grid voltage, which enables both instantaneous power sharing and a metric for determining the available grid power. Overall control of DC micro grid is classified into local and coordinated control levels according to respective functionalities in each level. As opposed to local control which relies only on local measurements, some line of communication between units needs to be made available in order to achieve coordinated control. Depending on the communication method, three basic coordinated control strategies can be distinguished, i.e. decentralized, centralized and distributed control as shown in Fig.3. Decentralized control can be regarded as an extension of local control since it is also based exclusively on local measurements. In contrast, centralized and distributed control strategies rely on digital communication technologies. [12] - [16]

From communication perspective, overall control of DC MGs can be divided into the following three categories as : i) Decentralized control: DCLs do not exist and power lines are used as the only channel of communication, ii) Centralized control: Data from distributed units are collected in a centralized aggregator, processed and feedback commands are sent back to them via DCLs. Iii) Distributed control: DCLs exist, but are implemented between units and coordinated control strategies are processed locally.

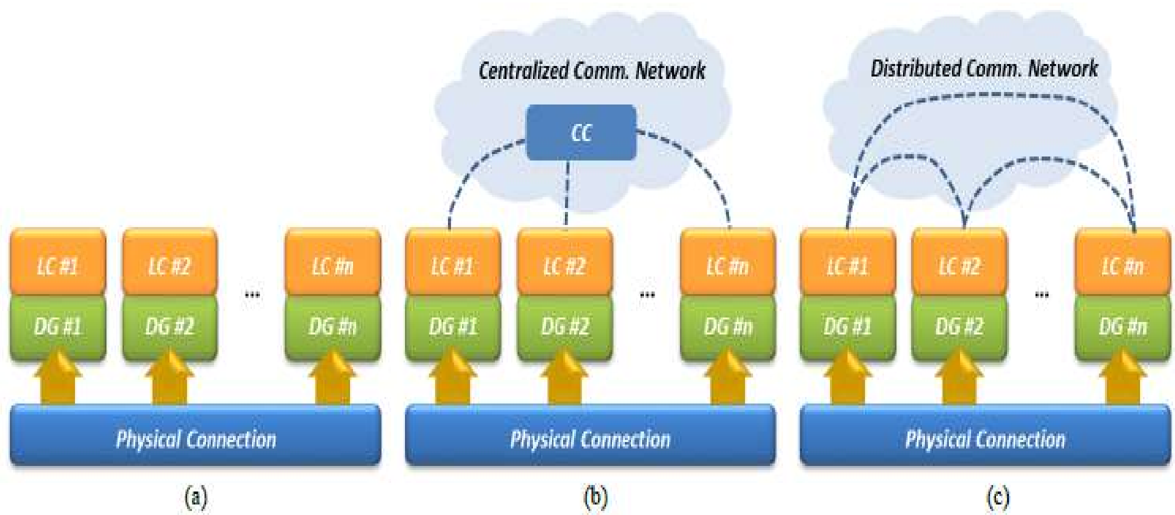


Fig. 3. Operating principles of basic control strategies.
(a) Decentralized control. (b) Centralized control. (c) Distributed control.

There are some obstacles in the practical implementation of the DC microgrid, which are: 1) Protection of the DC grid system is more difficult compared to the AC distribution system as there is no natural zero crossing of the current, 2) Transition from AC to DC system in low voltage distribution networks requires several stages such as new standards for products and voltage levels, 3) Grounding and corrosion issues in DC systems. An interface with the AC grid is very important in order to improve the reliability and availability of power in a DC microgrid system. There are a few options to interface a DC microgrid with an AC grid such as, radial configuration, ring or loop configuration and interconnected configuration such as mesh type and zone type configuration. The most common power quality issues in DC microgrid system are: Voltage transient from AC grid, Harmonics due to resonances and power electronics based converters, Electromagnetic Interference Compatibility (EMC) issues, Communication failures, Inrush currents, DC bus faults, Voltage unbalance in bipolar DC bus and circulating currents. [17] -[19]

5. TECHNO ECONOMICAL ASPECTS, STANDARDS OF DC MICROGRID PROJECTS

DC micro grids offer several advantages such as: 1) higher efficiency and reduced losses due to the reduction of multiple converters used for dc loads; 2) easier integration of various dc DERs, such as energy storage, solar photovoltaic (PV), and fuel cells, to the common bus with simplified interfaces; 3) more efficient supply of dc loads, such as electric vehicles and LED lights; 4) eliminating the need for synchronizing generators, which enables rotary generating units to operate at their own optimum speed; and 5) enabling bus ties to be operated without the need for synchronizing the buses. These benefits, combined with the significant increase in dc loads such as personal computers, laptop computers, LED lights, data and telecommunication centers, and other applications where the typical 50- and 60-Hz ac systems are not available, could potentially introduce dc micro grids as viable and economic solutions in addressing future energy needs. The available DC microgrid standards are listed in the following table. 1.

Table: 1 DC Microgrid Standards

Sl.No.	Standards	Specifications
1	International Electrotechnical Commission	IEC 62040-5-3, IEC 61643-3 and IEC 61643-311
2	The Institute of Electrical and Electronic Engineering Standard Association (IEEE-SA	WG946, P2030.10, IEEE DC@Home
3	Emerge Alliance	EMerge Alliance Occupied Space Standard, EMerge Alliance Data/Telecom Center Standard
4	European Telecom Standard Institute (ETSI)	ETSI EN 300 132-3-1
5	International Telecommunication Union (ITU)	ITU L.1201/1202/1203
6	Chinese Communication Standards Association (CCSA)	YD/T2378-2011, YD/T 3091-2016

:

DC micro grids can be economical in following cases: 1) when the ratio of dc loads is high, 2) It can be installed with PV based power generation as its generation pattern matches with the market price and load variations. 3) suitable in the case of critical loads, thereby decreasing the operational cost and increasing the reliability. Application of DC micro grids are: 1) Commercial and residential building, 2) Industrial systems, 3) data centers, 4) Telecommunication systems, 5) Electric vehicle fast charging stations, 6) Traction/Ship/marine/aircraft systems.[20,21]

6. CONCLUSIONS

DC micro grid with hybrid power generation and decentralized storage is the simplest, reliable, cost effective, scalable and highly efficient solution to provide access to electricity to people living without access to electricity. DC grids have been resurging due to technological advancements in power electronics and energy storage devices, and increase in the variety of dc loads. For successful implementation of DC micro grids project, proper planning and development, effective construction, reliable energy generation and power delivery is required.

Best operation and maintenance activities including constant plant monitoring and control, preventive maintenance, fault detection and response and corrective action was needed.

ACKNOWLEDGEMENTS

This work was supported by Wind Energy Division, Ministry of New & Renewable Energy, Government of India under financial grant (IFD Dy. No. 1429 dated 04/11/2016, Demand No. 61/69, Budget Head: 2810.00.104.04.05.31/35).

REFERENCES:

1. Installed Capacity, November 2017, Central Electricity Authority, Ministry of Power, Government of India, http://www.cea.nic.in/monthlyinstalledcapacity.html (Accessed on 15.12.2017)
2. http://mnre.gov.in//[Accessed on 15.12.2017]
3. Discussions and deliberations by V. Saravanan at ISGAN Knowledge Exchange on Distributed Generation, Microgrids and Smart Metering organized by the International Smart Grid Action Network (ISGAN), in partnership with National Smart Grid Mission, Ministry of Power, Government of India at Central Power Research Institute, Bengaluru, India on 14 November 2017.
4. Vijay A. Subramony, Suryanarayana Doola, Mukul Chandorkar, “Microgrids in India: Possibilities and Challenges”, IEEE Electrification Magazine, pp. no. 47 -55, June 2017.
5. Krishna Shenai, Ashok Jhunjhunwala, Prabhjot Kaur , “Electrifying India: Using solar dc microgrids”, IEEE Power Electronics Magazine, Vol.3, No.4, pp.no. 42-48, 2016.
6. Ashok Jhunjhunwala, Aditya Lolla, Prabhjot Kaur , “ Solar-dc Microgrid for Indian Homes: A Transforming Power Scenario”, IEEE Electrification Magazine , Vol. 4, No.2, pp.no. 10 -19, 2016.
7. Hossein Lotfi, Amin Khodaei , “AC Versus DC Microgrid Planning”, IEEE Transactions on Smart Grid, Vol.8, No.1, pp.no. 296 – 304, 2017.
8. Mashood Nasir, Hassan Abbas Khan, Arif Hussain, Laeeq Mateen, Nauman Ahmad Zaffar,"Solar PV-Based Scalable DC Microgrid for Rural Electrification in Developing Regions”, IEEE Transactions on Sustainable Energy, Vol.9, No.1, pp.no. 390-399, 2018.
9. Parimalram Achintya Madduri, Jason Poon, Javier Rosa, Matthew Podolsky, Eric A. Brewer, Seth R. Sanders ,“Scalable DC Microgrids for Rural Electrification in Emerging Regions”, IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 4, No.4, pp.no. 1195 -1205, 2016.
10. K. T. Tan, B. Sivaneasan, X. Y. Peng, P. L. So, “Control and Operation of a DC Grid-Based Wind Power Generation System in a Microgrid”, IEEE Transactions on Energy Conversion, Vol. 31, No.2, pp.no. 496 -505, 2016.
11. www.tiruvannamalai.tn.nic.in/District statistical Handbook_2016- 2017.pdf[Accessed on 15.12.2017]
12. Daniel Salomonsson, Lennart Soder, Ambra Sannino, “Protection of Low-Voltage DC Micro grids”, IEEE Transactions on Power Delivery, Vol.24, No.3, pp.no. 1045 -1053, 2009.

13. Josep M. Guerrero, Mukul Chandorkar, Tzung-Lin Lee, and Poh Chiang Loh, “Advanced Control Architectures for Intelligent MicroGrids – Part I: Decentralized and Hierarchical Control” , IEEE Transactions on Industrial Electronics, Vol.60, No.4, pp.no.1254 – 1262, 2013.
14. Josep M. Guerrero, Poh Chiang Loh, Tzung-Lin Lee, Mukul Chandorkar, “Advanced Control Architectures for Intelligent Microgrids—Part II: Power Quality, Energy Storage, and AC/DC Microgrids”, IEEE Transactions on Industrial Electronics**,** Vol.60, No.4, pp.no.1263 – 1270, 2013.
15. Mahesh Kumar; S. C. Srivastava; S. N. Singh, “Control Strategies of a DC Microgrid for Grid Connected and Islanded Operations”, IEEE Transactions on Smart Grid, Vol.6, No.4, pp.no. 1588 -1601, 2015.
16. Lexuan Meng, Qobad Shafiee, Giancarlo Ferrari Trecate, Houshang Karimi, Deepak Fulwani, Xiaonan Lu, and Josep M. Guerrero, “ Review on Control of DC Micro grids”, IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol.5, No.3, pp.no. 928 -948, 2017.
17. Tomislav Dragičević, Xiaonan Lu, Juan C. Vasquez, Josep M. Guerrero, “DC Micro grids—Part I: A Review of Control Strategies and Stabilization Techniques”, IEEE Transactions on Power Electronics, Vol.31, No.7, pp.no. 4876 -4891, 2016.
18. Tomislav Dragičević, Xiaonan Lu, Juan C. Vasquez, Josep M. Guerrero, “DC Microgrids—Part II: A Review of Power Architectures, Applications, and Standardization Issues”, IEEE Transactions on Power Electronics, Vol.31, No.5, pp.no. 3528 -3549, 2016.
19. Dinesh Kumar; Firuz Zare; Arindam Ghosh ,“DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects”, IEEE Access, Vol.5, pp. no. 12230 – 12256, 2017.
20. https://www.schneider-electric.co.in/en/product-range-presentation/62210-dc-micro-grid#tabs-top [Accessed on 30.12.2017]
21. http://w3.usa.siemens.com/smartgrid/us/en/microgrid/pages/microgrids.aspx [Accessed on 30.12.2017].

Biodata of the Head Researcher:

Dr. V. SARAVANAN, received his B.E, M.E and Ph. D in Electrical & Electronics Engineering from University of Madras, in 2001, M.E. in Power System from Annamalai University, Chidambaram, in 2005 and Ph.D. degree in the Department of Electrical & Electronics Engineering, College of Engineering, Guindy, Anna University, Chennai in 2013. His research interests include Z Source Inverters, Solar photovoltaic power systems. He is working as Associate Professor in Department of Electrical & Electronics Engineering, Arunai Engineering College (AEC), Tiruvannamalai, Tamilnadu and holding the responsibility as Head/PG/EEE. He carrying out R & D activities at AEC sponsored by Central Power Research Institute, Bangalore and Ministry of New and Renewable Energy, Government of India in the area of renewable energy systems. He published more than 55 research papers in National/International Journals/Conferences/Exhibitions. He guided few projects which won Indian Electrical & Electronics Manufacturers Association (IEEMA) and Indian Society for Technical Education (ISTE) awards. He received ISTE- Stripes of Redeemer National Award for the Best ISTE Chapter Chairman (College) for the year 2014 by Indian Society for Technical Education (ISTE), New Delhi. He is member of Institution of Electrical and Electronics Engineers (IEEE), Indian Society for Technical Education (ISTE) and International Association of Engineers(IAENG). He is a reviewer of selected SCI Journals and Technical/Advisory committee member of National/International Conferences. He visited countries like Germany and Singapore through state sponsored events.

He can be contacted at Phone: 04175 255101, Fax: 04175 237789, Mobile: +91 9994062645. Email: vsaranaec@yahoo.co.in, vsaranaec@gmail.com.

A novel approach for improvement of the system power factor by optimally placed DG and STATCOM in distribution systems

Bindeshwar Singh
Kamla Nehru Institute of Technology (KNIT),
Sultanpur, Uttar Pradesh, India
bindeshwar.singh2025@gmail.com

Prabhakar Tiwari
Madan Mohan Malviya Technical University,
Gorakhpur, UP, India
profptiwari@gmail.com

S. N. Singh
Indian Institute of Technology, Kanpur
(Vice-Chancellor, Madan Mohan Malviya Technical University, Gorakhpur, UP, India)
snsingh@iitk.ac.in

***Abstract*—This paper presents a a novel approach such as hybrid approach based on Genetic Algorithms (GA) and Monte Carlo Simulation (MCS) are used as a optimization technique of objective function such as minimization of real power loss of the system for improvement of the system power factor (SPF) by optimally placed distributed generations (DG) (such as T2 operating at different power factors i.e. 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) and incorporated static synchronous compensator (STATCOM) with different load models (DLMs) such as constant load models (CONL), industrial load models (INSL), residential load models (RESL), commercial load models (COML) and reference load models (REFL), in distribution systems from minimum total real power loss of the system viewpoint. In this paper, T2 type of DG is considered on the basis of real and reactive power delivered/absorbed characteristics from the system bus. Optimally placed DG incorporated with STATCOM can work in different modes of operations such as generating, floating and load modes, respectively in distribution systems with different loading conditions. The proposed methodology has been tested for IEEE-16 bus test system. This work is very much useful for researchers and scientific persons regarding the improvement of the SPF by optimally placed DG and STATCOM with DLMs in the distribution systems from minimization of real power loss of the system.**

Keywords*— *Distributed generation (DG), Static synchronous compensator (STATCOM), Distribution systems, Different load models (DLMs), Genetic algorithm (GA), Monte corlo simulations (MCS).

***Abbreviationss*—**

COML	Commercial load models	INSL	Industrial load models
CONL	Constant load models	LFA	Load flow analysis
DLMs	Different load models	MCS	Monte carlo simulation
DISCO	Distributed company	RESL	Residential load models
DGs	Distributed generations	REFL	Reference load models
DSs	Distributed systems	PF	Power factor
GA	Genetic algorithms	STATCOM	Static-synchronous compenstor

***Symbols*—**

DG-T2	T2 type Distributed generation	P_{STAT}, Q_{STAT}	Real power and reactive power delivered to the system by STATCOM (0 p.u.)
α	Real power exponent	*f*	Supply frequency (50Hz)
β	Reactive power exponent	OPF	Operating power factor
P_{m_bus}	Real power of static load (p.u.)	PF_{sys}	System power factor without DG and STATCOM
Q_{m_bus}	Reactive power of static load (p.u.)	$PF_{sys+WDG}$	System power factor with DG
P_L	Real power loss of the system (p.u.)	$PF_{sys\_WDG+STAT}$	System power factor with DG and STATCOM
P_{intake_sys}	Real power intake of system (p.u.)	ld	Leading power factor
Q_{intake_sys}	Reactive power intake of system (p.u.)	S_{sys}	Apparent power of main substation (p.u.)
S_{intake_sys}	Apparent power intake of system (p.u.)	P_{DG}, Q_{DG}	Real power and reactive power supported to the system by DG (p.u.)

I. INTRODUCTION

In present scenario of all over world, the load demand is increasing continuously in power system networks. But with increase in load demand the generation is not increase to that much level means the generation is not sufficient to supply the huge loads. So it is difficult to manage the load demand. It is results in the overloading of the lines which causes more losses due to the over loading condition. It makes the system unstable because of the large real and reactive power demand and low voltage conditioned. It stresses the equipment into the power system and reduces its life. The solution is to place new transmission lines and extra generations. But the cost is not economical, and land problems are also occurs [1-2].In order to cope with such problems and increase usable power distribution capacity, DG technology and Flexible AC Transmission Systems (FACTS) have been developed and introduced into the market. Optimal placement and sizing of distribution generation is a well-researched subject that in recent years has been of interest to many professional engineers. Efficient placement and sizing of DG and STATCOM in practical networks can result in minimizing operational costs, environmental protection, improved voltage regulation, power factor correction, and power loss reduction [1-2]. The proposed scheme is shown in Fig.1

which shows how to optimally place and size the DG and STATCOM in distribution network. IEEE-16 bus distribution system is taken as test system.

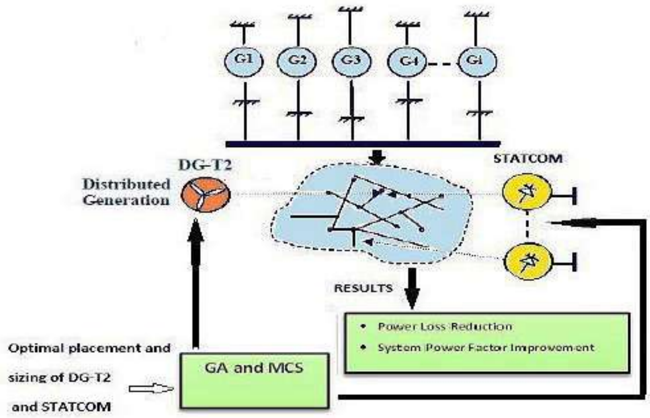


Fig.1: The proposed scheme for optimal placement and sizing of DG and STATCOM in distribution network

A. Literature Review

Belkacem Mahdad et al. [1], presented a dynamic methodology of optimal allocation and sizing of DG units for a given practical distribution network, so that the cost of active power can be minimized. The approach proposed is based on a combined Genetic/Fuzzy Rules. B. Singh et al.[3], presented a comprehensive survey on historical background of Flexible Alternating Current Transmission System (FACTS) controllers such as series, shunt, series-series, and series-shunt FACTS controllers. Nasiru B. Kadandan iet al. [4], presented a technological review on the FACTS devices used for power quality improvement especially during the integration of non-conventional sources of energy such as wind and solar into the grid network. Mehta and Mehta [5], discussed the distribution generation planning in power system form different power system performances point of view. Debabrata Kundu [6], provided a brief overview of the types of DG available. It also provides a streamlined methodology of DG connection to the GRID. A protection requirement of DG is a important factor. B. Singh et al. [7] have been presented a comprehensive survey on application of various conventional, optimization and artificial intelligence based computational techniques for impact assessment of optimally placed and coordinated control of DGs and FACTS controllers in power systems. B. Singh et al. [8] presented the impact assessment of optimally placed different types of DGs such as DG-1(T1), DG-2 (T2), DG-3 (T3), and DG-4 (T4) with DMLs by using GA in distribution systems from minimum total mega volt ampere (MVA) intake viewpoint of main substation. R. P. Payasiet.al [9], presented the multi-objective optimization for high penetration of different type of DGs considering voltage step constraint. In most of the studies in literature, the commonly used constraints are bus voltage limits and line power capacity limit. Eltaib Said Elmubarak et al.[10], presented the recent attention paid to DG is not surprising in many ways. The flaws of the centralized generation paradigm led to look for a complement generation technique, a role that was endorsed to the extent possible by the distributed generators before the energy deregulation. Kumar and Samuel [11] presented the overview of DG in power sector. Champa Nandi [12], described the SVC and STATCOM operation on voltage collapse. The critical fault clearing time obtained for the different FACTS Controllers are compared. The simulations carried out confirmed that Static Var Compensator (SVC) and STATCOM could provide the fast acting voltage support necessary to prevent the possibility of voltage reduction and voltage collapse at the bus to which it is connected. Hingorani and Gyugyi [13] discussed the understanding of FACTS concepts. Amit Garget al.[14], investigated the effects of STATCOM on voltage stability of a power system. Bisen and Shrivastava [15], discussed the comparison between SVC and STATCOM FACTS devices for power system stability enhancement. Youssef et al. [16], discussed the dynamic performance comparison between STATCOM and SVC. Payasi et al. [17], discussed the Planning of different types of distributed generation with seasonal mixed load models. Singh et al. [18], suggested the effect of load models in DG planning. Singh et al. [19], addressed the impact assessment of optimally placed different DGs with DLMs (such as DG-1, DG-2, DG-3 and DG-4) and FACTS controllers like SVC by employing GA in a distribution systems from minimum total real power loss of the system viewpoint. D. Singh et al. [22], addressed a novel technique for placement of DG in electric power systems. A GA based approach for sizing and placement of DG keeping in view of system power loss minimization in different loading conditions is explained. Minimal system power loss is obtained under voltage and line loading constraints. Proposed strategy is applied to power distribution systems and its effectiveness is verified through simulation results on 16, 37-bus and 75-bus test systems. M. Marseguerra et al.[23], presented an optimization approach based on the combination of a GA maximization procedure with a Monte Carlo simulation. The approach is applied within the context of plant logistic management for what concerns the choice of maintenance and repair strategies. Samik Raychaudhuri [24], discussed the methodology, theoretical basis, and application domains for MCS. MCS is a very useful mathematical technique for analyzing uncertain scenarios and providing probabilistic analysis of different situations. The basic principle for applying MCS analysis is simple and easy to grasp. Various software has accelerated the adoption of MCS in different domains including mathematics, engineering, finance etc. Metropolis et al.[25], discussed about MCS in detail. R.F.W. Coates et al. [26], presented the methods of generating pseudorandom number sequences that might have predetermined spectral and probability distribution functions are discussed. Such sequences are of potential value in MCS of communication, radar, and allied systems. Chen et al. [27] presented the method for optimal allocation of power-electronic interfaced wind turbines using a GA and MCS Hybrid optimization method. Payasi et al. [28] presented the multi-objective optimization of DG with voltage step constraint. Singh et al. [29], DG planning strategy with load models in radial distribution system. Yang et al. [30], presented a chance constrained programming approach to transmission system expansion planning. Peng et al. [31], proposed a novel approach combination of crisscross optimization algorithm and Monte Carlo simulation. This hybrid optimization method is proposed to effectively obtain the best sizes, locations and types of DGs in the distribution system.

B. *Contribution of Paper*

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

II. MATHEMATICAL PROBLEM FORMULATION

The objective function of the optimal DG placement may be of single or multi-objective type. The single-objective function include in this work is to reduction of the total real power loss of the system. The most common constraints are considered in this analysis such as power flow equality constraints, bus voltage or voltage drop limits and transmission line overloading capacity for the optimal DG placement formulation in distribution systems. Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled.

A. *Types of static load models*

In traditional power flow analysis, different static load models such as the real and the reactive power load models are assumed as constant power load but in real life problem the loads can be voltage dependent i.e. CONL, INSL, RESL,COML and REFL load models[25-30].The real and reactive power static load models are represented in equs. (1) - (2).

$$P_{p\_bus} = P_{0p\_bus}\left(\frac{|V_{p\_bus}|}{|V_{0p\_bus}|}\right)^{\alpha_{RLPL}} \qquad (1)$$

$$Q_{p\_bus} = Q_{0p\_bus}\left(\frac{|V_{p\_bus}|}{|V_{0p\_bus}|}\right)^{\beta_{REPL}} \qquad (2)$$

Where α_{RLPL} and β_{REPL} are the real and the reactive power exponents in (1)-(2). P_{p_bus}, Q_{p_bus}, P_{0p_bus}, Q_{0p_bus}, V_{p_bus} and V_{0p_bus} all are in per units. The exponent values for DLMs are given in Table I. Thus, the value of $P_{\text{int}ake\_sys}$ and $Q_{\text{int}ake\_sys}$ are decided, mainly, by the real and reactive power load exponents i.e. α and β.

TABLE I. EXPONENTIAL VALUES OF DLMS [1-4]

DLMs	α	β
CONT	0	0
INSL	0.18	6.0
RESL	0.92	4.04
COML	1.51	3.40
REFS	0.91	1.0

B. *Different types of DGs*

The different types of DGs (such as DG-T1, DG-T2, DG-T3 and DG-T4) are available in open power market. The details of such different type of DGs are explained are in Table II.

TABLE II. DIFFERENT TYPES OF DGS AND ITS EXAMPLES

OPF_{DG}	**DG Models**	**Power injection capability**	**Practical example**
Unity	DG-T1	Active power only	Photovoltaic, micro turbines and fuel cells *etc.*
$0.80<OPF_{DG}<0.99$, leading	DG-T2	Active and reactive power both	Diesel engines as diesel generators and synchronous machines, co-generation *etc.*
Zero	DG-T3	Reactive Power only	FACTS controllers, bank of inductors and bank of capacitors
$0.80<OPF_{DG}<0.99$, lagging	DG-T4	Active power and consumes reactive power	Doubly fed induction generators

In this paper, DG-T2 type is used for analysis point of view for investigation of IEEE-16 bus test system.

C. Mathematical modeling of DG and STATCOM

The reduction total real power loss of system by optimally placed DG in distribution systems is the main objective function [20-25]. The power loss (P_L) of the system is given in equ. (3).

$$P_L = \sum_{p,q \in N_{line}} \frac{P_{pq\_bus}{}^2 + Q_{pq\_bus}{}^2}{\left|V_{p\_bus}\right|^2} R_{pq\_bus} \qquad (3)$$

The P_L is a function of all system bus voltage (V_{p_bus}), line resistances (R_{pq_bus}), P_{pq_bus} and Q_{pq_bus}. The total loss, mainly, depends on the voltage profile. Apparent power intake at main substation [20-25] is expressed in equ. (4).

$$S_{intake\_sys} = \left[\left(P_{intake\_sys}{}^2\right) + \left(Q_{intake\_sys}{}^2\right)\right]^{1/2} \qquad (4)$$

Where P_{intake_sys} is the real power intake at main substation without DG, Q_{intake_sys} is the reactive power intake at main substation without DG. The reactive power supplied by the STATCOM to the system is expressed by equ.(5).

$$Q_{STAT} = -\frac{V_{intake\_sys}{}^2}{X_{TL}} + \frac{E_{bus} V_{intake\_sys}}{X_{TL}} \cos\beta \qquad (5)$$

The real power support by STATCOM is negative that means STATCOM absorbed the real power from system bus. Hence the real power support by STATCOM to the system is zero. Apparent power requirement for distribution system with DG and STATCOM is expressed by equ. (6).

$$S_{sys} = \left[\left(P_{intake\_sys} + P_{DG} + P_{STAT}\right)^2 + \left(Q_{intake\_sys} \pm Q_{DG} \pm Q_{STAT}\right)^2\right]^{1/2} \qquad (6)$$

Where P_{DG}, P_{STAT} and Q_{DG}, Q_{STAT} are the real and reactive power supplied by DG and STATCOM respectively. It is observed that equs. (6) and (7) hold good for a distribution system in ref. [62].

$$\sum_{p=1}^{N_{Bus}} P_0(\left|V_{p\_bus}\right|)^{\alpha_{RLPL}} > P_L \qquad (7)$$

$$\sum_{p=1}^{N_{bus}} Q_0(\left|V_{p\_bus}\right|)^{\beta_{REPL}} > Q_{Loss} \qquad (8)$$

The system power factor [26] without DG and STATCOM is calculated by equ.(9).

$$SPF_{sys} = \frac{P_{intake\_sys}}{(P_{intake\_sys}{}^2 + Q_{intake\_sys}{}^2)^{1/2}} \qquad (9)$$

The system power factor with DG is calculated based on the DG *i.e.* real and reactive power supplied or absorbed in ref. [27] is given by equ. (10).

$$SPF_{sys+WDG} = \frac{P_{intake\_sys} + P_{DG}}{((P_{intake\_sys} + P_{DG})^2 + (Q_{intake\_sys} \pm Q_{DG})^2)^{1/2}} \qquad (10)$$

The system power factor with DG and STATCOM is calculated; according to the STATCOM mode of operation *i.e.* whether reactive power is absorbed or supported in ref. [19-21] is given by equ. (11).

$$SPF_{sys\_WDG+STAT} = \frac{P_{intake\_sys} + P_{DG}}{((P_{intake\_sys} + P_{DG})^2 + (Q_{intake\_sys} \pm Q_{DG} \pm Q_{STAT})^2)^{1/2}} \qquad (11)$$

III. A HYBRID APPROACH BASED ON GA AND MCS IMPLEMENTAION

The GA is very sensitive to the initial population. In fact, the random nature of the GA operators makes the algorithm sensitive to the initial population. This dependence to the initial population is in such a manner that the algorithm may not converge if the initial population is not well selected. However, if the initial population is well selected, the performance of the algorithm may be enhanced. The idea behind this thesis is the combination of the GA and MCS in such a way that the performance of the newly established algorithm is better than the MCS or GA. In the first stage of solving the problem of optimization the MCS will create an initial population. After that the algorithm switches to the GA and the GA takes this initial population and continues to solve the optimization problem [20-22].

In case of uncertainties in the input variables of the power system, it is desirable to assess the system output variables (bus voltages and line flows) for many load and generation conditions. It is necessary to run many times the deterministic power flow routine in order to evaluate possible system states. Many methods have been proposed for estimating the state of the power systems considering uncertainties [23]. The most accurate method is a MCS. The chance constraints are not crucial limitations and it is possible to be violated a few times under a confidence level. The following chance constraints are considered as follows:

$$\Pr\left\{V_{\min} \le \left|V_{i\_bus}\right| \le V_{\max}\right\} \ge a \tag{12}$$

$$\Pr\left\{S_{(m,n)} \le S_{(m,n)\max}\right\} \ge b \tag{13}$$

Where, a and b are the confidence level of permissible voltage and power flow. $V_{\min}$ and $V_{\max}$ are the upper and lower limits of voltage amplitude; $S_{(m,n)}$ and $S_{(m,n)\max}$ are the power flow and the permitted maximal power flow limit in the feeder between node m and node n, respectively. $\Pr\{.\}$ represents the probability of the event included in $\{.\}$. Where confidence levels are a =0.95, b =0.95. MCS procedure for checking of chance constraints is shown in Fig.2.

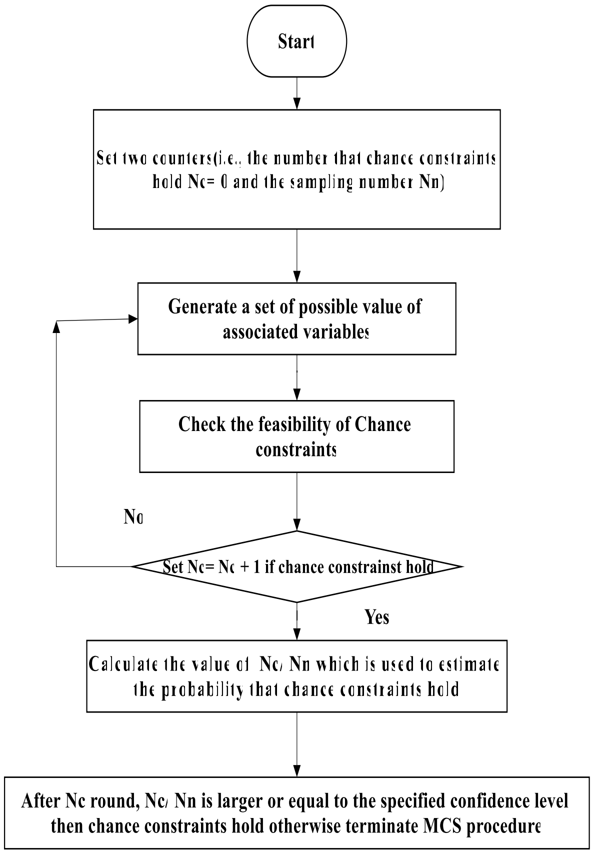


Fig. 2: MCS method

A hybrid approach based on GA and MCS is employed to solve the optimization problem. First, the chance constraints are dealt with by the penalty function method. Second, the fitness function is formed by the objective function and penalty constraints together [24]. The various steps for hybrid approach based on GA and MCS is employed to solve the optimization problem are as follows:

Step 1: Read the IEEE 16-bus distribution system data, different load models data, DG data, and STATCOM data and the ones associated with the GA, such as the population size, the crossover probability, and the mutation probability, and the maximum-permitted generation number (N).

Step 2: Create chromosomes (i.e. size-placement pairs of DG and STATCOM) on the basis of random generation and check their feasibilities with SCS procedure.

Step 3: Check chromosomes feasibilities with MCS.

Step 4: If feasibilities associated with chromosomes satisfied update the chromosomes (i.e. size-placement pairs of DG and STATCOM) by using genetic operator such as crossover and mutation according to the specified probabilities. If feasibilities associated with chromosomes not satisfied then create again chromosomes (i.e. size-placement pairs of DG and STATCOM) on the basis of random generation.

Step 5: Check their feasibilities again with MCS.

Step 6: If feasibilities associated with chromosomes (i.e. size-placement pairs of DG and STATCOM) satisfied then calculate the objective function value (total real power loss) of all such chromosomes (i.e. size-placement pairs of DG and STATCOM) produced. If feasibilities associated with chromosomes not satisfied then update again the chromosomes (i.e. size-placement pairs of DG and STATCOM) by using genetic operator such as crossover and mutation according to the specified probabilities.

Step 7: Select the chromosomes (i.e. size-placement pairs of DG and STATCOM) in the current population by the roulette wheel method (selection according to their fitness value).

Step 8: Check the generation number.

Step 9: If the generation number reached to maximum-permitted generation number (N) then select the best chromosome (i.e. size-placement pairs of DG and STATCOM) found in the above solving procedure as size-placement pairs of DG and STATCOM. Also calculate the corresponding system power factor otherwise repeats Step 6-8.

The flowchart of the GA-embedded with MCS for enhancement of the SPF by DG and STATCOM in distribution systems for DLMs from minimum total real power loss of the system viewpoint is shown in Fig.3.

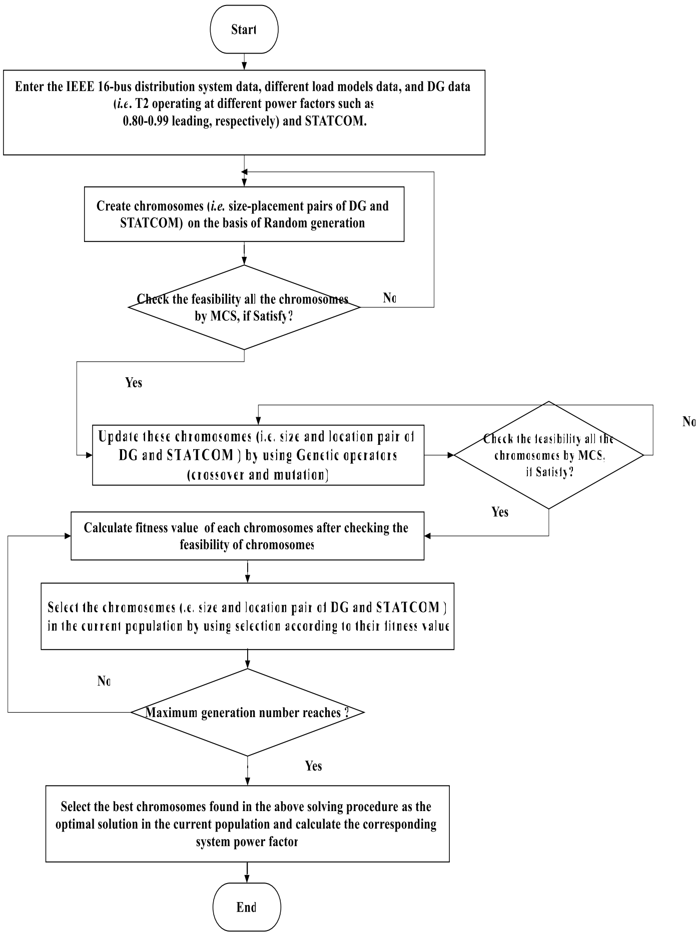


Fig.3: The flowchart of hybrid approach based on GA and MCS as a optimization technique for improvement of the *SPF* by DG and STATCOM in distribution systems.

IV. Simulation Results and Discussions

The simulation results and discussion are presented in sub-sections as 5.3-5.6, respectively.

A. General

The software is written in MATLAB 2008a computing environment and applied on a 2.63 GHz Pentium IV personal computer with 3 GB RAM. The simulation results and discussions corresponding to DG (i.e.DG-T2 type operating at different power factors such as 0.80-0.99 leading, respectively) and STATCOM operating in generating modes with DLMs such as CONL, INSL,RESL, COML and REFL are presented as follows.

B. IEEE 16 bus test system and its data

The IEEE-16 bus test system [28-29] and its data are given in Fig.3 and Table III, respectively.

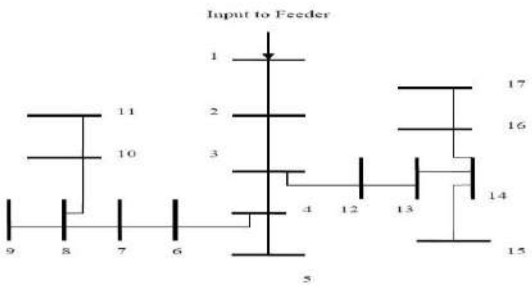


Fig.3: Single line diagram of the IEEE 16-bus test system.

TABLE III. THE IEEE-16 BUS TEST SYSTEM DATA

F	**T**	**Line impedance (p.u.)**		**Line no.**	**Ratings (p.u.)**	**Load on the bus (p. u.)**	
		R	**X**			**P**	**Q**
1	2	0.000574	0.000293	1	2.8	0.1	0.06
2	3	0.001021	0.000974	2	2.5	0.09	0.04
3	4	0.009366	0.00844	3	2.1	0.12	0.08
4	5	0.00255	0.002979	5	0.84	0.06	0.03
4	6	0.004414	0.005836	6	1.5	0.06	0.02
6	7	0.00307	0.001564	11	1.3	0.20	0.10
7	8	0.002809	0.00192	7	1.04	0.20	0.10
8	9	0.005592	0.004415	12	0.48	0.06	0.02
8	10	0.005579	0.004366	13	1.5	0.06	0.02
10	11	0.003113	0.003113	15	0.18	0.045	0.03
3	12	0.002279	0.001161	9	0.64	0.06	0.035
12	13	0.002373	0.001209	4	0.55	0.06	0.035
13	14	0.0051	0.004402	8	0.45	0.12	0.08
14	15	0.001264	0.000644	14	0.12	0.06	0.01
14	16	0.00177	0.000901	16	0.15	0.06	0.02
16	17	0.006594	0.005814	10	0.07	0.06	0.02

F = From bus, T = To bus, *P* = Real power load, *Q*= Reactive power load

C. SPF profile enhancement by DG-T2 without STATCOM for DLMs

The SPF profile enhancement by DG-T2 without STATCOM for DLMs is shown in Table IV.

TABLE IV. *SPF* ENHANCEMENT BY DG-T2 WITHOUT STATCOM

***SPF* with DG-T2 without STATCOM for DLMs**						
DLMs	***SPF* without DG-T2**	***SPF* with DG-T2**				
		DG-T2 (0.91 ld)	**DG-T2 (0.92 ld)**	**DG-T2 (0.94 ld)**	**DG-T2 (0.96 ld)**	**DG-T2 (0.98 ld)**
CONL	0.75	0.7987	0.7982	0.7969	0.7952	0.7928
INSL	0.75	0.8000	0.7994	0.7982	0.7955	0.7937
RESL	0.75	0.7997	0.7996	0.7975	0.7960	0.7938

COML	0.75	0.8000	0.7998	0.7985	0.7963	0.7942
REFL	0.75	0.7992	0.7990	0.7976	0.7960	0.7937

Table IV, shows the simulation results for DG-T2 operating at different power factor (0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) for DLMs. The *SPF* with DG-T2 for DLMs is shown in TableIV. Finally, it can be concluded that when DG-T2 is connected to test system then *SPF* improvement is better than the *SPF* without DG-T2. The *SPF* profile with DG-T2 (*i.e.* operating at different power factors such as 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively)) for DLMs are shown in Fig.5.

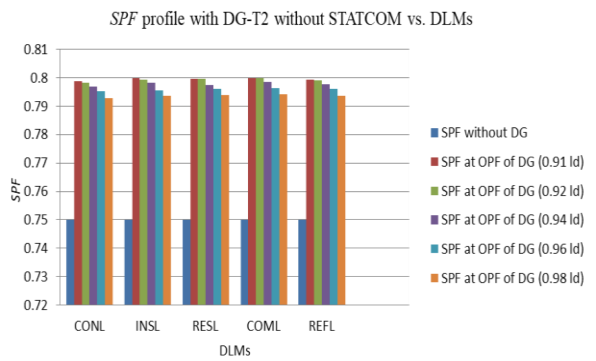


Fig. 5: *SPF* with DG-T2 without STATCOM (0.00 p.u.)

Fig. 5, it is observed that the minimum values of *SPF* are obtained when DG-T2 is not connected to the test system because the system losses are higher in this case. The *SPF* profile enhancement is maximum with DG-T2 (operating at 0.91 ld power factor) as comparison to *SPF* without DG-T2. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

D. SPF profile enhancement by DG-T2 incorporated with STATCOM for DLMs

The *SPF* profile enhancement by DG-T2 incorporated with STATCOM for DLMs is shown in Table V.

TABLE V. SPF PROFILE WITH DG-T2 INCORPORATED WITH STATCOM

***SPF* with DG-T2 incorporated with STATCOM**						
DLMs	***SPF* without DG-T2**	***SPF* with DG-T2 and STATCOM**				
		DG-T2 (0.91 ld)	**DG-T2 (0.92 ld)**	**DG-T2 (0.94 ld)**	**DG-T2 (0.96 ld)**	**DG-T2 (0.98 ld)**
CONL	0.75	0.8199	0.8195	0.8183	0.8164	0.8144
INSL	0.75	0.8204	0.8202	0.8190	0.8171	0.8142
RESL	0.75	0.8211	0.8206	0.8193	0.8176	0.8149
COML	0.75	0.8214	0.8201	0.8194	0.8179	0.8156
REFL	0.75	0.8208	0.8198	0.8186	0.8171	0.8149

Table V, shows the simulation results for DG-T2 operating at different power factor (0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) incorporated with STATCOM for DLMs. The *SPF* profile with DG-T2 (operating at different power factor such as 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) incorporated with STATCOM for DLMs is shown in Table V. Finally, it is concluded that when DG-T2 (operating at 0.91 ld power factor) is incorporated with STATCOM then *SPF* improvement is better than other remaining cases and it is true for each load model (*i.e.* CONL, INSL, RESL, COML and REFL). The *SPF* profile with DG-T2 (operating at different power factors such as 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) & STATCOM is shown in Fig.6.

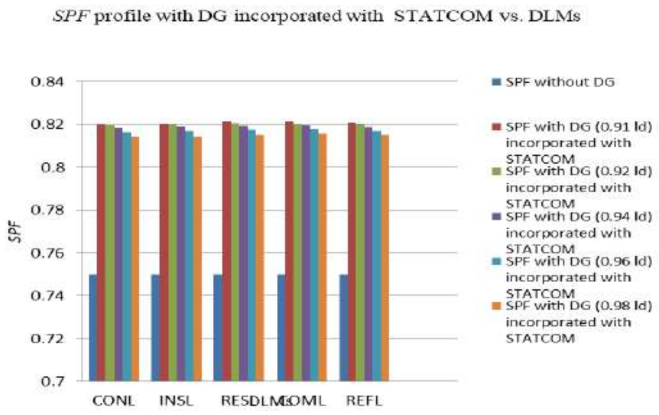


Fig. 6*:* *SPF* with DG-T2 incorporated with STATCOM

Fig. 6, it is observed that the minimum values of *SPF* are obtained when DG-T2 is not connected to the test system. The *SPF* profile enhancement is maximum when DG-T2 (operating at 0.91 ld power factor) and STATCOM both are incorporated to test system. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

E. SPF profile enhancement using DG-T2 incorporated with two STATCOM for DLMs

The *SPF* profile enhancement using DG-T2 incorporated with two STATCOM for DLMs is shown in Table VI.

TABLE VI. SPF PROFILE FOR DG-T2 INCORPORATED WITH TWO STATCOM

SPF with DG-T2 and two STATCOM

DLMs	*SPF* with out DG-T2	*SPF* with DG-T2 and two STATCOM				
		DG-T2 (0.91 ld)	DG-T2 (0.92 ld)	DG-T2 (0.94 ld)	DG-T2 (0.96 ld)	DG-T2 (0.98 ld)
CONL	0.75	0.8439	0.8434	0.8422	0.8419	0.8382
INSL	0.75	0.8443	0.8441	0.8428	0.8417	0.8380
RESL	0.75	0.8450	0.8444	0.8431	0.8422	0.8387
COML	0.75	0.8452	0.8440	0.8432	0.8425	0.8393
REFL	0.75	0.8447	0.8437	0.8425	0.8417	0.8387

Table VI, shows the simulation results for DG-T2 (operating at different power factor) incorporated with two STATCOM for DLMs. The *SPF* profile enhancement with DG-T2 incorporated with two STATCOM for DLMs is shown in Table VI. Finally, it can be concluded that when DG-T2 (0.91 ld) and two STATCOM both are connected to the test system then *SPF* profile improvement is better than other remaining cases for each load model (i.e. CONL, INSL, RESL, COML and REFL). The *SPF* profile with DG (operating at different power factors such as 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) & two STATCOM is shown in Fig. 7.

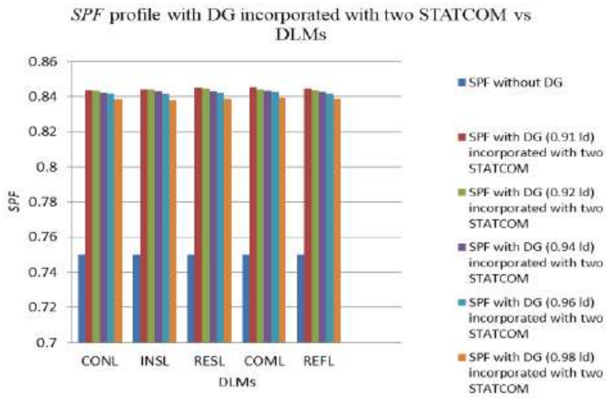


Fig.7: *SPF* with DG-T2 incorporated with two STATCOM

Fig. 7, it is observed that the minimum values of *SPF* are obtained when system is operated without DG. The SPF profile enhancement is maximum with DG-T2 (operating at 0.91 ld power factor) incorporated with two STATCOM as comparison to other remaining cases. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

F. Comparison of SPF profile enhancement

The comparison among different operating conditions of test system in respect of SPF enhancement point of view for DLMs is discussed in sub-sections 5.6.1-5.6.6, respectively. Where different operating conditions at which test system operates are as follows:

Case 1: The test system is operated without DG-T2 and STATCOM.

Case 2: The test system is operated with DG-T2 (operating at different power factors such as 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively)

Case 3: The test system is operated with both DG-T2 (operating at different power factors such as 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) and STATCOM.

Case 4:The test system is operated with DG-T2 (operating at different power factors such as 0.91, 0.92, 0.94, 0.96 and 0.98 leading, respectively) and two STATCOM.

a) SPF profile with DG-T2 (0.91 ld) and STATCOM

The comparison among different operating conditions of test system in respect of SPF enhancement point of view for DLMs is shown in Fig.4.

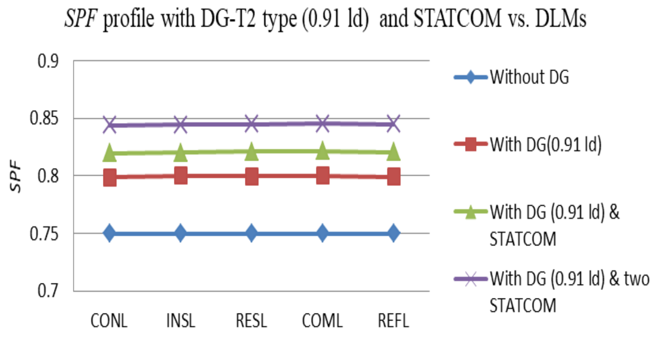


Fig. 4: SPF profile with DG-T2 (0.91 ld) and STATCOM

Fig.4, it can be concluded that the minimum values of SPF are obtained without DG and maximum value of SPF are obtained with both DG-T2 (0.91 ld) & two STATCOM. Similarly the test system with DG-T2 &STATCOM is the second best for SPF improvement and system only withDG-T2is the third best for SPF improvement. Without DG-T2, SPF is worst among the all the cases. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

b) SPF profile with DG-T2 (0.92 ld) and STATCOM

The comparison among different operating conditions of test system in respect of SPF enhancement point of view for DLMs is shown in Fig.5.

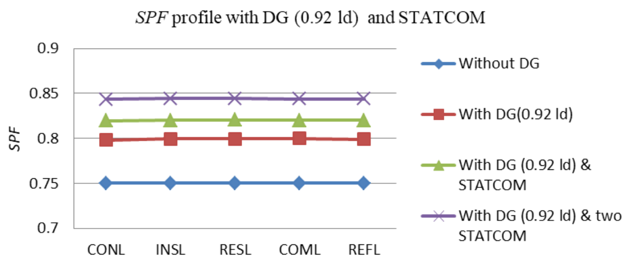


Fig.5: SPF profile with DG (0.92 ld) and STATCOM

Fig.5, it can be concluded that the minimum values of SPF are obtained without DG-T2 and maximum value of SPF are obtained with both DG-T2 (0.92ld) & two STATCOM. The second best SPF improvement are obtained when test system is operated with DG-T2 (0.92 ld) & single STATCOM. The third best SPF improvement is obtained when system is operated only with DG-T2 (0.92 ld). Without DG-T2, SPF is worst among the all the cases. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

c) SPF profile with DG-T2 (0.94 ld) and STATCOM

The comparison among different operating conditions of test system in respect of SPF enhancement point of view for DLMs is shown in Fig.6.

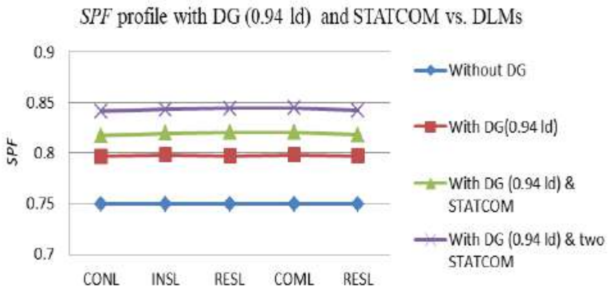


Fig.6: SPF profile with DG-T2 (0.94 ld) and STATCOM

Fig.6, it can be concluded that the minimum values of SPF are obtained without DG-T2 and maximum value of SPF are obtained with DG-T2 (0.94ld) & two STATCOM. The second best SPF improvement are obtained when the test system is operated with DG-T2 (0.94ld)& single STATCOM. The third best SPF improvement is obtained when the test system is operated only with DG-T2 (0.94 ld).Without DG-T2, SPF is worst among the all the cases. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

d) SPF profile with DG-T2 (0.96 ld) and STATCOM

The comparison among different operating conditions of test system in respect of SPF enhancement point of view for DLMs is shown in Fig.7.

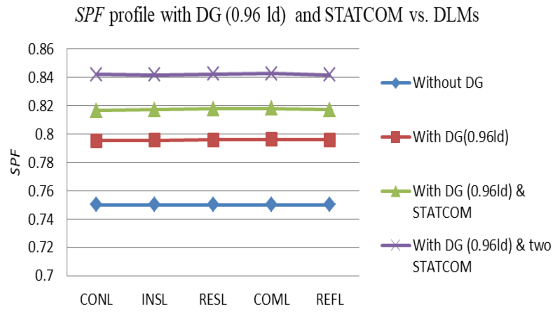


Fig. 7: SPF profile with DG-T2 (0.96 ld) and STATCOM

Fig.7, it can be concluded that the minimum values of SPF are obtained without DG-T2 and maximum value of SPF are obtained with DG-T2 (0.96 ld) & two STATCOM. The second best SPF improvement are obtained when system is operated with DG-T2 (0.96 ld) & single STATCOM. The third best SPF improvement is obtained when the test system is operated only with DG-T2 (0.96 ld). Without DG-T2, SPF is worst among the all the cases. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

e) SPF profile with DG-T2 (0.98 ld) and STATCOM

The comparison among different operating conditions of test system in respect of SPF enhancement point of view for DLMs is shown in Fig.8.

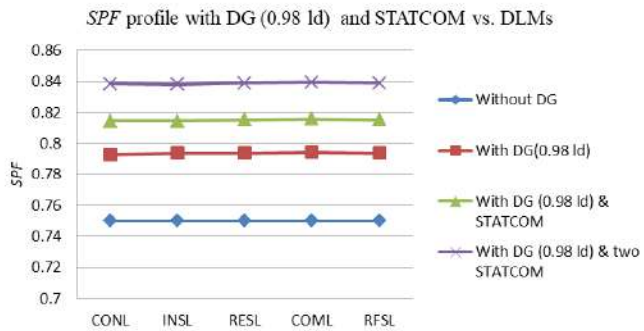


Fig. 8: SPF profile with DG-T2 (0.98 ld) and STATCOM

Fig.8, it can be concluded that the minimum values of SPF are obtained without DG-T2 and maximum value of SPF are obtained with DG-T2 (0.98 ld) incorporated with two STATCOM. The second best SPF improvement are obtained when system is operated with DG-T2 (0.98 ld) incorporated with single STATCOM. The third best SPF improvement is obtained when the test system is operated only with DG-T2 (0.98 ld). Without DG-T2, SPF is worst among the all the cases. These conclusions are true for each load model (i.e. CONL, INSL, RESL, COML and REFL).

G. Summary of Results

The *SPF* profile enhancement for different operating condition of distribution system with DLMs is shown in Table 7.

TABLE VII. SUMMARY OF RESULTS WITH DLMS

Different operating condition	*SPF* with DLMs				
	CONL	**INSL**	**RESL**	**COML**	**RESL**
Without DG	0.75	0.75	0.75	0.75	0.75
With DG (0.98 ld)	0.7928	0.7937	0.7938	0.7942	0.7937
With DG (0.96 ld)	0.7952	0.7955	0.7960	0.7963	0.7960
With DG (0.94 ld)	0.7969	0.7982	0.7975	0.7985	0.7976
With DG (0.92 ld)	0.7982	0.7994	0.7996	0.7998	0.7990
With DG (0.91 ld)	0.7987	0.8000	0.7997	0.8000	0.7992
With DG (0.98 ld) & STATCOM	0.8144	0.8142	0.8149	0.8156	0.8149
With DG (0.96 ld) & STATCOM	0.8164	0.8171	0.8176	0.8179	0.8171
With DG (0.94 ld) & STATCOM	0.8183	0.8190	0.8193	0.8194	0.8186
With DG (0.92 ld) & STATCOM	0.8195	0.8202	0.8206	0.8201	0.8198
With DG (0.91 ld) & STATCOM	0.8199	0.8204	0.8211	0.8214	0.8208
With DG (0.98 ld) & two STATCOM	0.8382	0.8380	0.8387	0.8393	0.8387
With DG (0.96 ld) & two STATCOM	0.8419	0.8417	0.8422	0.8425	0.8417
With DG (0.94 ld) & two STATCOM	0.8422	0.8428	0.8431	0.8432	0.8425
With DG (0.92 ld) & two STATCOM	0.8434	0.8441	0.8444	0.8440	0.8437
With DG (0.91 ld) & two STATCOM	0.8439	0.8443	0.8450	0.8452	0.8447

(i) With DG-T2: Table VII, it is concluded that system incorporated with DG (operating at 0.98 ld) have some better power factor in comparison to initial SPF. When system incorporated with DG (operating at 0.96 ld) then it have better SPF form both previous cases. So further SPF can be improved by reducing the DG-T2 operating power factor from 0.98 ld to 0.91 ld for DLMs.

(ii) With DG-T2 & STATCOM: Table VII, it is observed that system incorporated with DG (operating at 0.98 ld) & STATCOM have some better power factor in comparison to initial SPF. When system incorporated with DG-T2(operating at 0.96 ld) and STATCOM then it have better SPF form previous cases. So further SPF can be improved by reducing the DG-T2 power factor from 0.98 ld to 0.91 ld with STATCOM for DLMs.

(iii) With DG-T2 & two STATCOM: Table VII, it is observed that system incorporated with optimally placed DG (operating at 0.98 ld) and two STATCOM have some better SPF in comparison to initial SPF. When system incorporated with DG (operating at 0.96 ld) & two STATCOM then it have better SPF form previous cases. So further SPF can be improved by reducing the DG-T2 power factor from0.98 ld to 0.91 ld with two STATCOM for DLMs. So it can be concluded that when the test system is connected with DG-T2 (0.91 ld) and two STATCOM then the SPF profile enhancement is the best among the all cases.

V. CONCLUSIONS AND FUTURE SCOPE OF WORK

A. *Conclusions*

The following conclusions are made from this research:

- Enhance System PF depends on the size of DG and STATCOM and their suitable locations in the distribution power networks.
- The system power factor when DG and STATCOM is operating in generating mode(reactive power delivered to the system bus), is better than system power factor when STATCOM is operating in load mode(reactive power absorbed from the system bus).
- At Small Scale it is possible that this proposed Scheme will not give significant results (i.e. enhancement of system PF) but at Large Scale this proposed Scheme will give good results i.e. enhancement of system PF using DG and STATCOM for different load models in distribution networks.
- Enhance the reactive power support to the system by DG and STATCOM.
- The real and reactive power losses of the system should be minimized by optimally placed DG and STATCOM.
- Enhance the power system stability by DG and STATCOM.
- Also enhance other power system performances by DG and STATCOM.

B. *Future scope*

The following future scopes of this research work in this direction are as follows:

- The proposed methodology also used for other FACTS controllers such as dynamic voltage restorer (DVR), hybrid power flow controllers (HPFC) and generalized unified power flow controllers (GUPFC) etc.
- In future, Enhancement of System PF using DG and STATCOM for dynamic load models can be used.

- In future, also improved other power system performances such as power quality parameters (voltage sag and swell etc.) by DGs and FACTS controllers.
- Practical implementations are possible for renewable energy sources.

References

[1] Belkacem Mahdad, Kamel Srairi and Tarek Bouktir, "Optimal Coordination and Penetration of Distributed Generation with Shunt FACTS Using GA/Fuzzy Rules," Journal of Electrical Engineering & Technology, vol. 4, no.1, pp. 1-12, 2009.

[2] Bindeshwar Singh, K.S. Verma, Pooja Mishra, Rashi Maheshwari, Utkarsha Srivastava and Aanchal Baranwal, "Introduction to FACTS Controllers: A Technological Literature Survey," International Journal of Automation and Power Engineering, vol. 1, issue 9, pp. 193-234, 2012.

[3] Bindeshwar Singh, Abhiruchi Srivastava and Manisha, "Applications of FACTS Controllers," Jounral of Automation & Systems Engineering, vol. 8, no.1, pp. 1-24. 2014.

[4] Nasiru B. Kadandani and Yusuf A. Maiwada, "An Overview of FACTS Controllers for Power Quality Improvement," The International Journal Of Engineering And Science (IJES), vol.4, issue 9, pp. 09-17,2015.

[5] V.K. Mehta and Rohit Mehta, Application of power system: Distribution generation system, S. Chand, 2015.

[6] Debabrata Kundu "An Overview of the Distributed Generation (DG) Connected to the GRID,"Power system technology & IEEE Power India Conference, POWERCON, Joint international conference, pp. 1-8, 2008.

[7] Bindeshwar Singh, V. Mukherjee and Prabhakar Tiwari, "A Survey on impact assessment of DG and FACTS controllers in power systems," Renew. Sustain. Energy Rev., vol. 42, pp. 846-882, 2015.

[8] Bindeshwar Singh, V. Mukherjee and Prabhakar Tiwari, "Genetic algorithm for impact assessment of optimally placed distributed generations with different load models from minimum total MVA intake viewpoint of main substation," Renew. Sustain. Energy Rev., vol. 57, pp. 1611-1636, 2016.

[9] Deependra Singh, Devender Singh, and K. S. Verma, "Multiobjective Optimization for DG Planning With Load Models," IEEE transactions on power systems, vol. 24, No. 1, pp. 427-436, 2009.

[10] Eltaib Said Elmubarak, Ali Mohamed Ali, "Distributed Generation: Definitions, Benefits, Technologies & Challenges," International Journal of Science and Research (IJSR), vol. 5 issue 7, pp. 1941-1948, 2016.

[11] M. Kumar, C. Samuel and A. Jaiswal, "An Overview of Distributed Generation in Power Sector," International Journal of Science, Technology & Management, vol. 04, no. 01, 2015.

[12] Champa Nandi, Sumita Deb, Minakshi Deb Barma, and A.K. Chakraborty, "Study and Simulation of the SVC and STATCOM Effect on Voltage Collapse and Critical Fault Clearing Time," International Journal of Modeling and Optimization, vol. 2, no. 4, 2012.

[13] N. G. Hingorani and L.Gyugyi, Understanding FACTS Concepts and Technology of Flexible AC Transmission Systems Piscataway, NJ; IEEE press, New York, 2000. Ch. 5, pp. 160-206.

[14] Amit Garg and Sanjai Kumar Agarwal, "Voltage control and dynamic performance of power transmission system using STATCOM and its comparison with SVC," International Journal of Advances in Engineering & Technology, vol. 2, issue 1, pp. 437-442, 2012.

[15] Prity Bisen and Amit Shrivastava, "Comparison between SVC and STATCOM FACTS devices for powersystem stability enhancement," International Journal on Emerging Technologies, vol. 4, no. 2, pp. 101-109, 2013.

[16] Fathi M. H. Youssef, E. A. Badran and S. Abulanwar, "Dynamic Performance Comparison between STATCOM and SVC," The Online Journal on Electronics and Electrical Engineering (OJEEE), vol. 3, pp. 425-429, 2011.

[17] Rajendra Prasad Payasi, Asheesh K. Singh and Devender Singh, "Planning of different types of distributed generation with seasonal mixed load models," International Journal of Engineering, Science and Technology, vol. 4, no. 1, pp. 112-124, 2012.

[18] Devender Singh, R. K. Misra, and Deependra Singh, "Effect of Load Models in Distributed Generation Planning," IEEE transactions on power systems, vol. 22, no. 4, pp. 2204 -2012, 2007.

[19] Bindeshwar Singh, V. Mukherjee and Prabhakar Tiwari, "Genetic algorithm optimized impact assessment of optimally placed DG and FACTS controllers with different load models from minimum total real power loss viewpoint," Energy and Building , vol. 126, pp. 194-219,2016.

[20] D.E. Goldberg, Genetic Algorithms in Search, Optimization & Machine Learning, Addison Wesley, 1989.

[21] Srinivasan Sundhararajan and Ani1 Pahwa, "Optimal selection of capacitors for radial distribution systems using a Genetic Algorithm," IEEE Transactions on Power Systems, vol. 9, no. 3, pp. 1499-1507, 1994.

[22] Deependra Singh, Devender Singh and K.S. Verma, "GA based energy loss minimization approach for optimal sizing & placement of distributed generation," International Journal of Knowledge-based and Intelligent Engineering Systems ,vol. 12, pp. 147–156, 2008.

[23] M. Marseguerra and E. Zio, "Optimizing maintenance and repair policies via a combination of genetic algorithms and Monte Carlo simulation," Reliability Engineering and System Safety, vol. 68, pp. 69–83, 2000.

[24] Samik Raychaudhuri, "Introduction to Monte Carlo simulation" Proceedings of the 2008 Winter Simulation Conference IEEE, pp. 91-100, 2008.

[25] Nicholas Metropolis and S. Ulam, "The Monte-Carlo Method," J. Amer. Stat. Assoc.1949, vol. 44, pp. 335–341, 1949.

[26] R.F.W. Coates, G.J. Janacek and K.V. Lever, "Monte Carlo simulation and random number generation," IEEE journal on selected areas in communications, vol. 6, no. I, 58-66, 1988.

[27] Peiyuan Chen, Pierluigi Siano, Zhe Chen and Birgitte Bak-Jensen, "Optimal allocation of power-electronic interfaced wind turbines using a Genetic Algorithm – Monte Carlo Hybrid optimization method," Wind Power Systems, Green Energy and Technology, pp. 1–23,2010.

[28] R. P. Payasi , Asheesh K. Singh, Devender Singh and Navneet K. Singh, "Multi-objective optimization of distributed generation with voltage step constraint," International Journal of Engineering, Science and Technology, vol. 7, no. 3, pp. 33-41, 2015.

[29] Deependra Singh, Devender Singh and K S Verma, "Distributed Generation Planning Strategy with Load Models in Radial Distribution System," International Journal of Computer and Electrical Engineering, vol. 1, no. 3, pp. 1793-8163, 2009.

[30] Ning Yang and Fushuan Wen, "A chance constrained programming approach to transmission system expansion planning," Electric Power Systems Research, vol. 75, pp.171–177, 2005.

[31] Peng X, LinL,Zheng W, Liu Y, "Crisscross optimization algorithm and Monte Carlo simulation for solving optimal distributed generation allocation problem" Energies, vol.8, no.(12), pp.13641–13659,2015.

[32] Kejun Q, Chengke Z, Malcolm A, and Yue Y, Effect of load models on assessment of energy losses in distributed generation planning. Int J. Electrical power and Energy Systems 2011; 33: 1243-1250.

[33] Singh D, Singh D, and Verma K S, GA based Optimal Sizing & Placement of Distributed Generation for Loss Minimization. International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering 2007; 1(11): 1604-1610.

[34] Singh D, Singh D and Verma K S, Multi-objective Optimization for DG Planning With Load Models. IEEE Transactions on Power Systems 2009; 24(1): 427-436.

[35] Mishra D, and Singh B, Enhancement of Power System Performance by Optimal Placement of Distributed Generation using Genetic Algorithms, IRJET 2017; 4(9): 370-377.

[36] Mahdi sedghi, Ali Ahmadian, Masoud Aliakbar-Golkar. Optimal Storage Planning in Active Distribution Network Considering Uncertainty of Wind Power Distributed Generation. IEEE Transactions on Power Systems 2016; 3(1):304 – 316.

[37] Singh B, Mukherjee V, Tiwari P. A survey on impact assessment of DG and FACTS controllers in power systems. Renewable and Sustainable Energy Reviews February 2015; 42:846-882.

[38] Singh AK, Parida SK. Allocation of distributed generation using proposed DMSP approach based on utility and customers aspects under deregulated environment. International Journal of Electrical Power & Energy Systems June 2015; 68:159-169.

[39] Rajendran A, Narayanan K. Optimal Installation of Different DG Types in Radial Distribution System Considering Load GrowthJournal Electric Power Components and Systems 2017; 45(7): 739-751.

[40] Srivastava A, Tripathi JM, Mohanty SR, Panda B. Optimal Over-current Relay Coordination with Distributed Generation Using Hybrid Particle Swarm Optimization–Gravitational Search Algorithm. Journal Electric Power Components and Systems 2016; 44(5):506-517.

[41] Avyappa SK, Gaonkar DN. Performance Analysis of a Variable-speed Wind and Fuel Cell-based Hybrid Distributed Generation System in Grid-connected Mode of Operation. Journal Electric Power Components and Systems 2016; 44(2):506-517.

[42] Lu Wang, Suleiman S, Andy C. Optimal decentralized coordination of electric vehicles and renewable generators in a distribution network using a search technique 2018; 98: 474-487.

[43] IEEE Task Force on Load Representation for Dynamic Performance, Load representation for dynamic performance analysis. IEEE Trans. Power System 1993; 8(2): 472-482.

[44] Tiwari D, and Ghatak S R, Performance enhancement of distribution system using optimal allocation of distributed generation & DSTATCOM, IEEE Conference 21-23 Feb. 2017.

[45] Herlambang S, Awan UK, Mithulananthan N, Hossain MJ. Modal interaction of power systems with high penetration of renewable energy and BES systems 2018; 97: 385-395.

[46] Payasi R P, Singh A K and Singh D, Effect of Voltage Step Constraint and Load Models in Optimal Location and Size of Distributed Generation. IEEE International Conference on Power, Energy and Control (ICPEC); 2013: 710-716.

[47] Raju M, Saikia LC, Sinha N. Automatic generation control of a multi-area system using ant lion optimizer algorithm based PID plus second order derivative controller. International Journal of Electrical Power & Energy Systems2016; 80:52-63.

DAY 2: 21ST FEB 2018

SESSION 4:

TRADING/MARKETING AND TARIFF

India and Cross-Border Energy Trading

The potential to trade electricity across a broader geographic area has many potential benefits. Access to transmission can open up new markets for regions that have an excess of generation and can also provide a greater number of resources to be used for balancing variations in demand and supply. Growth in renewable energy can increase the value of larger balancing areas as generation from weather-dependent sources like wind and solar increases variability on the supply-side. NREL has undertaken a study as part of the South Asia Regional Initiative/Energy Integration initiative to quantify the value of cross-border energy trade between India and its neighboring countries of Sri Lanka, Nepal, Bhutan, and Bangladesh. This analysis builds upon the extensive data collection and modeling of the MOP-USAID *Greening the Grid* program to perform an operational cost-benefit analysis of increasing electricity trades across these borders. Analysis has been completed for the India-Sri Lanka connection, while analysis for Nepal, Bangladesh, and Bhutan cross-border trade is in the data collection stage.

India – Sri Lanka

Previous studies have been conducted to look at the cost of connecting Sri Lanka and India via an HVDC link, although the detailed production cost model compiled for Greening the Grid adds new insights into the value of such a connection. Production cost models allow for a time-series based analysis that takes into account hour-to-hour balancing requirements. The 2022 India load and power system, in which India has met its 175 GW renewable energy target, was chosen as the study year to quantify the potential value of such a line for both India and Sri Lanka. To measure value, India and Sri Lanka operations with no connection are compared to a scenario where a 1000 MW interconnection between New Anuradhapura (Sri Lanka) and Madurai (India) connects the two countries.

Results

India has energy demand that is seventy times that of Sri Lanka, therefore the impact of adding a single HVDC line between the two countries has very different scales. Nevertheless, value for both countries is observed when they are connected. Figure 1 shows the generation in Sri Lanka in a scenario with the HVDC connection (DC_Med) and that without (noDC_Med). Imports to Sri Lanka drastically change the generation portfolio for the country, displacing over 18% of the most expensive generation in the country (gas, diesel, and fuel oil) while decreasing the operating costs by over 50%.

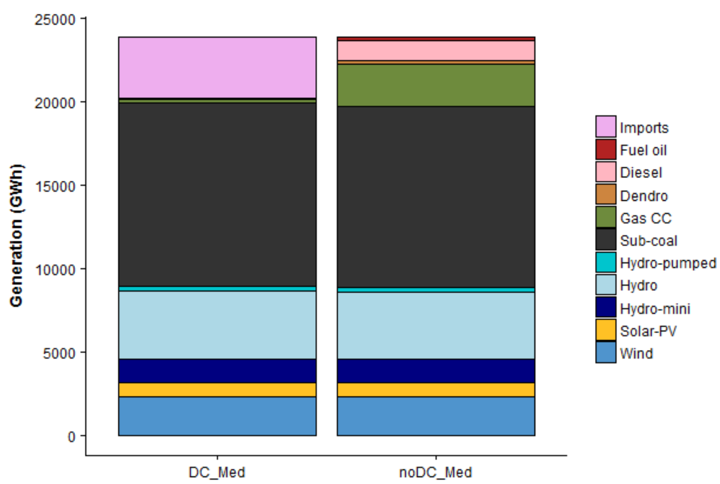


Figure 1. Annual generation in Sri Lanka, including imports from India

The energy generated in India increases to fulfill the export to Sri Lanka, and in some instances leads to a reduction in curtailment of wind and solar as a result (Figure 2). India-wide, the curtailment of wind and solar is reduced by 14%, or about 730 GWh. The combined annual operational cost of India and Sri Lanka decreases by about $350 million when the HVDC line is added.

NoDC_Med ***DC_Med***

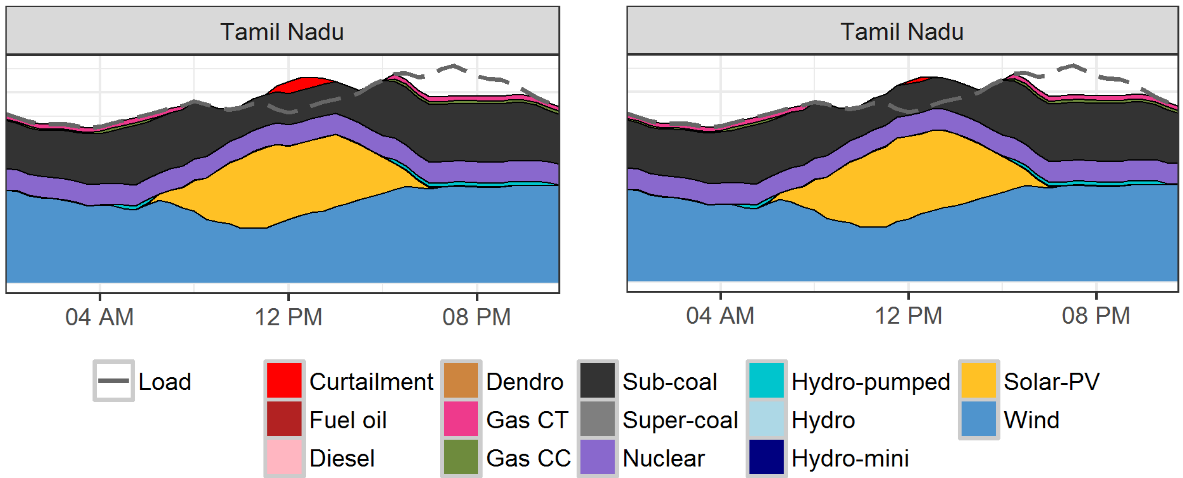


Figure 2. Generation for Tamil Nadu for one-day

The full capacity of the HVDC line is utilized during a large portion of the year in the direction of India to Sri Lanka. However, there are periods of the year, typically during summer evenings, when India imports from Sri Lanka.

Conclusion

Cross-border electricity trade between India and Sri Lanka has the potential to benefit both countries. Sri Lanka would be able to reduce reliance on expensive generation resources such as gas and diesel, and India would be able to reduce curtailment of wind and solar and increase utilization of thermal plants. Capturing the total value of these benefits, including operational cost savings, increased reliability, and market value of electricity sales, helps inform decisions on whether to pursue this HVDC connection.

See the attached slides for a comprehensive overview of the results.

Brazil Transmission Market – Experience of concession model

Amitanshu Srivastava and Namrata Mukherjee | Sterlite Power Transmission |
amitanshu.srivastava@sterlite.com, namrata.mukherjee@sterlite.com

Abstract

Brazil's national interconnected power system comprises of 140 hydropower plants that have capacities ranging from 30 MW to 14,000 MW which are interconnected in a transmission system with more than 130,000 kms of lines at 230 kV and above. The interconnection in the country is based on the concept that Brazil operates a hydropower system comprised of water reservoirs and hydropower plants that were planned in such a way that they could take the advantage of the rainfall diversity in the existing basins, which have various weather and streamflow patters. To take advantage of this diversity, the National System Operator (ONS) dispatches the entire hydropower system as a portfolio, by transferring the power from wetter regions to drier regions. National dispatch is based on merit order (marginal cost).

ONS is responsible for the coordination and control of the power generation and transmission of Brazil's National Grid (SIN). ONS develops various electric system studies and ensures the continuous supply of energy in Brazil. ONS is also tasked with providing favorable conditions that foster the growth of the electric system, consider the market stakeholders, and benefit society.

The electricity generation and transmission market is regulated by the Ministry of Mines and Energy and the National Electricity Agency (ANEEL) with ONS responsible for administration of transmission services. ANEEL's current functions include managing concessions for electric energy generation, transmission and distribution, including the approval of electricity tariffs; proposing and enacting regulations for the electricity sector; and promoting public bidding procedures for the granting of new concessions.

Since transmission services are considered a public service, participation of private concessionaires is by concession granted by the Brazilian Federal Government, through ANEEL. The Concession includes construction, assembly, operation and maintenance of the power transmission facilities for 30 years from date of signing the contract. ANEEL determines Allowed Annual Revenue (RAP) of the companies, covering capital costs and O&M costs. Transmission companies entering into concession contracts have a revenue cap where RAP is subject to periodic revision and tariff adjustment. During bidding, RAP is obtained as a result of auction and paid to the concessionaires from the start of COD. Annual tariff readjustment is only for monetary restatement of RAP. Most concession contracts use IPCA (inflation index) as readjustment index of the RAP. The auction process from date of auction notification to award of project to signing of contract is 150 days.

Brazil has one of the oldest concession model in the power sector internationally characterized by extremely well governed auction process which has attracted private and public capital in the country. This research paper will analyse the Brazil transmission auction process and the concession model including role of the regulator, key features of the concession contract and learnings for India.

I.% Introduction

Brazil is the world's fifth largest country by area, behind only Russia, Canada, China, and the United States (first to fourth largest countries, respectively). Brazil's total area of 8.5 million square kilometers (km2) (5th largest in terms of population) Characterized by large and well-developed agricultural, mining, manufacturing, and service sectors, and a rapidly expanding middle class, Brazil's economy outweighs that of all other South American countries and is expanding its presence in world markets. This presents a unique challenge in terms of the transmission and distribution of electricity. Additionally, most of the country's generation is sited far from the load consumers, further adding to the complexity.

Brazil has a power system whose characteristics are unique, not found anywhere else in the world. With hydropower prevailing (85% of installed capacity and more than 90% of average energy produced), these generation plants are scattered all over the country. The basic transmission network is a large and complex system, which allows for the electrical integration among different water basins, or among different regions of Brazil. This enables constant interchanges of energy with the aim of optimizing the operating costs of the generation matrix (operating as a complement to thermal energy), by replacing high-cost thermal generation with hydraulic generation.

In Brazil, the Federal Government is responsible for services and activities linked to power services in the country, handled either directly or through concessions. While federally owned Electrobras continues to own majority of Brazil's transmission grid, new concessionaires have actively entered the transmission sector. Thirty-year renewable concessions have been awarded to bidders offering the largest discount on the initial Permitted Annual Revenues of the auction, meaning the lowest transmission tariff. From 1999 to 2010, 15 auctions were held, with 67 projects awarded, for a total of 21,317 kilometers of new transmission lines. The auctions attracted both public and private capital, with the latter prevailing.

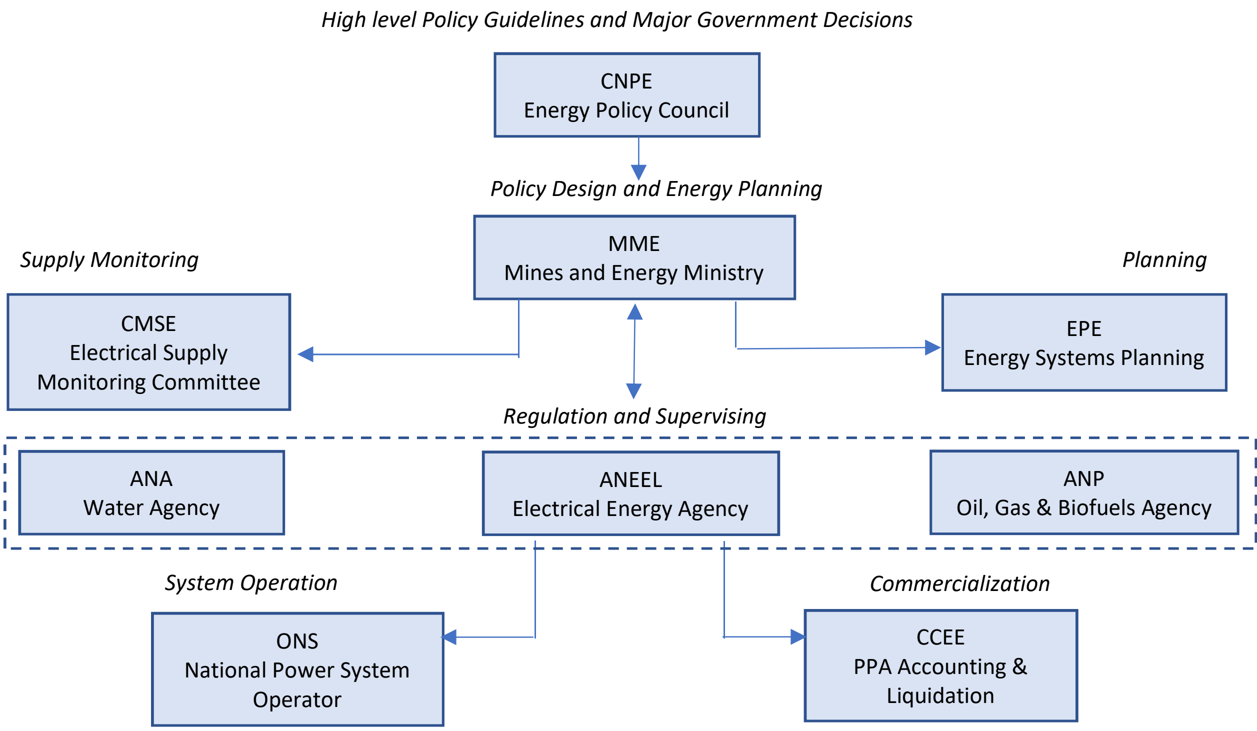
Restructuring of the Brazil power sector has been characterized by:

- Unbundling of generation, transmission, distribution, and trading/marketing
- Generation became a competitive activity at the risk of the entrepreneur, with prices set by the market
- Independent transmission facilities that would ensure open access by generators to the market, with free consumers allowed to access sources of generation or free traders competing to render their services
- The National System Operator (ONS) handles the generation and transmission systems independently, seeking optimal utilization of available energy resources and enabling the institution of open access to promote competition in the market;
- The Wholesale Electricity Market (MAE) is the setting where free competition underpins price formation, without adversely affecting optimization;
- An Independent Regulator serves as a watchdog for this model, interpreter of specific legislation, and guarantor of stability of rules

II.%   Governing Bodies and Their Roles

This section outlines the regulatory and governing framework of the power sector in Brazil.

Figure 1: Institutional structure of Brazilian Power Sector



Regulatory and Planning Agencies

➢ **National Council for Energy Policy (CNPE)**

Created in 1997 its responsible for developing national policies for the Brazilian electric sector, and protecting the interests of Brazilian consumers regarding energy quality, prices, and supply. It also formulates energy policies to promote the optimal use of Brazilian energy resources.

➢ **Ministry of Mines and Energy (MME)**

Fostering the investments in mining and energy related activities, funding energy related research, and enacting national energy policies.

➢ **Electric Research Company (EPE)**

Created in 2004, EPE is part of MME. The EPE is in-charge of long-term planning of Brazil's electric system. EPE develops planning studies covering the power sector, the oil and gas sector, and renewable development/energy efficiency.

In addition, EPE supports the public auction process by developing generation and transmission grid planning studies.

- **National Electricity Agency (ANEEL)**

Created in 1996 this is also part of MME. It is charged with the regulation and supervision of the Brazilian electric sector including power generation, transmission, distribution, and commerce.

ANEEL's current functions include, among others:

1. Managing concessions for electric energy generation, transmission and distribution, including the approval of electricity tariffs;
2. Proposing and enacting regulations for the electricity sector;
3. Implementing and regulating the exploitation of various energy sources, including the use of hydroelectric energy;
4. **Promoting public bidding procedures for the granting of new concessions;**
5. Settling administrative disputes between generators and purchasers of electricity; and
6. Defining the criteria and methodology to determine transmission and distribution tariffs.

- **National Electric System Operator (ONS)**

ONS is responsible for the coordination and control of the power generation and transmission of Brazil's National Grid (SIN). ONS develops various electric system studies and ensures the continuous supply of energy in Brazil. ONS is also tasked with providing favorable conditions that foster the growth of the electric system, consider the market stakeholders, and benefit society.

The principal objectives and responsibilities of the ONS include, among others,

1. operational planning for the generation sector;
2. organizing the use of the SIN and international interconnections;
3. guaranteeing all players access to transmission network in non-discriminatory manner;
4. planning for the expansion of the electric energy system;
5. proposing plans to the MME for extensions of the basic grid; and
6. proposing and submitting new rules for the operation of the transmission system for ANEEL's approval.

III.% Transmission System Operations, Control and Revenue Collection - Regulatory Framework

Transmission System Operations are governed through mechanism of different contracts signed between Authorities (Regulator & Operator), users and concessionaires which enable and enforce the faithful fulfillment on obligations of all concerned.

The ONS is the institution responsible for the operation, monitoring and controlling the National Integrated system (SIN) and managing the GRID. Its main objective is fulfillment of load requirement, cost optimization and system reliability assurance, with the authority to govern the conditions of access to the high voltage grid in the country.

For Brazilian Electric System conceived and operated in an integrated manner, mainly in view of multi basin hydroelectric organization, a tailor-made business model was developed to allow the formation of a market concept of sector players composed of both public and private companies.

The Transmission Business Model addresses the following issues;

- Main Transmission network Access Management
- Definition of Transmission Expansion
- Concession Grants (carried out by MME & ANEEL)
- Contract Management

Main Transmission network Access Management

The first pillar of the business model is related to the amount of transmission needed by the "Market", understood here as the Generators, distribution utilities and the free consumers.

These agents may request access to either ONS or to the transmission concessionaire detailing rights over the installations at the connection points, under ONS defined access conditions. Sometimes there is a need to expand or reinforce the system to accommodate the access so the request must become part of cycle of procedures for the expansion and reinforcement program carried out by ONS.

ONS on its own through system availability study, for enhancement of reliability and system performance may also propose such expansion and reinforcements.

Concession Grant:

The transmission installations defined in the expansion plan are sent to MME for approval and posterior concession of Grants. The award of grants is a result of tendering process for installations and winner is the agent that demands the smallest revenue. The transmission contract include

- Full Compliance to Grid Procedures
- Payment of Transmission charges
- Financial Guarantees
- Discounts for Transmission installation unavailability
- Payments by GENCOs / DISCOMs for transformer overload.

The following set of Contracts / Documents control the Transmission System:

1. **Concession Agreement:**
   The agreement between ANEEL, acting on behalf of MME, and the SPE controlled by the successful bidder. The concession agreement defines the complete scope of the facilities, terms and conditions of the Concession, Guaranteed performance parameters, functional and other Guarantees, the Allowed Annual Revenue (RAP) as discovered from the bidding process, Key milestone dates and the Agreed date of Commercial Operations.

2. **CPST: Contract for Providing Transmission Services (equivalent to TSA)**
   Agreement between ONS and Transmission concessionaire, primarily establishes the technical and financial terms and conditions of operation of services.

3. **CCG: Guarantee Agreement**
   Agreement entered between ONS and USERs, the Bank Account manager which grats access to ONS to the resources available with the USER's designated bank Account.

4. **CUST: Contract for Usage of Transmission System**
   Agreement entered by ONS, on its own behalf and as representative of Transmission concessionaires and USERs of the system, which regulates the terms and conditions for the use of basic network including charging & payment terms and terms of coordination and control.

5. **CCT: Contract for Connection to Transmission network**
   Agreement between concessionaire and users that establishes technical terms and conditions of connection to Basic network through facilities & connection points controlled by concessionaire.

6. **CCI: Contract for sharing of facilities:**
   Between two transmission concessionaires for shared use of transmission system installations.

Revenue Collection:

The payment of the use of transmission system is made through application of Tariff for the use of Transmission System – TUST.

Tariffs are adjusted annually in the same period in which readjustments of the RAP (Annual permissible Revenue) happens for Concessionaires. The tariff period begins from 1st July to 30th June of following year.

Calculation of TUST is based on a simulation of the Nodal program, which uses the input data of network configuration represented by Transmission lines, substations, generation and load and Total RAP to be collected in the cycle.

The main component of TUST, known as TUST-RB is referred as TRUS associated with facilities that are part of the Basic network (network at 230kV OR more voltage level), used to promote the optimization of resources and therefore is equally applicable to all USERs.

Transmission Services provided by procession plants provided is paid by distributors that benefit from it through a specific part of TUST, called TUST-FR, which also includes transportation cost including other Transmission facilities (outside the basic network).

IV.% Governing Framework for Transmission Tariff

The services of Energy Transmission, like any other part of the works, are subject to a context of economic regulation aimed to ensure economic equilibrium to service provider and low tariff to users.

Transmission services are considered public services, and participation of private players in the sector is by the way of Concession granted by ANEEL for and on behalf of federal government, through competitive bidding process.

Concession includes Construction, Assembly and O&M of the facilities for a term of 30 years. Regulatory model adapted for Transmission Sector is a 'variant' of traditional English Price Cap Model termed as the Revenue Cap Model. In this model Allowed Annual revenue (RAP) for the transmission project is discovered through competitive bidding process, which must cover the capital cost, O&M and expected returns. Subject to the condition of maintaining the required availability and fulfilling all other conditions of the contract, RAP is the maximum revenue the concessionaire can expect from its operations.

In order to protect the consumers and to ensure a proper revenue cap, the regulator 'ANEEL', as part of bidding process, determines a Maximum Allowable RAP (Maximum RAP). Bidders in the auction process are not allowed to quote above the same. Maximum RAP is discovered based on ANEEL's estimated project cost, optimal capital structure, cost of equity, average regulated depreciation rate, O&M cost defined in percentage terms, income tax and sectoral charges as per prevailing legislation, cost of third party capital (interest rate and spread) etc.

The Allowable Annual Revenue of a Concession Contract is subject to two different adjustments;

- Periodic Tariff Revision which occurs every five years
- Annual Tariff re-adjustment, which is basically a Monetary Correction

The annual tariff readjustment is only for monetary restatement. Most concession contracts are IPCA (inflation index) as readjustment index of RAP.

A periodic tariff revision, happens every five years. And the purpose of the same is to re-instate the concessionaire's financial situation to the same level of the bid. It takes into account any revenue adjustment required in view of any change in long term interest rates, taxes and O&M efficiencies etc.

Periodic review is undertaken through a revenue simulation model that uses the Allowed Annual Revenue as the input data and the other paraments such as:

- Cost of Equity
- Optimal Capital structure & cost of third party capital
- Average regulatory depreciation rate
- O&M costs
- Income tax and sectoral charges as per latest legislation

The revision scheduled for 5th, 10th and 15th year of the concession would include a recalculation of the WACC taking into account long-term interest rates as well as cost reductions from O&M efficiency gains.

Over and above these two, the Concession is subject to extraordinary revisions regarding change in tax regime, regulatory changes, to reimburse certain type of investment made by concessionaire which do not require ANEEL's prior approval. Besides, it includes extraordinary reviews of unforeseen events that, at the discretion of granting authority, affect the economic and financial balance of the concession. Depending on the nature of the event the Authority may conduct such reviews suo-moto or at the request of concessionaire.

V.% Auction Process – Discovery of Competitive RAP

1.%Public Hearing

The Auction process starts with Notification of Public Hearing by ANEEL. The objective of the public hearing is to;

a. Inform the public in general about the upcoming projects and the proposed bidding document
b. Seek prospective participants view on the projects and bidding document

During this period public at large and prospective participant(s) can express their view on the provisions of bidding document, while public at large and the beneficiaries (users) can raise any objection they may deem fit. The entire exercise is completed in 30~60 days. Mostly there are no issues raised by anyone.

2.%Auction Notification

The detailed Auction program is notified once public hearing deadline is over. The typical Auction Notification is given 45 days before the Date of Auction. Auction Notification lays out the entire list of projects (called “Lots”) proposed for next round of Auctions, along with scope, qualification, and key dates.

3.%Auction Process

The complete auction process consists of following stages:

a. Registration – To be done on line, during the pre-specified 48 hrs window (normally 10 days before Auction). Bidders select the lots for which they will bid on the portal.

b. Delivery of Bid Bond - To be Online in the form of Bank Guarantee, Insurance Guarantee OR Security Bond, through an agency or Bank which is registered on BOVESPA’s system.
    a. BOVESPA is the stock exchange where the Auction is carried out.

c. Auction parameter - Based on the estimated project cost, market rates of interest on debt, inflation index and cost of equity, ANEEL calculates a Maximum Allowed Annual Revenue (Maximum RAP - Receita anual permitida). This is equivalent to first year revenue of the concession that is subject to annual inflation as per given inflation Index.
    a. The bidders in the physical auction are allowed to quote their required “RAP” for the complete scope of the project (Lot), which MUST NOT EXCEED the Maximum RAP specified by ANEEL in the bidding document.

d. The Physical Auction Process -
    i. ANEEL follows the Policy of Non-Discriminate Right to Participate, with a post Auction Qualification process. Which means that all the entities which DEEM themselves as qualified and have registered for participation for a given lot and have furnished the required Guarantee, are allowed to participate in the Auction without any pre-qualification process.

    ii. The ONUS of meeting the qualification, as specified in the bidding document, rest with the “Successful” Bidder”. Only the Successful bidder is required to submit their Qualification Documents (called “Credentials”).

    iii. By following this process ANEEL optimizes time of scrutiny of all the prospective bidders, thereby enabling it to Auction many projects at a time.

    iv. For maintaining transparency, the Credentials submitted by Successful bidders are put for public scrutiny. In case of dispute and objections, a high level committee of ANEEL takes the final decision. The complete process of filing, scrutiny of the Credentials is completed in a period of 30-40 days after the Date of Auction. Upon completion of the same LOI is issued to the selected bidder, and the formal concession agreement is signed within 15 days thereafter.

4. **The "Call Out" process -**

This is a very unique practice followed by ANEEL during the physical auction process. This is equivalent to the Reverse Auction process in India but with a difference that this is conducted at the same time and spot of the Auction, without any time lag in between.

The methodology of the same is as below;

a) In the event of the quoted RAP of "Any Bidder(s)" falling within 5% of the "Quoted RAP of the Lowest Bidder", such bidder(s) is given a chance to entre into a Call out (voice auction) against the Lowest Bidder.

b) The call out happens on the spot and minimum reduction required for call out is decided by the Auction convener on the Spot. The process carries on till discovery of the LOWEST RAP.

c) Advantages of above ANEEL Auction process**:**
   - There is no pre-information of a Pre-Qualified Bidders available to Bidders.
   - For Being Qualified Everybody quotes the Best and most competitive RAP.

VI.% Key Differentiators

1. Robust planning process – which gives the USERs (mainly generators) a fare estimate of the transmission tariff for the usage of basic network and allows them to factor the same for long term generation contracts.
2. Upper CAP on Transmission Tariff: the British price cap model for determination of RAP allows regulator to fix the Maximum RAP (or a ceiling tariff), with the conditions that all bidders must quote below the same, thus protects consumers against any possible situational profiteering.
3. Process of posterior assessment of qualification credentials of the "Successful Bidder" only saves lot of time to the Regulator (ANEEL) compared to time lost in India in assessment of qualification of multiple bidders.
4. This also takes away pre -visibility of possible competition and therefore no chances of Collusive or Corrupt practices.

5. Overall the auction process is conducted extremely efficiently within a period of 120-150 days including all activities from Notification to Award of concession, controlled parallelly.
6. The call out condition that prevents bidders with quoted RAP of more than 5% of the bidder keeps all the serious players interested in the process till the end, fighting to price out the competition by more then 5% or in other way securing to be within 5% (which is more unpredictable). Thus, increasing the competition and forcing bidders to put their best foot forward at the first instance, at the same time giving equal chance to competitively placed serious bidders to further reduce the price during call out, and thus bring the best price to consumers.
7. Apart from the above, the Concession format incentivizes "Early Completion" of the project within prescribed limits of the usance (usability) of the element provided within the frame work. Such provision helps and incentivizes those concessionaires who expedite the system faster.

   The Concession agreement within itself defines, apart the Scheduled date of Commercial operation, an earlier possible date on which the commercial operation can occur provided all interconnection facilities are in place and a USER defined date, in case the user wants the system earlier than the Scheduled date.

   The concession agreement within itself, provides for the clause for the purpose of interpretation and implementation of System, at an earlier date provided it is mutually useful for the USERs, Concessionaire and the System.

VII.% Conclusion

While the payment security under POC mechanism (collection and disbursement mechanism) is the most robust in India, thus giving much needed security to the investor, many of the concepts in Brazilian system are worth emulating:

a. Annual adjustment of Tariff against inflation: a practice that protects the investor to a large extent against any possible escalation of price of commodities and services and thus giving him the opportunity to put most aggressive pricing.
b. Periodic review of RAP: Regular periodic review of Tariff gives both Investor and the Consumer protection against variation in the interest rates and spread on long term financing a concept missing in India so far.
c. Provision within the Concession Agreement to incentivize the "Early completion" of the project subject to system usability thus making it flexible for the concessionaire attractive enough to out his efforts.
d. Robust bidding process which enable and forces the bidders to Quote the most aggressive "Tariff" and provides all bidders an equal opportunity to participate in the commercial bid process.

References:

1. International Experience with Private Sector Participation in Power Sector, Brazil Case Study, The World Bank Group, October 2012
2. Framework for transmission line Public-Private-Participation (PPP) project, USAID and Power Africa, December 2016
3. Overview of the Transmission Lines Sector in Brazil, KPMG, April 2017

ADDRESSING CHALLENGES FOR GRID INTEGRATION OF RENEWABLE ENERGY IN INDIAN POWER SYSTEM AND FRAMEWORK FOR HYBRID RENEWABLE ENERGY DEVELOPMENT

(In order to accomplish the target of 175 gigawatt [GW] of renewable energy [RE] capacity addition by 2022, there are several key implementation challenges that need to be addressed. Several measures and initiatives on planning standards, process, interconnection modalities, operating code, forecasting/scheduling and imbalance handling mechanisms are necessary to manage such large variable RE generation into grid. However, this Research Paper focuses on thematic issues on managing grid integration and identifying key challenges in the development of hybrid RE projects, exploring options to address them and evaluate potential policy, regulatory and utility process level intervention measures. The paper also suggests framework for harnessing hybrid RE potential in the country.)

Title of the Project	**Addressing Challenges for Grid Integration of Renewable Energy in Indian Power System and Framework for Renewable Energy Hybrid Development**
Name of the Head Researcher	**Mr. Ajit Pandit** **(Email): ajit.pandit@idaminfra.com** **(Cell): +91 98211 08222** **(Tel): +91 022 4057 0202**
Affiliation to Industry/Institution	**Director, Idam Infrastructure Advisory Pvt. Ltd.**

1 Introduction: Renewable Capacity Addition Target of 175 GW

India has witnessed substantial addition of RE capacity over the past two decades. Presently, India's installed RE capacity has grown from a mere 0.34 GW in 1995 to over 62 GW, registering more than 150-fold growth during this period. Looking ahead, India plans to achieve another three-fold increase by 2022, reaching 175 GW of installed RE capacity, with a mix of 100 GW from solar, 60 GW from wind, 10 GW from biomass and 5 GW from small hydropower *(revised timeline by 2019)*. As per the commitments at Conference of Parties (COP21), India has proposed to develop 40% of the installed capacity from renewable sources by 2030.

With such a huge quantum of capacity addition planned over the next four to five years, it is critical that the frameworks and building blocks required to achieve this capacity addition be in place — ranging from proactive policy and regulatory regime, availability of finance and basic infrastructure such as land, approach roads, ability to access and evacuate the power, facilitative framework for offtake arrangements, and ease of market access. The latter points are particularly important, since the development of appropriate grid evacuation and access infrastructure is critical to absorb power into the grid once the RE projects are commissioned.

2 Key Challenges: Large Scale Capacity Addition of RE

To facilitate large-scale grid integration of RE sources, it is important to address the major challenges in existing framework and evolve measures dealing with every aspect of planning, construction, operation and market access to facilitate RE integration within the power system.

Following sections cover the key thematic issues, challenges and potential mitigation measures associated with large scale proliferation of RE.

Figure 1: Key Focus Areas for Large Scale Capacity Addition of RE

Grid Integration of RE *(Supply Measures)*	**Market Access for RE** *(Demand Measures)*
Key Focus Areas • Aligning grid planning process for RE • Uniform approach for interconnection processes across states • Managing variability and infirm nature of RE generation • forecasting and scheduling (F&S) regime • Institutional capacity building requirement at State Load Despatch Centre (SLDC)/RE • Development of ancillary services • Hybrid approaches and solutions • Energy storage development • Creation of RE infrastructure zones — RE UMPPs, Parks	**Key Focus Areas** • RE procurement models • Pricing framework — Feed-in tariff (FiT) and/or competitive procurement of RE • Resource Purchase Obligation (RPO) target setting: National versus state perspective • Enforcement measures and compliance monitoring framework • Enhancing voluntary participation in RE market • Transmission pricing and wheeling charges for RE • Ease of market access

Several key focus areas have been broadly categorised into two thematic issues, namely, (a) supply side measures for managing grid integration of RE and (b) demand side measures enabling market access for RE proliferation. However, this Research Paper focuses on thematic issues on managing grid integration on supply side and suggests potential intervention measures thereof. Further, this Research Paper focuses on identifying the key challenges in the development of hybrid RE projects, exploring options to address them and evaluate potential policy, regulatory and utility process level intervention measures. The paper also suggests framework for harnessing hybrid RE potential in the country.

3 Managing Grid Integration of RE (Supply Measures)

The process of managing grid integration of renewable entails critical analysis of governing rules, codes, implementation processes and practice directions covering three phases, viz., planning, construction and development and operational phases.

3.1 Planning Phase

3.1.1 Aligning Grid Planning Process for RE

The activity of transmission planning has been aligned with conventional generation and transmission requirements for conventional power evacuation. The planning for expansion of transmission infrastructure rarely considers the need for RE evacuation requirements. Central Electricity Authority (CEA) has been vested with the function to formulate a National Electricity Plan, of which, National Transmission Plan forms a crucial component. The state level transmission plans are formulated by the state transmission utilities (STUs) in accordance with the provisions of the State Grid Code. Unless the process for planning transmission capacity incorporates a long-term vision of planned RE capacity additions and involves RE stakeholders at the planning stage, it is expected that bottlenecks in RE evacuation capacity will remain. In 2013, CEA has devised Transmission Planning Manual which recognises the need to have separate transmission planning criteria and standards for the development of evacuation infrastructure regarding wind-solar power. However, it has been rarely followed at state level by the STUs. Instead, STUs insist on the transmission planning criteria as applicable for conventional power onto RE projects.

Potential Intervention Measures:

- There is a need to devise separate planning standards and criteria for evacuation and transmission for RE (especially wind-solar) projects. Transmission Planning Manual and conditions formulated by CEA for wind-solar should be reflected in the State Grid Code and RE transmission plans approved by the STU at the state level.
- There is a need for separate institutional arrangement to address concerns of evacuation and transmission planning for RE projects. A separate RE Transmission Planning Authority or Dedicated Wing within CEA may be constituted for the purpose.

3.2 Construction and Development Phase

3.2.1 Ensuring Uniform Approach for Inter-Connection Processes Across States

One of the major barriers encountered by RE generators and developers is the non-uniform approach and diverse set of practices followed by the utilities across states for interconnection of RE projects. Numerous differences exist regarding interconnection, such as definition of an interconnection point, applicable charges for interconnection, permission and clearance, and the contractual framework for an interconnection agreement.

In addition, practices vary depending upon the type of RE project (e.g., wind or solar), and this often results in significant delays in implementation. There is an urgent need to devise a standard methodology to be followed across states, and the protocols that institute uniformity in the interconnection processes. Central Electricity Regulatory Commission (CERC) has recently formulated draft Connectivity and General Network Access Regulations, 2017, and initiated stakeholder consultation process for connectivity to ISTS connected projects. Detailed procedures are yet to be formulated. However, there is an urgent need to evolve Standard Connectivity Regulations and Model Procedures for connectivity of RE projects at the state level.

Potential Intervention Measures:

- It is desirable to develop standard, or model, interconnection procedure(s) for interconnection of various RE technologies at the national level and state level for similar voltage levels.
- Appropriate model for sharing responsibility among RE developers and transmission and distribution utilities, regarding development and construction of evacuation infrastructure should be put in place with clear demarcation of roles/responsibilities.
- Options for funding and sharing the evacuation infrastructure among RE generators, transmission utilities, transmission system users should be explored.

3.3 Operational Phase

3.3.1 Managing Variability and the Non-Firm Nature of RE Generation

The generation pattern from renewable sources is not uniform resulting in intermittency in generation. With the present practice of state boundary as area control centre, the state grid can accommodate small amounts of intermittent electricity generation. However, large-scale penetration requires rebalancing the different elements of electricity system: generation, transmission, demand management, and regulation. At present, the states are using hydro resources, limited gas based generation with peaking capacity, unscheduled interchange mechanism and load management as tools to deal with variable renewable generation in renewable rich states. The mitigation of intermittency must address both variability and uncertainty. A variable, but predictable resource can be managed with careful day-ahead scheduling.

3.3.2 F&S

Mechanism for F&S is crucial; however, no F&S regime would be adequate without addressing the associated issues of load-generation balancing rules, despatch mechanism, deviation settlement mechanism, mechanism for generator payments and institutional framework to operationalize the same. Several wind rich states have state specific grid codes but differ in eligibility criteria for generators to be covered under scheduling regime, load generation balancing and generator payments. In fact, in most of the states, generator payments for intra-state transaction is linked to actual generation whereas for all inter-state transactions, generator payment is linked to schedule generation. This calls for operationalization of state imbalance pool to facilitate the state entities undertaking inter-state transactions. However, except in few states, state imbalance pool and intra-state availability based tariff (ABT) mechanism is not yet operationalised. Model framework for composite F&S regime (viz., decentralised forecasting and centralised scheduling) at the state level is essential to address several implementation issues. The Technical Committee of Forum of Regulators (FOR) has formulated Model F&S Regulations and Model Deviation Settlement Mechanism (DSM) Regulations at the state level and also initiated steps to roll out the same at various states. However, the same will be adopted at the state level upon due regulatory process expeditiously. The status update of F&S Regulations at the state level is summarised in Table 1.

Table 1: Status Update of F&S Regulations at State Level (as on December 2017)

Sr. No.	Particulars	FOR Model F&S	APERC (final)	KERC (final)	RERC (final)	MPERC (draft)	TNERC (draft)
1	Applicability	Wind and solar generators selling power within or outside the state	Wind and solar generators selling power to discoms/third party sale/captive consumption through OA within or outside the state	Wind generators combined capacity 10 MW and above. Solar generators capacity 5 MW and above within or outside the state	Wind and solar generators selling power to discoms/third party sale/captive consumption through OA: >5MW connected to state grid	Wind and solar generators selling power within or outside the state	Wind and solar generators (excluding Rooftop PV Solar Projects) selling power within the state
2	Forecasting Responsibility	Wind and solar generator or by QCA Or forecast by SLDC to be accepted	Wind and solar generator or by QCA Or forecast by SLDC accepted	Wind and solar generator or QCA or aggregator Alternatively through REMC	Wind and solar generator or by QCA Or forecast by SLDC accepted	Wind and solar generator or by QCA Or forecast by SLDC accepted	Wind and solar generator or by QCA Or forecast by SLDC accepted
3	Scheduling Responsibility	Wind and solar generator or by QCA	Wind and solar generator or by QCA	Wind and solar generator or QCA or aggregator. Alternatively through REMC	Wind and solar generator or by QCA	Wind and solar generator or by QCA	Wind and solar generator or by QCA
4	Computation of Error Formula	Available Capacity in denominator	Available Capacity in denominator	Available Capacity in denominator	Available Capacity in denominator	Available Capacity in denominator	Available Capacity in denominator
5	Tolerance Band for DSM	10% new wind and solar generator. <=15% existing wind and solar generator	± 15% for wind and solar generators	± 15% for wind and solar generators	± 15% for wind and solar generators	<=10% new wind and solar generator, <=15% existing wind and solar generator	± 10% for wind & solar generators.
6	Scheduling Requirement	Weekly and day-ahead with maximum 16 revisions during a day	Weekly, day-ahead and intra-day with maximum 16 revisions during a day for wind and max. 9 revision for solar	Weekly, day-ahead and intra-day with maximum 16 revisions during a day	Weekly and day-ahead with maximum 16 revisions during a day	Weekly and day-ahead with maximum 16 revisions during a day	Weekly and day-ahead with maximum 16 revisions during a day
7	Reference point for DSM	Pooling station	Pooling station	Pooling station/ Aggregator Level	Pooling station	Pooling station	Pooling Station

3.3.3 Capacity Building of SLDCs

Numerous states have inadequate information technology (IT) infrastructure to track real time generation at pooling stations and visibility of wind-solar generating stations (embedded or otherwise) to SDLCs is still a challenge. This calls for developing standardised practises and protocols that can be adopted across states on one hand and setting up of a robust institutional framework at the state level for buoying up the grid integration of wind-solar generators. Institutional framework and capacity building of SLDC is the key for implementation and managing variable RE into the grid. National Load Despatch Centre (NLDC)/Forum of Load Despatchers (FOLD) regularly conducts several capacity building and training/certification programs. SLDCs should ensure continuous participation in such programmes.

3.3.4 Ancillary Services Operations

One of the tools that the system operator can use to manage the grid is the development of framework for ancillary service operations through market mechanism or otherwise. Using the ancillary services market, system operators can maintain the stability of the grid even in cases where there are sudden variations in RE generation. CERC has notified Ancillary Services Market Regulations and its successful operations at the national/regional level. It has also witnessed active participation by various stakeholders facilitating quick ramping up/down as per grid requirements. However, the industry response and learning for such market operations to expand wider participation and operations at the state level is need of the hour.

3.3.5 Energy Storage Devices

Energy storage devices play a key role in optimizing supply and demand imbalance, and thereby support the growth of intermittent RE sources. It is estimated that the market potential for energy storage devices and applications in India is in excess of 20 GW. However, no suitable policy and regulatory frameworks exist for integration of storage into the grid and its operations. Effective policy and regulatory signals should be developed to allow the development of a stand-alone energy storage market, with energy storage operators servicing large scale grid integration of RE.

3.3.6 Hybrid RE Solutions

The development of hybrid RE solutions (typically wind-solar) allows improved utilisation of the use of evacuation infrastructure, and at the same time can at least partially address variability in generation. Hybrid RE solutions can be designed to ensure a more consistent power generation output that can be fed to the grid. However, the development of such schemes face various technical, commercial and regulatory challenges. The technical challenges include interconnection arrangements, metering and energy accounting mechanisms. The commercial and regulatory challenges include applicable tariff and regulatory treatments for RPO, frameworks for commercial settlements, offtake arrangements etc. It is a prerequisite that suitable policy measures and regulatory frameworks should be established before these hybrid solutions are developed.

4 Framework for Promoting Development of Hybrid RE

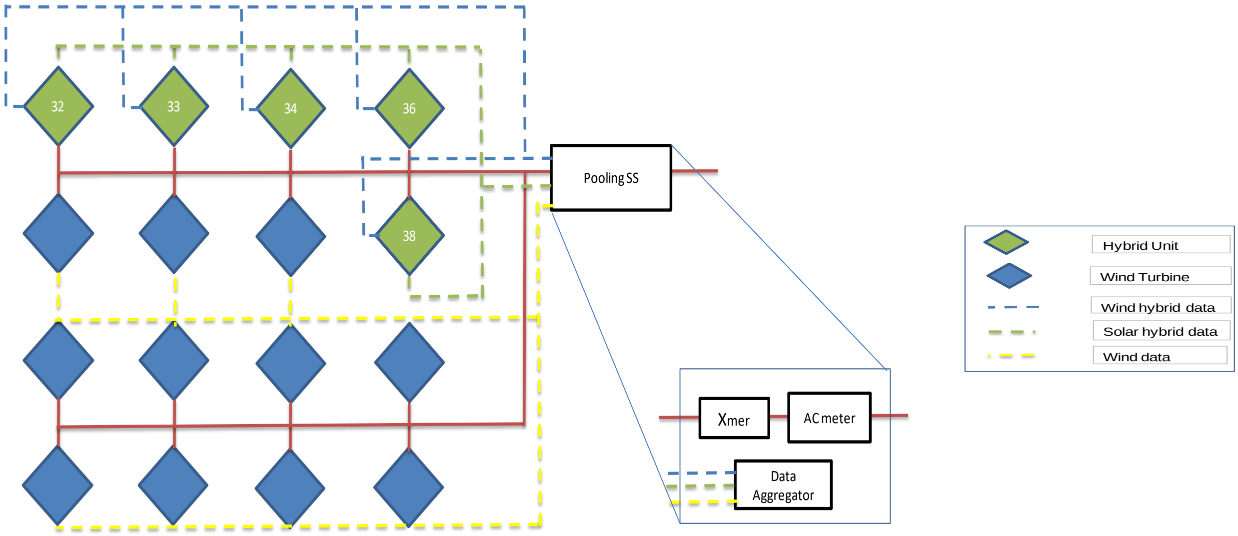
The Government of India has announced ambitious target of over 100 GW of solar and 60 GW of wind capacity addition by 2022. These technologies present commercially viable solutions to mitigate climate change, enhance energy security, as well as improve access to clean energy. However, there exists scope for further optimisation on various parameters such as improvement in capacity utilisation factors, grid integration and commercial integration. Standalone power projects based on wind or solar energy technology suffers from the following limitations as compared to hybrid RE (wind-solar):

- Sub-optimal utilisation of land
- Need for establishment of separate connectivity and evacuation infrastructure
- High cost of interconnection, evacuation infrastructure and lower utilisation
- Variable power generation profile with seasonal variation in power output

Above limitations can be addressed by devising wind-solar hybrid RE project. A typical wind-solar hybrid power plant consists of a separate wind power generating system and solar power generating system which are connected via a common interconnection point (pooling substation) and evacuation arrangement. The two power generation systems (wind-solar) may function independently or can be programmed to be despatched simultaneously. For the purpose of energy accounting and billing, the two systems are separately metered, and the combined power is obtained only beyond the interconnection point[1]. The structure and operation of typically co-located wind-solar hybrid RE power plant is represented in Figure 2.

[1] As per CEA (Technical Standards for Connectivity to the Grid) Regulations, 2007, interconnection point means a point on the electricity system, including a substation or a switchyard, where the interconnection is established between the facility of the requester and the grid and where electricity injected into or drawn from the grid can be measured unambiguously for the requester.

Figure 2: A Co-Located Wind-Solar Hybrid RE Power Plant



4.1 Advantages of Hybrid RE (Wind-Solar) Project Development

There are essentially two ways to develop hybrid (wind-solar) RE project, namely, (a) Greenfield hybrid (wind-solar) RE project and (b) Brownfield hybrid (wind-solar) RE project. Under Greenfield hybrid RE project, significant flexibility exists to devise configuration, capacity mix (wind-solar), generate and evacuate planning regarding resource assessment and site specific considerations. However, under Brownfield hybrid (wind-solar) RE project, while design flexibility and configuration options are limited, the development time can be significantly curtailed due to the availability of land and existing infrastructure. In a typically co-located Brownfield hybrid (wind-solar) RE project, solar panels are installed in the vacant spaces between the wind turbines upon addressing the shadow effect. This enhances power generation from the given land mass harnessing both the RE sources. The said hybrid models address the above referred limitations as under:

- **Improved Land Usage:** Wind farms with turbines of higher capacities have vacant land in between turbines which can be productively used by installing solar power plants on the land after considering the shadows cast by the wind turbine.
- **Shared Interconnection Infrastructure:** As the solar and wind power generating units of the hybrid power plant are located in the same area, the same pooling substation being used for interconnection of wind power can be used for solar power as well. This reduces the cost that may be incurred in commissioning a separate evacuation infrastructure or a substation for the solar power generation.
- **Improved Power Generation Profile:** Maximum wind power generation occurs during the night and during high wind season commencing predominantly from June to September. Whereas, maximum solar power generation occurs during the day time and in the summer months. Thus, in general, a lower generation from one source is

compensated by a higher generation from the other. Therefore, a more consistent power generation profile is obtained.

4.2 International Experience of Hybrid RE (Wind-Solar) Development

Globally, wind-solar hybrid RE development is at an initial stage of development with few wind-solar hybrid RE projects commissioned in the past two to three years and few hybrid projects are under planning stage.

There are few demonstration and pilot projects that have been successfully implemented.

Grand Ridge Energy (111 Megawatt [MW] Wind and 20 MW Solar), Merseilles, Illinois, United States (U.S.) 	**Zhangbei National Wind and Photovoltaic (PV) Energy and Storage (100 MW Wind, 40 MW PV and 39 MW Storage)** Zhangbei, Hebei Province, China 

Source: www.cleanenergyactionproject.com

Some relevant features about such projects are briefed in Table 2.

Table 2: Salient Features

Name of the Project	Location	Commissioning Date	Rated Capacity	Project Owner	Generation Off Taker
Pacific Wind and Catalina Solar Project	Kern Country, California	**Phase 1:** 60 MW Solar in April 2012 **Phase 2:**70 MW Solar in 2013 **Phase 3:** 140 MW Wind Under Construction	Catalina Solar: 130 MW Wind:140 MW	EnXco	San Diego Gas and Electric 25 Year Power Purchase Agreement (PPA)

Name of the Project	Location	Commissioning Date	Rated Capacity	Project Owner	Generation Off Taker
Zhangbei National Wind and PV Energy Storage Project	Zhangbei, Hebei Province, China	2011	Wind – 100 MW Solar PV – 40 MW Battery Storage – 36 MW	State Grid Corporation of China (SGCC)	SGCC
Grand Ridge Energy Centre	Merseilles, Illinois, U.S.	GRI-2008 GR II-IV-2009 GR Solar – Under Construction	GRI-99 MW GR II-IV – 111 MW GR Solar – 20 MW	Invenergy LLC	Unknown

Source: www.cleanenergyactionproject.com

4.3 Key Implementation Challenges for Hybrid RE Project Development

While several small scale (Watt [W] and kilowatt [kW] range) hybrids schemes are operational for some time, there are no MW class hybrid installations yet established in India. Several technical studies and implementation roadmap for promoting hybrid RE installations have been contemplated by policy makers and planners. The main challenges associated with implementation of such a model is briefed below:

- **Interconnection Point:** The grid connectivity regulations and state grid code defines the interconnection point in case of wind generating station or solar PV power plant as a line isolator on high-voltage (HV) side of outgoing feeder of pooling substation located at wind farm or solar farm generation site. However, there are different practices being followed across states wherein interconnection point is stipulated as interface point with the grid/transmission substation. It is necessary to clearly define interconnection point and interconnection requirement for hybrid RE project as hybrid RE project design is based on exploiting the available interconnection and evacuation infrastructure.
- **Metering and Energy Accounting:** The key challenge in metering arrangement for hybrid scheme is to establish the mechanism to measure generation output of individual turbine/plant and simultaneously measure the aggregate generation at the pooling station level. This is important to measure the solar and wind energy generation separately. In this context, it will be difficult to establish the generation from wind turbines and solar plant separately, which is an important requirement from tariff

perspective as well as for the purpose of energy accounting towards the fulfilment of solar and non-solar RPO targets by utility/obligated entity.

- **Treatment for Commercial Settlement:** In case of brownfield hybrid RE projects, modification will be incorporated for the treatment of commercial settlement under the existing power sale arrangement. The commercial settlement of the existing power sale would involve multiple stages of joint meter reading, issuance of energy credit notes, energy accounting by SLDC on 15-min basis and finally adjustment in the bill as per the state-wide energy accounting mechanism prevalent in the state. Thus, there exists clarity on these stages of commercial settlement for the standard RE (non-hybrid) transactions. However, there is no clarity on the treatment of commercial settlement in terms of transaction involving hybrid RE plants. Necessary modifications will be done to identify the requirement of hybrid RE project and its treatment under the existing energy accounting and settlement process. Detailed procedures will be laid down in this context.
- **Tariff Treatment and Offtake Arrangement:** While hybrid RE (wind-solar) has not been separately covered under the existing generic RE Tariff Orders by SERC/CERC, separate preferential tariff rates for wind energy and solar PV technology has already been specified by many SERCs/CERCs. Suitable modifications in the PPA would be necessary in case of brownfield Hybrid RE projects. Upon suitable modification and approval of metering arrangement as relevant for hybrid RE, it is possible to separately account for actual generation from wind power and solar energy. Further, it is essential for hybrid RE developer to enter into Energy Purchase Agreement (EPA) or modify the existing PPA to cover for sale of wind-solar energy separately.
- **RPO Treatment:** The present regulatory framework by any SERC does not stipulate composite RPO settlement for solar and non-solar based on power purchase from hybrid RE projects. Accordingly, for RPO settlement in case of purchase from hybrid RE project is to separately consider the wind-solar energy generation towards non-solar RPO and solar RPO respectively. This mechanism again depends on the suitable modification in the metering arrangement and its acceptance by the concerned utilities.

4.4 Potential Policy and Regulatory Intervention Measures

With an aim to encourage large scale deployment of hybrid RE (wind-solar) power projects in India, several policy and regulatory intervention measures is essential. Some of the key policy and regulatory intervention measures have been highlighted below:

- **Guidelines and Eligibility Criteria for Recognition of Hybrid RE:** At present, preferential tariff (FiT) as approved by CERC/SERC is applicable only in case of eligible RE technologies as approved by CERC/SERC under RE Tariff Regulations.

Most of the RE tariff regulations do not explicitly recognise hybrid (wind-solar) RE as eligible RE technology for the purpose of applicability of preferential RE tariff. CERC's RE Tariff regulations have covered hybrid solar thermal and defined the eligibility criteria. However, it has not covered hybrid (wind-solar) RE as eligible RE technology. It is necessary that Ministry of New and Renewable Energy (MNRE) issue guidelines to cover standard definition and eligibility criteria to cover 'Hybrid RE' (wind-solar) including the configuration/capacity mix to be eligible for regulatory and policy benefits. Accordingly, CERC/SERCs can allow such hybrid RE (wind-solar) projects for preferential tariff treatment and RPO compliance, as necessary.

- **Priority of Preference in Transmission/Evacuation Planning:** Considering significant advantages and better utilisation of evacuation/transmission infrastructure, it is necessary that hybrid RE schemes receive priority preference in terms of interconnection and despatch as against standalone RE schemes. As a part of National Electricity Policy and Plan, the central government can issue guidance to CEA to consider transmission and evacuation planning of hybrid RE schemes on priority. Accordingly, the same would form basis for transmission system plan(s) to be formulated by Central Transmission Utilities (CTUs)/STUs, an important aspect of overall transmission and evacuation planning for renewable energy. Some of the ongoing schemes under green energy corridor could be reviewed with a focus on hybrid RE development.
- **Funding Support to STU/CTU Through Power System Development Fund (PSDF):** In addition to planning, the states may be encouraged to invest in evacuation/transmission infrastructure specifically catering to hybrid RE schemes, as covered under the CTU/STU plans. As an encouragement to STU to prioritise evacuation/transmission schemes for hybrid RE, evacuation schemes for hybrid RE up to 500 MW could be provided with funding support/incentive/concessional funding/loan support.
- **Applicability of Fiscal Incentives/Benefits:** It is necessary to confirm that Generation Based Incentive and Accelerated Depreciation Benefits as available for standalone wind or standalone solar generation projects shall continue to be available/applicable for hybrid RE projects as well. Suitable modification in the existing ongoing programs/schemes to this effect will be undertaken.
- **RPO Compliance/Renewable Energy Certificate (REC) Benefits:** Investment in the hybrid RE projects shall be eligible for fulfilment of solar and non-solar RPO targets on proportionate basis of actual generation (wind-solar). Further, to encourage investment in hybrid RE and to offset initial incremental investments, the multiple

RECs by factor (say 1.25) could be made applicable for generation from hybrid RE (wind-solar).

- **Amendment to Metering Procedure/Protocol:** Existing practices and codes for metering will be modified to recognise separate metering and energy accounting requirement for wind-solar generation despite having single metering point/common metering infrastructure at common interconnection point. This requires separate data aggregators and de-pooling arrangement and modification to existing joint meter reading practices. A common protocol for modification to metering procedures could be evolved in consultation with the CEA.
- **Simplified Procedures for Energy Accounting and Commercial Settlement:** Standard procedures and protocol may be evolved for simplified procedures of energy accounting and commercial settlement of hybrid RE transactions. FOR could evolve Model Guidelines for the same which can act as a reference document for the state utilities and SLDCs.

4.5 Summary for Hybrid RE Development

There are several advantages for encouraging hybrid (wind-solar) RE installations in the country. From the utility perspective, higher utilisation factor for evacuation and transmission infrastructure, improved generation profile and reduced variability/intermittency in generation are the key advantages, whereas from the developer perspective, additional generation, exploiting economies for operations and maintenance (O&M) set up and gainfully utilising available land and other infrastructure are the key driving factors for hybrid RE.

However, there are several implementation challenges and risks perceived by the developers/utilities alike, as global experience is also limited for designing and operating such utility scale hybrid RE schemes. Suitable policy and regulatory interventions is necessary to encourage investments in this promising sector. Few pilot and demonstration projects in some states (brownfield or otherwise) with the support of MNRE would go a long way in garnering insights into technological, operational and commercial aspects of hybrid RE (wind-solar) schemes.

5 Summary of Potential Intervention Measures for Managing Grid Integration of RE

Table 3: Summary of Potential Intervention Measures

Focus Areas	Description of Thematic Issues	Potential Intervention Measures
Planning Phase	• Aligning grid planning processes for RE. • Emphasis on RE under state level planning.	• Recognition of planning standards and criteria for RE. • Creation of RE transmission planning authority.
Construction and Development Phase	• Uniform procedures and practices for interconnection for RE across states. • Facilitative framework for grid access and interconnection for RE. • Uniform standards for communication and metering infrastructure.	• Model interconnection standards for RE (wind-solar). • Options for funding and socialising the cost of RE evacuation infrastructure. • Common code for development of communication and metering infrastructure.
Operational Phase	• Framework for F&S regime and imbalance settlement at the state level. • Seamless integration of state level and regional level framework to facilitate inter-state/inter-regional transfer of RE power. • Need for institutional capacity building at SLDC and RE developers.	• Model regulations for F&S regime and Model DSM Code addressing state specific variations. • Model Code for communication to be formulated. • Need for empanelment of institutional set up — Qualified Coordinating Agency (QCA)/Renewable Energy Management Centre (REMC) etc. • Training and capacity building initiatives at the national level under the aegis of NLDC/FOLD.
	• Development of ancillary services market.	• Rules for ancillary services and amendment to expand the scope and coverage of ancillary services.
	• Deployment of storage capacities with variable RE generation.	• Development of multiple pilot /demonstration storage projects. • Mandatory installation of storages for mega/ultra-mega RE projects.
	• Development of hybrid RE solutions and integrated	• Amendments to codes to address technical challenges for hybrid RE

Focus Areas	Description of Thematic Issues	Potential Intervention Measures
	approach for harnessing multiple RE resources.	• Modifications to open access (OA)/FiT/RPO regimes and regulations to address commercial challenges of hybrid RE development.

Flexibility in Transmission Switching for Congestion Management

Akhil Kumar Gupta, Deep Kiran and A. R. Abhyankar

Abstract

In decentralized dispatch philosophy, system operator (SO) only deviate the final schedules in order to maintain network security (i.e. line overloading, outages, voltage and frequency deviations, etc.) in real time operation. Before going for the dispatch deviations, SO has the option of changing the network topology (i.e. switching of transmission lines) so as to redistribute the power from anticipated overloaded lines to under-utilized lines based on Kirschoff's laws. Presently, this is performed based on SO's experience which may alleviate the overloading, however, this may not be the optimal way. Moreover, change of network topology may initiate steady state angular stability issues in case of any erroneous set of schedules. Therefore, this paper proposes a mixed integer type transmission switching problem (TSP) so as to optimally define the set of lines to be opened in order to alleviate overloading such that the angular stability is maintained. A detailed comparison of the proposed formulation with and without steady state angular stability constraints are presented. It is observed that for the same set of schedules, the number of lines to be opened changes with respect to the steady state angular stability constraints. The proposed formulation is verified on PJM 5-bus and IEEE 118-bus system.

Nomenclature

α Upper limit on number of open transmission lines.

β_{ij} Difference between base case and post line switching angular differences between i^{th} bus and j^{th} bus.

δ_i Voltage angle at i^{th} bus.

δ_{ij} Angle difference between i^{th} bus and j^{th} bus post line switching (i.e. $\delta_{ij} = \delta_i - \delta_j$).

δ_{ij}^{base} Angle difference between i^{th} bus and j^{th} bus in the base case (i.e. $\delta_{ij}^{base} = \delta_i^{base} - \delta_j^{base}$).

$\overline{\beta_{ij}}$ Desirable angle difference between i^{th} bus and j^{th} bus for reliable and secure system.

$\overline{P_{ij}}$ Power flow limit of line connected between i^{th} bus and j^{th} bus.

G_i Unconstrained generation dispatch at i^{th} bus.

L_i Load at i^{th} bus.

M Large number.

N_l Number of lines in the base case.

P_{ij} Power flow in line connected between i^{th} bus and j^{th} bus.

u_{ij} Binary variable indicating status of line connected between i^{th} bus and j^{th} bus where $u_{ij} = 0$ represent open line and $u_{ij} = 1$ represent closed line.

x_{ij} Reactance of the line connected between i^{th} bus and j^{th} bus.

1 Introduction

With decentralized scheduling philosophy in India, demand and generation is to be balanced at State level. Each State is having its own generation as well as it schedules power from inter-State generating stations and merchant power plants to meet its load demand. The market participants provides schedule to SO and the generation of each plant is scheduled on “day ahead basis” but they are permitted to dispatch as per the system conditions with the aim to bridge demand-supply gap. Unlike the centralized dispatch where congestion management is integrated with SO optimization process for market clearing, in decentralized model, the SO will only deviate from the final contract schedules in the dispatch if it needs to do so in order to maintain network security. SO calculates and declares total transfer capability (TTC)/ available transfer capability (ATC) three months in advance and revise it based on outages and system condition changes. There is detailed procedure for relieving congestion in real time operation approved by the Central Commission [1]. SO declares congestion in real time in cases when the Grid voltage in the important nodes downstream/ upstream of the corridor is beyond the operating range specified in the Indian Electricity Grid Code (IEGC) [1] and/or real-time power flow along a corridor exceeds the ATC for that corridor for continuously one time block and/or transmission lines in the corridor are loaded beyond the operating limit. Once the congestion is declared, SO imposes the congestion charges [2].

In Indian grid, 6-7 years back, there were hardly any instances of congestion in inter-regional corridors. But now, congestion has become prominent due to advent of merchant power plants and evolution of power market where each buyer seeks to buy cheaper power available. States are backing down their own costly generations and procuring power from cheaper generating plants through inter-regional corridors either in bilateral trade or through power exchanges. Other reasons for congestion are such as delay in commissioning of critical inter-regional lines as well as intra-State transmission system, delayed commissioning of generating stations and skewed power flows due to power market etc. CAC sub-committee on congestion in transmission system in its report suggested measures to reduce congestion such as installation of more SPS, use of dynamic line rating, phase shifting transformers and expediting commissioning of transmission system etc [3].

Granelli et al. [4] has proposed transmission switching as a tool to manage congestion in the electrical grid. Operating procedures of the SO in Indian Grid specifies the line opening operation as a corrective measure in case of line overloading and to control high voltage conditions. SOs are not using line switching as a congestion management tool to relieve line overloading. These transmission assets are considered as static assets within OPF formulations and do not used flexibly as control asset by SO. However, it is acknowledged, both formally and informally, that SO can and do change the grid topology to improve voltage profiles, increase transfer capacity, and even improve system reliability [5]. In a large network, such flexibility of transmission switching in day-ahead dispatch can provide the optimal network topology for enhanced transfer capacity and better reliability [6]. Past research has shown that transmission switching can be used as a corrective mechanism to relieve line overloads and voltage violations, to reduce transmission losses and as a congestion management tool [5].

SOs follows the ad-hoc transmission switching protocols and usually on their discretion identify the key transmission lines that can be taken out of service for increasing transfer capability in other transmission lines, for controlling high voltages or for removing line overloading rather than adopting automated or systematic way. It is generally perceived that taking a line out of service for optimizing transmission topology reduces the system reliability as well as stability. But it is possible to relieve the line overloading by taking lines out of service and simultaneously maintaining the system security and reliability [6]. SO observes the angular differences between important buses through PMU to have reliable and secure power system. The Central Electricity Authority (CEA) manual on transmission planning criteria specifies that the angular separation between adjacent buses shall not exceed $30°$ as reliability criteria during no and single contingency [7]. In this paper, we do not ignore the importance of reliability, nor are we suggesting switching transmission at the expense of reliability and security of network operations. Therefore, we have considered the limit of $30°$ as the maximum angular separation between the connected adjacent buses while switching the transmission lines. In this paper, we have proposed a method to relieve overloading by transmission switching with considering steady state system stability by keeping the angular difference within limit between base case and post switching for all the connected transmission lines. Transmission lines that are open in the optimization of a network may be available to be switched back into the system as and when needed by the SO.

This paper is organized as follows: section II presents the mathematical formulations for the transmission switching problem. Section III discusses the results from using the proposed formulation on well known engineering test cases. Finally, the paper is concludes in section IV.

2 Mathematical Formulation

Our formulation of the transmission switching problem is a mixed integer type problem. Adding binary variables to a challenging non-convex, nonlinear program like in alternating current (AC) formulations may add the computational complexities. Therefore, direct current (DC) linear approximations are used for solving the transmission switching optimization problem.

We start with a basic formulation of economic load dispatch problem treating the network as *copper plate* (i.e. without considering line flow limits.). Therefore, some of the lines might get overloaded. We specify this as our base case solution. In the decentralized dispatch philosophy, the market participants provides injection and withdrawal schedules to the SO. The SO changes the schedule *only* in the case of non-secure network operation. Therefore, we consider the unconstrained generation of the base case to be fixed while solving the TSP to relieve line overloading by the SO. Additionally, we have considered the limit of 30° as the maximum angular separation between the connected adjacent buses and the angle difference between the base case and the post line switching within limit ($\overline{\beta_{ij}}$) as specified by SO.

Now we make changes to this base case to optimize TSP. In this new formulation, each line is assigned a binary variable, u_{ij}, that represents whether the line is in open (0) or closed (1) state. SO will restrict the optimization problem for the maximum number of transmission lines (α) to be opened. Because of the peculiar characteristics of electricity, it is possible to relieve the line overloading in the network by removing one or more number of lines from the network. Thus, the optimization problem will either return the result with one or more lines are opened such that the line overloading is removed or return the infeasible solution. In case of infeasibility, the system operator increases α to provide more flexibility. In the worst case scenario, if line overloading is not removed then it may re-dispatch the generations.

In this formulation, the power flow of an open line must be constrained to zero; an open circuit or conductor can transmit no power. Because of the constraint representing Kirchhoff's laws, the formulation of the problem is more complicated than simply limiting the power flow to $\overline{P_{ij}}$ times the binary variable. To avoid the possibility of limiting the power flows to zero on lines sharing the terminal nodes with the open line, the Kirchhoff's laws constraints is formulated as (3) and (4). In the proposed formulation, objective function is taken as to minimize the number of open lines to relieve line overloading as defined in (1). The nodal power balance is satisfied in (2). Using a large number (M), (3) and (4) represent the equality of power flowing in line based on angle difference and reactance. The equality is satisfied only when the line is in closed state. In case of the open state, the power flow becomes zero as mentioned in (5). The angular stability is satisfied by keeping the angle difference between the base case and post line switching within limit ($\overline{\beta_{ij}}$) as defined by the SO in (6), (7) and (8). It is to be noted that the angular stability is satisfied only for the closed lines as mentioned in (8). The SO defines the maximum number of open lines (α) as shown in (9). Additionally, the angle difference between adjacent buses are limited to ±30° as constraint in (10). The proposed TSP formulation is shown in (1)-(10).

$$\min_{u_{ij}} \sum_{ij}(1-u_{ij}) \tag{1}$$

subject to

$$G_i - L_i - \sum_j P_{ij} = 0 \ \ \forall i \tag{2}$$

$$\frac{\delta_{ij}}{x_{ij}} - P_{ij} + (1-u_{ij})M \geq 0 \ \ \forall i,j \tag{3}$$

$$\frac{\delta_{ij}}{x_{ij}} - P_{ij} - (1-u_{ij})M \leq 0 \ \ \forall i,j \tag{4}$$

$$\overline{-P_{ij}}u_{ij} \leq P_{ij} \leq \overline{P_{ij}}u_{ij} \ \ \forall i,j \tag{5}$$

$$\delta_{ij}^{base} - \delta_{ij} - \beta_{ij} + (1-u_{ij})M \geq 0 \ \ \forall i,j \tag{6}$$

$$\delta_{ij}^{base} - \delta_{ij} - \beta_{ij} - (1-u_{ij})M \leq 0 \ \ \forall i,j \tag{7}$$

$$-u_{ij}\overline{\beta_{ij}} \leq \beta_{ij} \leq u_{ij}\overline{\beta_{ij}} \ \ \forall i,j \tag{8}$$

$$\sum_{ij} u_{ij} \geq N_{br} - \alpha \tag{9}$$

$$-30^\circ \leq \delta_{ij} \leq 30^\circ \ \ \forall i,j \tag{10}$$

In the next section, we tested and analyzed the proposed formulation of PJM 5-bus system and IEEE 118-bus system.

3 Results and Discussion

To test the formulation presented above, we used the PJM 5-bus and IEEE 118 bus systems. For illustration purpose, the unconstrained DC optimal power flow (OPF) dispatches were taken as the base case schedules. Also, we assumed that resistance and shunt capacitance of lines were zero, ignored losses and reactive power, and did not perform any generator unit commitment, using instead the commitment profile of the base case. The proposed formulation was tested on the test systems to assess potential benefits of TSP.

3.1 PJM 5-bus system

The PJM 5-bus system was used to test and analyze the TSP formulation. The data for the test system was taken from [8]. The system consists of 5 buses, 6 transmission lines, 5 committed generators with a total capacity of 1530 MW, and 3 load buses with a total consumption of 1000 MW. The unconstrained generation dispatches were taken as base case schedules in which no transmission lines are opened. To observe the importance of stability constraints in the formulation, we ran the TSP with and without stability constraints as defined as (6), (7) and (8). Also, we kept α for both the cases as 6, i.e. all the lines are allowed to undergo switching.

Table 1: δ_{ij}^{base} of lines connected between i^{th} bus and j^{th} bus for the base case of PJM 5-bus system.

Line	1-2	1-3	1-4	2-3	3-4	4-5
$\delta_{ij}^{base}(degree)$	5.1134	3.65	-1.163	0.1089	1.5723	-4.8131

Table 1 represents the base case angle difference (δ_{ij}^{base}) between the adjacent buses. This solution was obtained when all lines in closed condition and no line flow limits were considered. It was observed in the base case that one line connected between 4-5, having capacity of 240 MW, was overloaded with the power flow of 282 MW.

Table 2: β_{ij} of lines connected between i^{th} bus and j^{th} bus with and without stability constraints. All the angles are in degrees.

Line	1-2	1-3	1-4	2-3	3-4	4-5
No stability limits	Off	10.4585	1.0372	1.9653	5.4046	Off
$\pm 10°$	0.2834	5.2331	1.0372	Off	0.2995	Off

When we ran the TSP without the stability constraints. Two lines, (i) 1-2 and (ii) 4-5, were opened to relieve the line overloading as shown in Table 2. In this case, the maximum β_{ij} found to be 10.4585° for line 1-3. For further improvement of system stability, maximum β_{ij} was specified as $\pm 10°$. When the stability constraints were imposed, the network topology changed to restrict the β_{ij} below $\pm 10°$. In this case, lines 2-3 and 4-5 were opened to relieve line overloading and to keep the angle differences within limits.

3.2 IEEE 118-bus system

As the PJM 5-bus system is a small system, therefore, to observe the efficacy of the proposed TSP formulation, a bigger configuration, IEEE 118-bus system was also used. The data for the test system was taken from [9]. The system consists of 118 buses, 186 transmission lines, 19 committed generators with a total capacity of 5859 MW, and 99 load buses with a total consumption of 4519 MW. The unconstrained generation dispatches were taken as base case schedules in which no transmission lines are opened. To observe the importance of stability constraints in the formulation, we ran the TSP with and without stability constraints as defined as (6), (7) and (8).

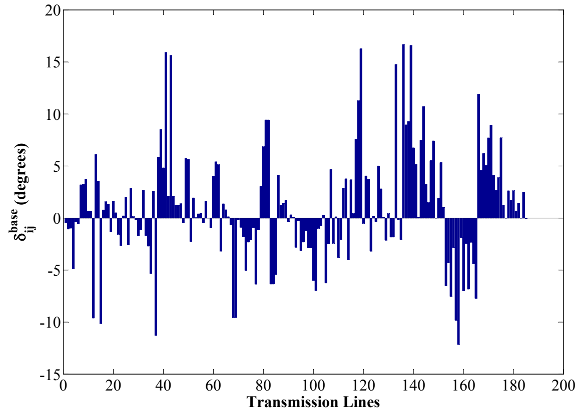


Figure 1: δ_{ij}^{base} of lines connected between i^{th} bus and j^{th} bus for the base case of IEEE 118-bus system.

Fig. 1 represents the base case angle difference (δ_{ij}^{base}) between the adjacent buses. This solution was obtained when all lines in closed condition and no line flow limits were considered. It was observed that total 5 lines were overloaded out of 186 lines in the base case as shown in Table 3.

Table 3: Overloaded lines in base case.

Line	$\overline{P_{ij}}$	P_{ij}
65-68	275	312.8943
68-81	275	318.3475
69-77	275	281.2639
77-82	275	302.102
81-80	275	318.3475

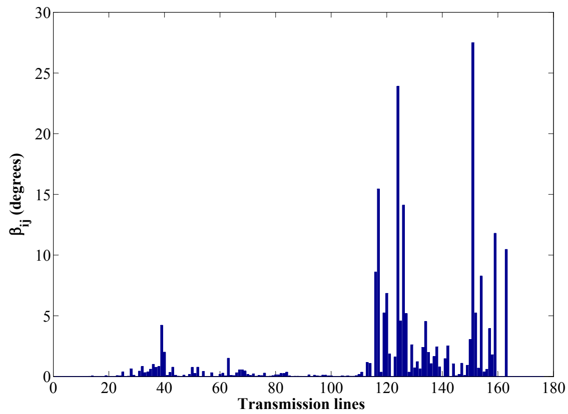


Figure 2: β_{ij} obtained without stability constrains for all lines connected between i^{th} bus and j^{th} bus of IEEE 118-bus system.

When the program was run without considering the stability constraints and considering the maximum number of open lines (α) as 10, total 7 lines (69-77, 77-80, 77-80, 79-80, 82-96, 92-94 and 93-94) were opened to relieve line overloading in the network. In this case, the maximum β_{ij} found to be 27.5005° for line 89-90 as shown in Fig. 2. It is also found that the maximum δ_{ij} between adjacent connected buses was increased from 16.6805° in base case for line 77-78 to $-39.6559°$ in post line switching case for line 88-89 as shown in Fig. 3. For further improvement of system stability, $\overline{\beta_{ij}}$ was specified as $\pm 25°$ and δ_{ij} is limited to $\pm 30°$.

When the program was run with considering the stability constraints as in (6), (7), (8) and (10) and considering the maximum number of open lines (α) as 10, total 8 lines (65-68, 69-77, 77-80, 77-80,

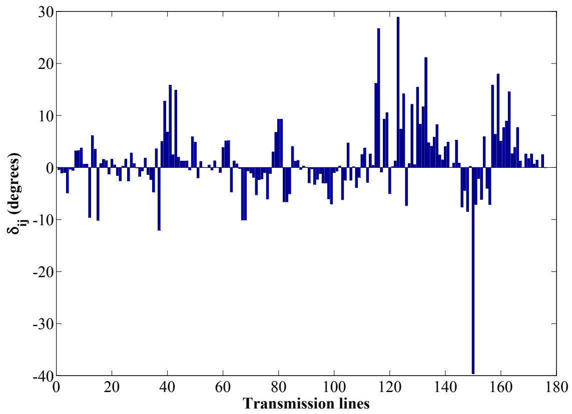


Figure 3: δ_{ij} obtained without stability constrains for all lines connected between i^{th} bus and j^{th} bus of IEEE 118-bus system.

78-79, 82-96, 93-94 and 94-96) were opened to relieve line overloading in the network. In this case, the maximum β_{ij} found to be 20.7483° for line 70-74 as shown in Fig. 4. The angle differences between all the connected adjacent buses were found to be within ±30° as shown in Fig. 5.

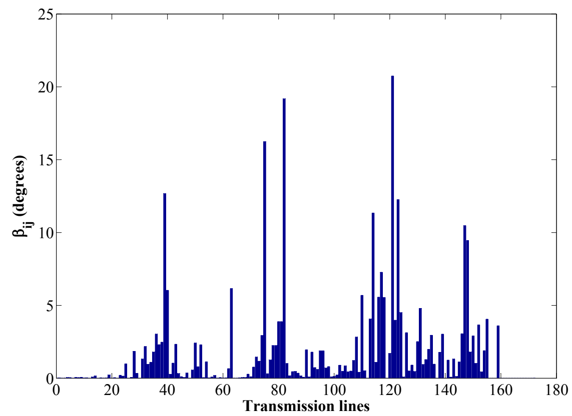


Figure 4: β_{ij} obtained with stability constrains for all lines connected between i^{th} bus and j^{th} bus of IEEE 118-bus system.

Therefore, one can infer that to achieve a more stable network topology the switching pattern changes with respect to the network stability constraints.

4 Conclusion

This paper presents an optimization model for determining optimal transmission network topology as congestion management tool for decentralized dispatch philosophy. We observed that line overloading can be removed by optimizing the transmission network topology, switching lines in and out, based on system conditions. The angle differences of connected adjacent buses between base case and post line switching constraints are used for maintaining the steady state system stability. Also the angle differences between connected adjacent buses are limited to ±30°. The improvement in line overloading is realized by changing the status of a few lines and takes a short time to compute. Switching transmission lines does not necessarily have a stable system. But after using the stability constraints, the lines are opened in such a way that angle differences of connected adjacent buses between base case and post line switching remains within limits and the system becomes more stable compared to the case when stability constraints are not imposed. Transmission switching control provides flexibility to SO in managing the congestion as preventive action and can result in more efficient transmission topology than static ones,

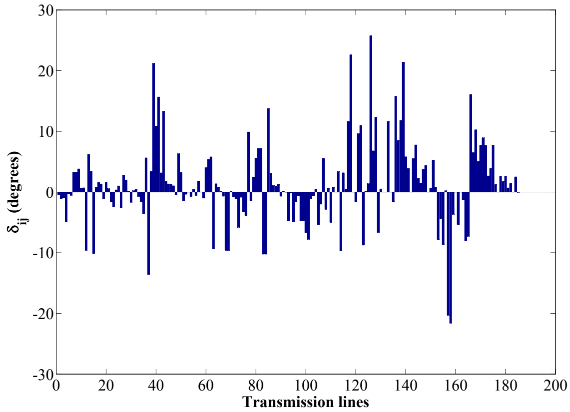


Figure 5: δ_{ij} obtained without stability constrains for all lines connected between i^{th} bus and j^{th} bus of IEEE 118-bus system.

even if the static ones were originally designed to be optimal. This paper is a first step in analyzing the potential benefits of transmission switching as congestion management tool in decentralized dispatch philosophy with steady state stability constraints.

References

[1] "Central electricity regulatory commission." [Online]. Available: http://cercind.gov.in/

[2] "National load dispatch center." [Online]. Available: http://www.nldc.in/

[3] "Report of the cac subcommittee on congestion in transmission," June 2015. [Online]. Available: http://www.cercind.gov.in/2015/Reports/congestion.pdf

[4] G. Granelli, M. Montagna, F. Zanellini, P. Bresesti, R. Vailati, and M. Innorta, "Optimal network reconfiguration for congestion management by deterministic and genetic algorithms," *Electric power systems research*, vol. 76, no. 6, pp. 549–556, 2006.

[5] K. W. Hedman, S. S. Oren, and R. P. O'Neill, "A review of transmission switching and network topology optimization," in *IEEE Power and Energy Society General Meeting*, 2011, pp. 1–7.

[6] E. B. Fisher, R. P. Neill, and M. C. Ferris, "Optimal transmission switching," *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1346–1355, 2008.

[7] "Manual on transmission planning criteria," January 2013. [Online]. Available: http://cea.nic.in/reports/others/ps/pspa2/tr_plg_criteria_manual_jan13.pdf

[8] F. Li and R. Bo, "Small test systems for power system economic studies," in *IEEE PES General Meeting*, July 2010, pp. 1–4.

[9] S. Blumsack, "Network topologies and transmission investment under electric-industry restructuring," 2006.

Long Term Power Purchase Agreements (PPA's) and its impact on Coal based Thermal Power Plants

Praveen Gupta
Chief Engineer
Central Electricity Authority

Ammi Toppo
Director
Central Electricity Authority

Rahul Raj
Deputy Director
Central Electricity Authority

Abstract

Thermal power plants make up to around 66% of the installed capacity of the country and contribute around 85% towards the total energy generated in the country. So in short, it can be said that Thermal Power Plants are the backbone of the electricity sector in the country. From the 10th plan onwards, (i.e. from the year 2002) private sector participation in setting up and operation of Thermal Power Plants has increased manifold. As on 31.01.2018 the share of private sector in Thermal Power Plant category is about 26% of the installed capacity of the country.

Power from Central and State generating power plants is tied up through long term Power Purchase Agreement's (PPAs) which are on cost plus basis (Regulated Tariffs) as per section 62 of the Electricity Act 2003 while Power from the Private Sector Power Plants is generally tied up through tariff based competitive bidding as per section 63 of the Electricity Act 2003.

The rapid capacity addition since 10th Five year plan especially in the private sector coupled with the poor financial health of Distribution companies along with other factors like addition of large amount of renewable energy sources in the Installed Capacity, situation has come where DISCOMs/States are unwilling to procure power on long term basis. This has put private sector generating companies in a situation where their capacities are stranded due to untied and unsold power and face the risk of their assets being declared as Non-Performing Assets.

This paper talks about the gradual decline in the Long term PPA's being executed, the growing interest of utilities in short term and medium term PPA's and the stress caused in the system due to Power Plants not being able to sell their power in the market. It further tries to assess the PPAs required on All India basis to meet the demand and talks about that this stranded capacity, which can only be utilized if some new demand is created in the system.

1. INTRODUCTION

A **power purchase agreement** (**PPA**) is a legal contract between two parties, one which generates electricity (the seller) and one which purchase electricity (the buyer). A Power Purchase Agreement (PPA) secures the payment stream for a Power Plant. The PPA defines all of the commercial terms for the sale of electricity between the two parties, including when the project will begin commercial operation, schedule for delivery of electricity, penalties for under delivery, payment terms, etc. A PPA is the principal agreement that also defines the revenue and credit quality of a generating project and is thus a key instrument of project finance. PPA is also a necessary pre-requisite for obtaining domestic coal linkage as the actual drawl of coal by the generator will depend on the capacity for which PPA has been executed (SHAKTI Policy-Scheme for Harnessing and Allocating Koyala Tansparently in India) [1].

There are many forms of PPA in use today and they vary according to the needs of buyer, seller, and financing counterparties. Depending on the tenure of PPA, there are three types of PPA's

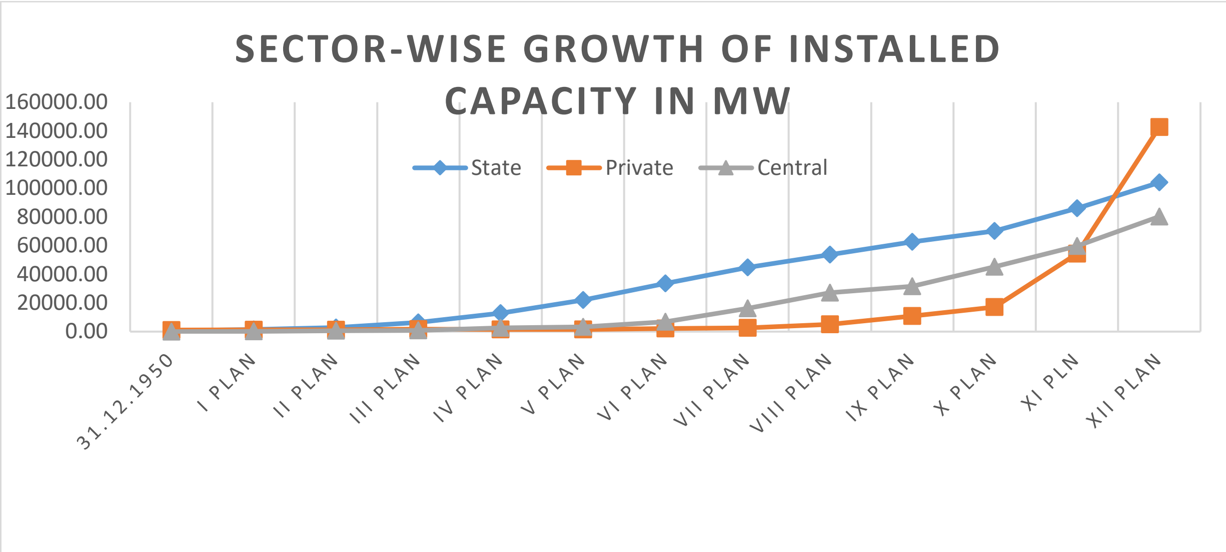
1) Long term PPA's having tenure of 7-25 years
2) Medium Term PPA's having tenure of 1-7 years
3) Short Term PPA's having tenure of less than 1 year

Long-term power contracts dominates in the Indian power sector because of predictable cost of electricity over 15-25years. Out of the total electricity produced in October 2017 i.e. 102,708.64 MU only 9,803.77 MU (9.55%) was transacted through short-term contracts comprising of 3543.45 MUs (3.45%) through bilateral (through traders and term ahead contracts on power exchanges and directly between distribution companies), followed by 4360.37 MUs (4.25%) through day ahead collective transactions on power exchanges (IEX and PXIL) and 1899.95 MUs (1.85%) through DSM (Deviation Settlement Mechanism). [2]

2. PRESENT POWER SECTOR SCENARIO

The All India Installed Capacity as on 31.01.2018 was 3,34,399.83 MW comprising of 44,963.42 MW Hydro, 219809.51 MW thermal , 6780 MW Nuclear and 62,846.90 MW RES. The coal-based capacity dominates among all sources of Generation, which is around 58% (Thermal capacity 66%). The Private Sector contributes to 44% of the total Installed Capacity of the Country. The Renewable Capacity addition increased by 134% during the period 2012-2017. During the 12th Plan, the Thermal capacity addition target was fixed at 72,340 MW but the capacity addition achieved was 91,730.50 MW with majority 53,660.50 MW (58.5%) coming from private sector. This has led to excess capacity addition. During 2016-17, PLF of thermal coal based capacity decreased to 59.8 % from 62.28% in 2015-16, and may further decrease in future. Further, coal based capacity of about 50,000 MW are in an advanced stage of construction[a]. The plan wise and sector wise growth of generation capacity is shown in the Exhibit 1.

Exhibit 1



Source:CEA

Due to the excess generation capacity, the focus in power sector has shifted from "Capacity addition" to "Capacity Utilization". The underutilization of Capacity has impacted PLF of thermal stations, which has come down to 59.8% during 2016-17. This is an undesirable trend as tariff gets impacted and the revenue is hit. Some of the contributory factors/ issues for underutilization of the capacity are less demand growth, excess capacity addition, untied PPAs, fuel non-availability, evacuation constraints and the financial issues.

It has been reported that there are 35 coal based Projects totaling to 41,480 MW with an outstanding debt of around Rs.1.4 lakh crores. These projects are stressed due to various reasons like inadequate fuel availability, evacuation constraints, untied PPAs etc. Out of the 35 stressed projects 25,395 MW are commissioned projects and 16,085 MW are at advanced stages of construction. A capacity totaling 8,300 MW is without any PPAs and 9,500 MW capacity is having partial PPAs (i.e. for less than 40% of the capacity). The balance capacity is having PPAs greater than 40%.

3. CAPACITY REQUIRED FOR MEETING THE PEAK & ENERGY REQUIREMENT DURING 2016-17

A. CAPACITY REQUIRED FOR MEETING PEAK LOAD

The peak demand during 2016-17 was about 160 GW. To meet this peak demand from conventional sources, a conventional capacity of around 190 GW is required. The capacity available from Central and State Sector is given in **Table 1**.

Installed Capacity of State and Central Sector

TABLE 1

(All figures in MW)

	Coal	Hydro	Nuclear	Gas	Total
State	64685.5	29683	0	7257.95	101,626.45
Centre	54335	11651.42	6,780	7490.83	80,257.25
Total	119,020.50	41,334.42	6,780.00	14,748.78	181,883.70

From the Table 1, out of the total installed capacity of 327 GW as on 31.03.2017 in the country, 182 GW comes from the different sources of the Centre and State sector which have PPA for full capacity. Now the peak demand in 2016-17 is about 160 GW, which requires a conventional capacity of around 190 GW. After considering 182 GW from the State and the Central Gencos, additional capacity required to meet the peak demand of about 160 GW from the IPPs is only around 8 GW.

Total IPP capacity as on 31.03.2017 is 87 GW. As per the information available with CEA of about 84 GW capacity 59 GW are having long-term PPAs .Therefore, surplus capacity to the tune of 51 GW (59 GW – 8 GW) is available in the system. Accommodating this capacity not having PPAs in this scenario looks to be difficult, unless the demand is substantially increased.

B. ENERGY AVAILABILITY VIS-A-VIS REQUIREMENT DURING 2016-17

The energy availability for the Installed capacity from the State and Central Sector Projects during 2016-17 is as given in Table 2.

TABLE 2

(Fig in MU)

SECTOR	THERMAL			NUCLEAR	R.E.S	TOTAL
	HYDRO	COAL	GAS		(MNRE)	
STATE	104009.23	368319.24	13987.52	0.00		486315.9902
CENTRAL	40826.57	356980.95	14436.33	44544.6		456788.4533
TOTAL	144835.80	725300.19	28423.85	44544.60	81,868.70	**1,024,973.14**

* considering PLF of Hydro project : 40%, State Sector Thermal project :65%, and Central sector Thermal projects -75%, Nuclear projects -75%, Gas projects -22%. RES energy on actual basis

The total Energy Availability from State and Central sector project works out to be around 943 BU. In addition, energy to the tune of 81.6 BU is also available from renewable energy sources.

The Energy requirement during the year 2016-17 was 1,143 BU. Therefore, to meet the energy requirement, contribution required from IPP projects is only 118 BU (1143BU-1025 BU). However, the energy available from IPPs is far in excess of this requirement. Therefore, at present, both in capacity terms and in energy terms, there is surplus power available in the existing IPPs. There appears to be no scope to immediately absorb this excess power from IPPs in the present scenario.

4. Shift from Long term to Medium and Short Term PPA

Lenders/ Financial Institutions are interested in Long Term PPA's as it gives them security of payment towards debt servicing as the term of long term PPA coincides with the Loan Period which is generally 15-25 years. Majority of PPAs of DISCOMS are for long term on cost plus basis as it ensures security for supply of power in long term.

However Long term PPA's are risky in the sense that there is always a possibility of over contracting power by the DISCOMs. It is understood that focus is being shifted away from Long term PPA's as Long term PPA's do not address the variabilities, future challenges of the Power Sector which is very dynamic. Also, power procurers/ DISCOMS are not able to take advantage of falling tariff. Therefore, to take advantage of falling tariffs, Power procurers are looking at developing a portfolio of Medium/short-term power procurement contracts ranging from "day ahead" to the ones spanning one, three or five years.

Ministry of Power launched DEEP (Discovery of Efficient Electricity Price) [3] an e-Bidding and e-Reverse auction portal for procurement of short term/medium term/long term power by DISCOMs, with the objective to introduce uniformity and transparency in power procurement by the DISCOMs and at the same time promote competition in electricity sector. The portal is meant for the short term procurement of the power for a period of more than one day up to one year and medium term procurement of power for 1-5 years. The Guidelines for short term procurement of power were notified on 30.03.2016 by Ministry of Power, Government of India, making it mandatory for all the Procurer(s) to procure short term power by using this e-Bidding portal. Power Procurement from Power Exchange has been excluded from the scope of these guidelines. The Guidelines for medium term procurement of power were notified on 17.01.2017 by Ministry of Power.

Ministry of Power also launched a mobile application "Vidyut PRAVAH"- Electricity, Price Availability and Highlights on 31st March 2016. This mobile application provides data pertaining to market price of power from power exchange, value of current all India demand in GW and all India and State shortage including peak hour and total energy shortage and allows consumers to find out the quantum and price of electricity available on the grid. Post "Ujwal Discom Assurance Yojana (UDAY), a debt restructure and efficiency improvement scheme launched in November 2015 and transparent information shared through Moblie APP Vidyut Pravah, utilities are becoming commercially savvy to engage and manage portfolio of power procurement contracts ranging from day ahead to 1-3-5 years rather than commit to long- term 15-25 year contracts[b].

In the Aggregate Revenue Requirement (ARR) and Tariff petition for Financial Year 2018-19 filed by Madhya Pradesh and Maharashtra DISCOMS to their respective State Electricity Regulatory Commission's, it is mentioned that these States are having surplus energy for most of the months of the preceding year, current year and the ensuing year [4].

Financial Year	Surplus Energy Madhya Pradesh DISCOMs (MU)	Surplus Energy Maharashtra DISCOMs (MU)
2016-17	3229	46,558
2017-18	12576	44,653
2018-19	7943	42,582

From the above table it can be seen that some of the big Power procurers of the country have become power surplus and may not require to tie up power for long term in the near future.

The signs of early disruption are already there. As per the information available on Ministry of Power website, 16 States/UT's have offered to surrender about 6625 MW of Power allocated from Central Generating Stations, which was tied up through Long term PPA's[c]. It is evident that States do not want to be tied for long term power especially when tariffs discovered through competitive bidding are much lower and with the tariffs of Renewable energy are falling fast.

5. Suggestions

1. It is not prudent at this stage to do away with the Long term PPA's, instead the Power procurers/ DISCOM's shall aim for a basket of PPA's comprising of Long term, Medium term and Short term. Long term PPA shall be for meeting the base load, medium term PPA shall be done for meeting the seasonal variations and short term PPA's for meeting the daily peak requirements.
2. Modifications in the present format of PPA's may be explored like initially a Medium term PPA for a duration of say 5 years may be entered into, with the provision that the term of PPA may be extended for a further mutually agreed term and tariff which may reflect the prevailing market conditions.
3. As of today only Central Generating Stations participate in providing Ancillary Services to the grid. This space shall be opened for other generating Stations also by creating an Ancillary service market. This may help in promoting competition in the electricity sector and also providing an opportunity for utilizing the stressed capacity in the generation space.
4. New avenues to raise demand in the country may be explored. With the increase in reliability of grid power and with the conducive policy measures the additional captive power capacity required can be shifted to the utility; Introduction and promotion of Electric Vehicles alongwith other supportive measures may be taken to increase electricity demand.

5. Central Electricity Authority carries out Electric Power Survey (EPS) for estimating the electricity demand of all the States/UT's , regions of the country. The exercise is carried out in association with the States/UT's. Power procurers/ DISCOM's of States/UT's may need to do a realistic projection of the demand. The demand projection is the basic data for carrying out the generation planning studies. If the demand projected does not confirm to the actual demand, it may lead to faulty generation planning, which may lead to under/ excess capacity in the system. It is suggested that a mid-term review of EPS may be carried out, so that capacity addition in the system is in line with the demand.
6. Central Electricity Authority (CEA) prepares a National Electricity Plan in accordance with the National Electricity Policy and notify such plan once in five years. The Plan prepared by CEA and approved by the Central Government can be used by prospective generating companies, transmission utilities and transmission/distribution licensees as reference document. It is suggested that based on the review of the demand projections, a mid-term review of the National Electricity plan may also be carried out so that a true picture of power demand and supply position in the country may be brought out and capacity addition may be in accordance with the System demand and may not run ahead of the requirement, thus excess capacity addition can be avoided and in turn saving the investments turning into NPA's.
7. The under-utilization of the capacity is caused due to projects taken up without due diligence for technical and commercial viability, which earlier used to get pre-addressed through mandatory requirements of TEC (Techno Economic Clearance). As such, there is no clear line of sight of private generating capacities planned and the time span of their coming on stream. However decision since taken, it will be worthwhile now to create a proactive window to facilitate the Developers for ensuring all parameters of TEC are satisfied before project is taken up for construction thus avoiding any subsequent possibility of under utilization.

6. Conclusion

Long term PPAs do not take into account the demand insecurities and variabilities. Therefore, new products may need to be designed products as per the requirement of Power generators and Power Procurers so as to address the seasonal and Peak variations such as PPA for only Peak/ Off-peak hours, Round the Clock etc. and Financial Institutions and Lenders may come up with solutions by designing products to suit the market requirements.

References:

Policies, Regulations and reports:
[1] Ministry of Coal order dated 22.05.2017
[2] Market monitoring Report of CERC for October 2017
[3] Ministry of Power letter no. 23/17/2013-R&R (Vol-IV) dated 16th Jan 2017 and Ministry of Power letter no. 23/25/2011-R&R (Vol-III) dated 30th March 2016

[4] MSEDCL revised Petition on 7June, 2016 for Aggregate Revenue Requirement (ARR) before MERC & MPPMCL Petition for Aggregate Revenue Requirement (ARR) for 2018-19 before MPERC
[5] 19th Electric Power Survey

Books and Reports :

[i] Central Electricity Authority, National Electricity Plan, Volume-1 Generation ,2012
[ii] Central Electricity Authority, All India Electricity Statistic: General Review,2015
[iii] Central Electricity Regulatory Commission, Economic Division, Report on Short-term power market in India: 2014-15

Web References:

[a] www.cea.nic.in
[b] www.livemint.com › Industry › Energy 21June 2017
[c] http://powermin.nic.in
[d] www.cerc.gov.in
[e] www.indianpowersector.com
[f] www.pfcindia.com/

THERMAL POWER PLANT ENVIRONMENTAL COMPLIANCE AT A MUCH REDUCED COST

AdvX

Pradip Dhir

Dr. Jonas S. Klingspor

R&D Conclave, February 15-16, 2018

LJUNGSTRÖM | ARVOS GROUP

VALUE PROPOSITION

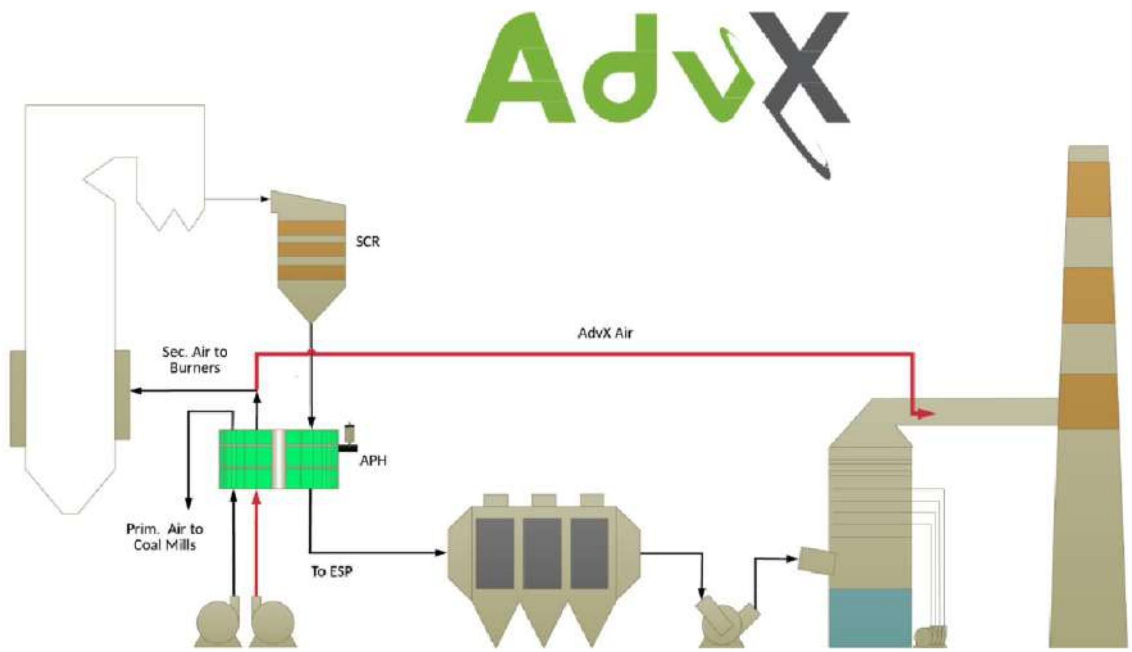
LJUNGSTRÖM | ARVOS GROUP

AdvX™ Technology can save India Thermal Power Plant owners more than **$2 Billion** in Compliance Cost

REHEAT TECHNOLOGY

LJUNGSTRÖM | ARVOS GROUP

- **AdvX™ Stack Gas Reheat**
  - Extract up to 15 percent more energy
  - Same PA temperature
  - Slight increase in SA temperature
  - Economizer outlet temperature unchanged
  - Boiler efficiency marginally higher
  - ESP operating at a reduced temperature
  - ESP efficiency significantly improved



KEY SYSTEM DESIGN COMPONENTS

LJUNGSTRÖM | ARVOS GROUP

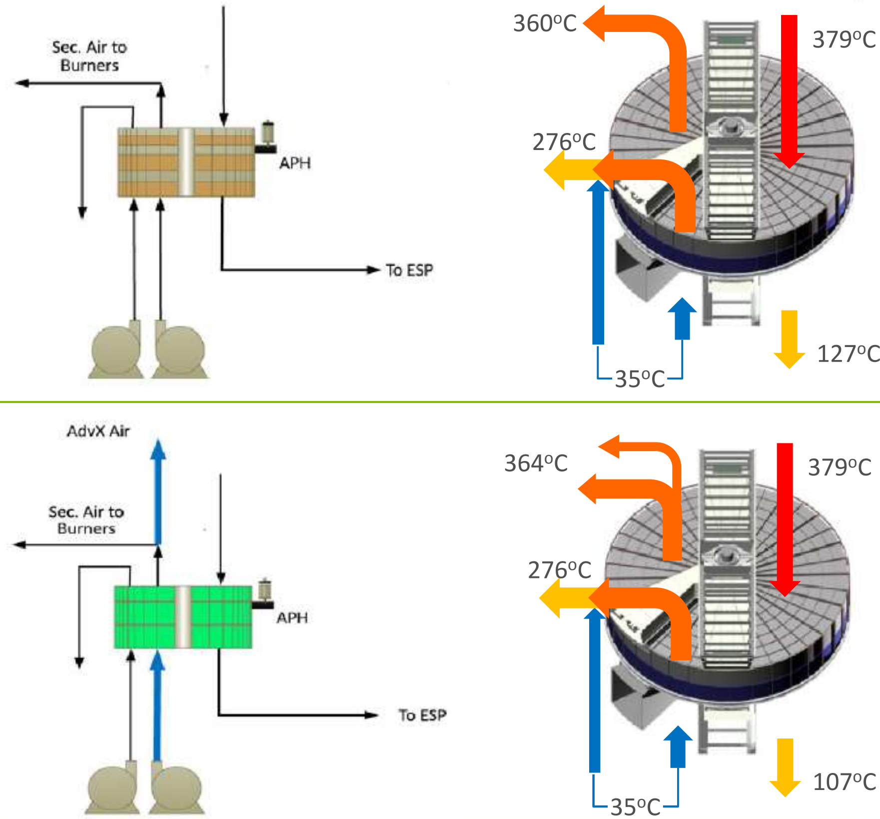
- **Key Elements of AdvX™ Technology**
  - – APH Upgrade
  - – High efficiency heating elements
  - – Additional heating element depth
  - – X-ratio management
    - Increased secondary air flow
      - – Option to reduced flue gas flow if SA fan is capacity limited

Advanced DUN8™ heating element

AIR HEATER PERFORMANCE

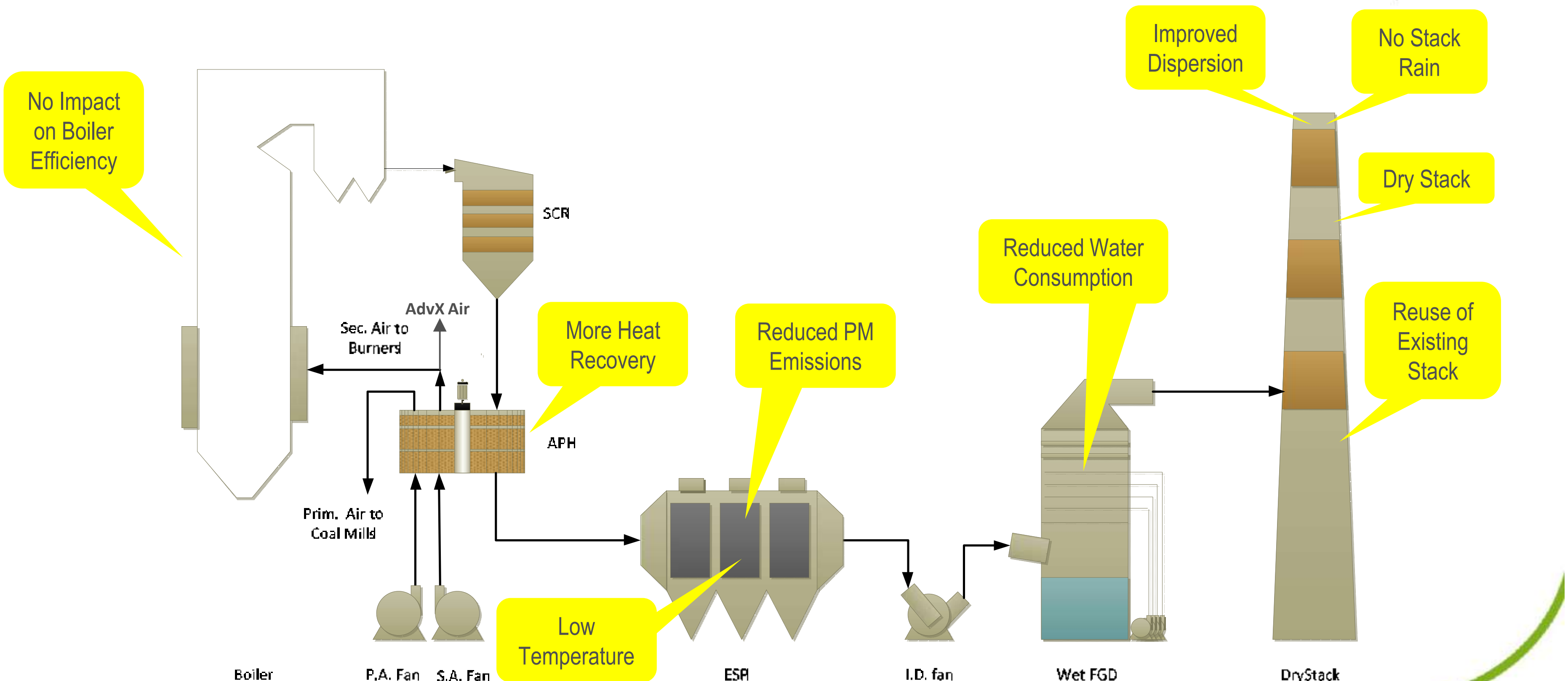
LJUNGSTRÖM | ARVOS GROUP

- **AdvX™ Technology**
  - Extracting up to 15 percent more energy
  - New heating elements have a lower pressure drop and higher efficiency
  - Most SA fans have additional capacity
  - Boiler efficiency marginally improved
  - Additional heating element surface area



BENEFITS OF AdvX™ TECHNOLOGY

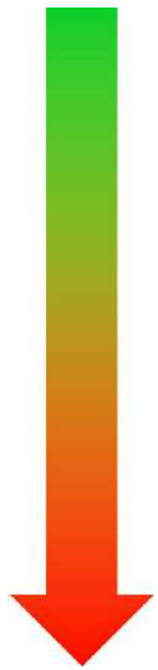
LJUNGSTRÖM | ARVOS GROUP



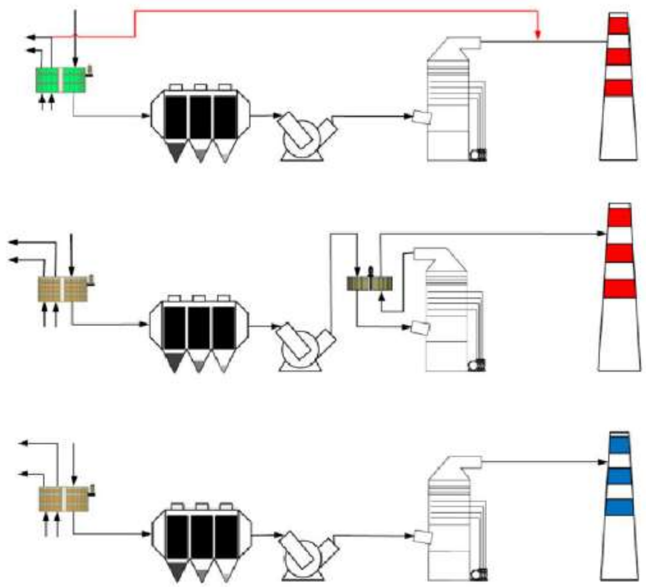
LOWEST COST OPTION

LJUNGSTRÖM | ARVOS GROUP

- AdvX™ Stack Gas Reheat is by far the lowest cost
- No need for a new wet stack
- No need for a GGH
- AdvX™ provides other benefits
  - Significantly reduced PM emissions and compliance with the new 50 mg/Nm^3 PM standard,
  - Reduced water consumption



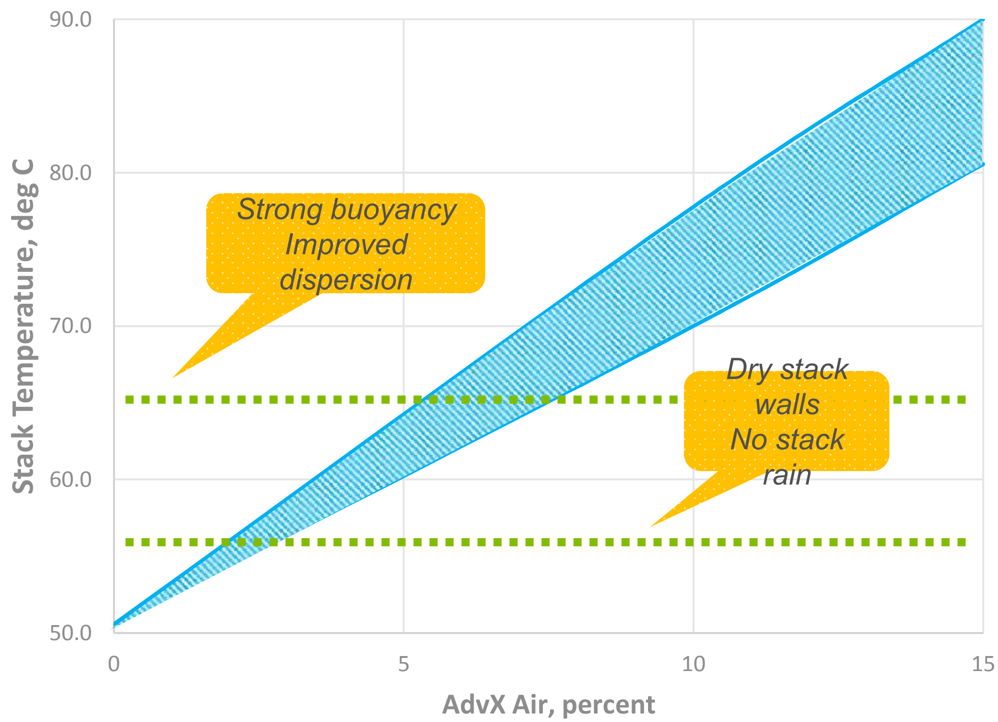
Increasing Cost



- AdvX™
- GGH
- Wet Stack

ROBUST REHEAT WITH BOTH OPTIONS

- Reheat of 6°C required for dry walls and to avoid stack rain
- Reheat of 15°C provides strong buoyancy
- AdvX™ Stack Gas Reheat can provide up to 30°C reheat
- No negative impact on boiler heat rate
- Compliance with PM limits



DRY STACK OPERATING EXPERIENCE

LJUNGSTRÖM | ARVOS GROUP

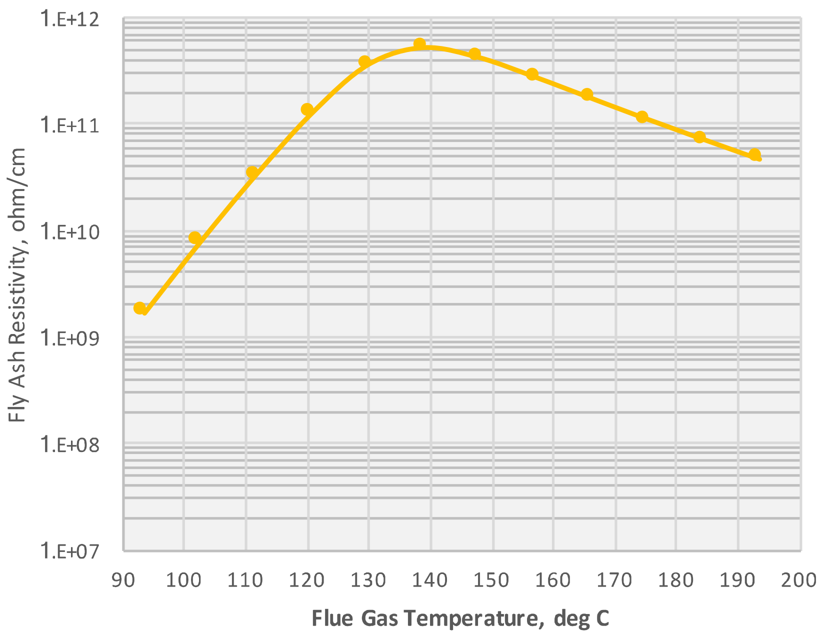
- Large experience with dry stack operation using GGH for reheat
- LJUNGSTRÖM Gas Gas heater Experience
  - 126,270 MW_e
  - Stack temperatures as low as 56 ^oC
- Reheat requirements
  – 6^oC required to maintain dry stack walls and avoid stack rain
  – 15^oC required for improved buoyancy and dispersion

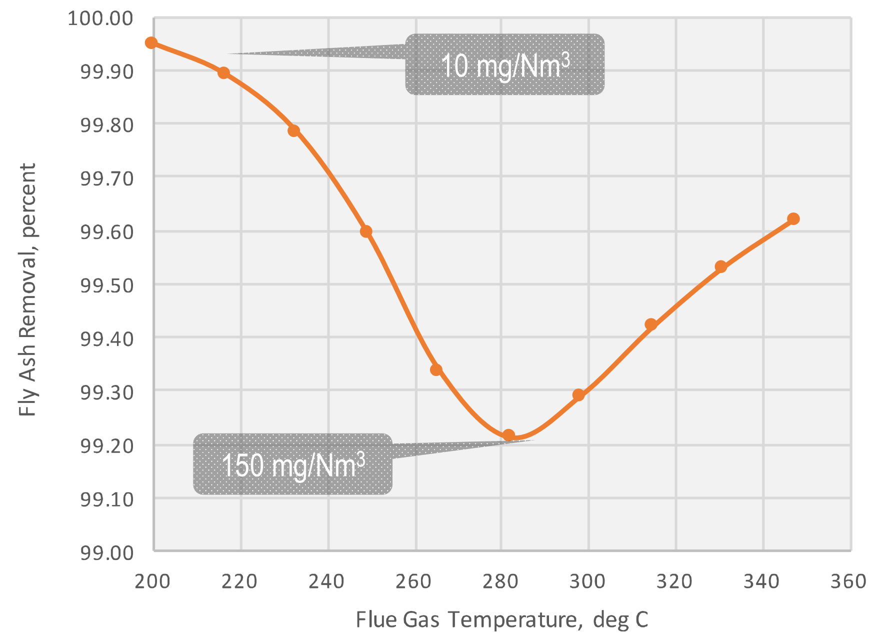
Typical GGH Stack Reheat References

Country	Plant	Size, MW_e	Stack Temp. ^oC
China	Shenzhen 5&6	2 x 350	70
China	Mawan	3 x 350	70
Wales	Aberthaw	3 x 300	65
Ireland	Kilroot	2x 150	56
Spain	Litoral de Almeria	600	75
Chile	Puerto Coronel	300	66
Thailand	Tanjung	1,000	71
Turkey	Karbiga	2 x 660	58
China	Vungang	2 x 550	69
China	Qianxi	2x 750	75

IMPROVED ESP PERFORMANCE
(RAMAGUNDAM COAL)

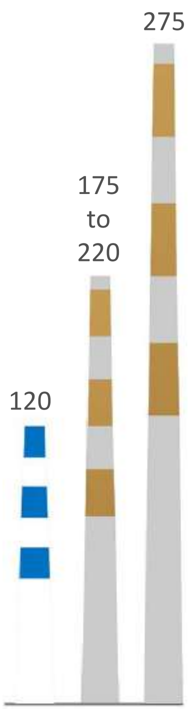
LJUNGSTRÖM | ARVOS GROUP



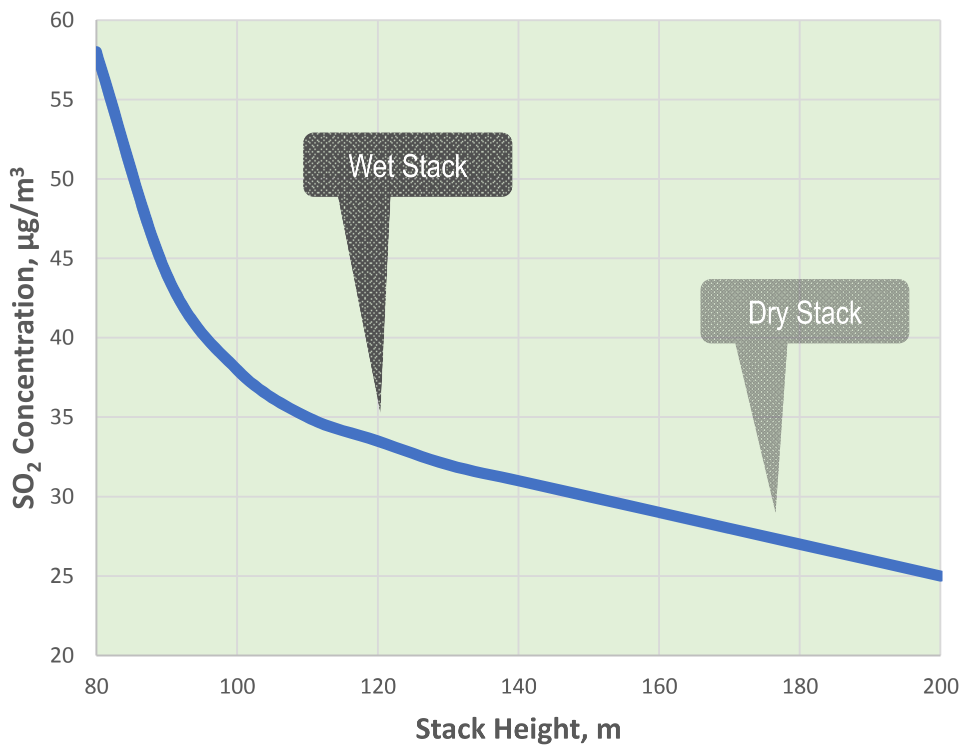


DRY VS WET STACK - DISPERSION

LJUNGSTRÖM | ARVOS GROUP

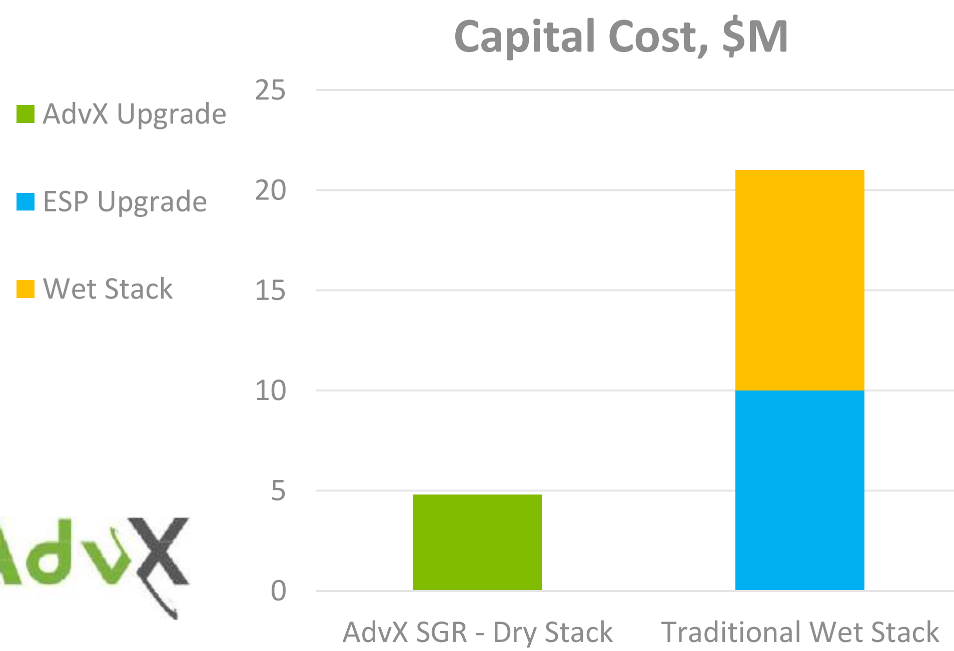


- Dry Stack
  - 175 to 220 m tall for conventional boilers
  - 275 m tall for super critical boilers
  - Dry invisible plume
  - Improved buoyancy
  - Improved dispersion
    - 30% lower ground concentration of pollutants
- Wet Stack
  - 120 m tall
  - Saturated and visible plume
  - Reduced buoyancy
  - Stack rain



CAPITAL COST BENEFITS

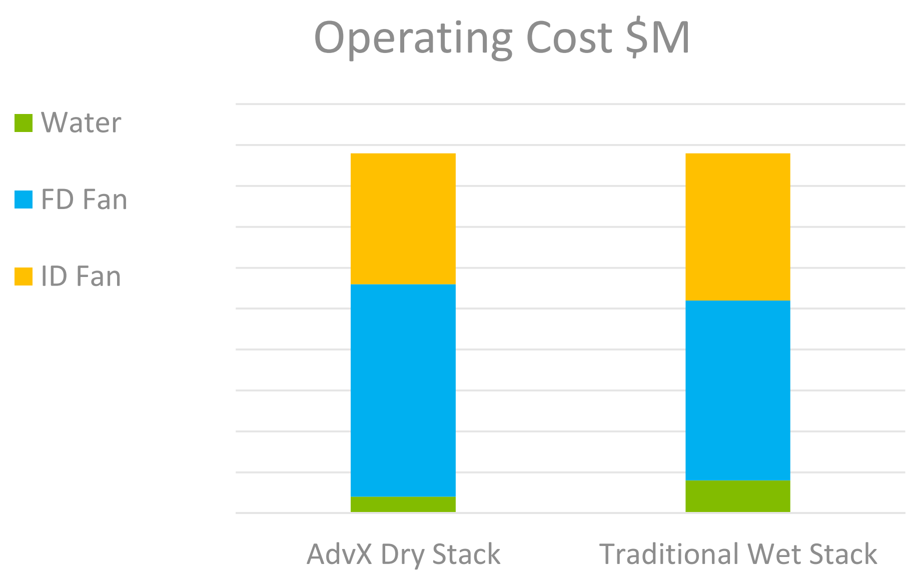
- 500 MW_e Plant
  - AdvX™ Stack Gas Reheat
    - Less than $5 million installed
    - Improved Hg removal
    - Improved ESP performance
    - Reduced FGD water consumption
    - Dry stack – no lining
    - Improved dispersion, reduce ground level pollutants
  - Traditional Wet Stack
    - $20 million installed
    - Stack rain



OPERATING COST BENEFITS

LJUNGSTRÖM | ARVOS GROUP

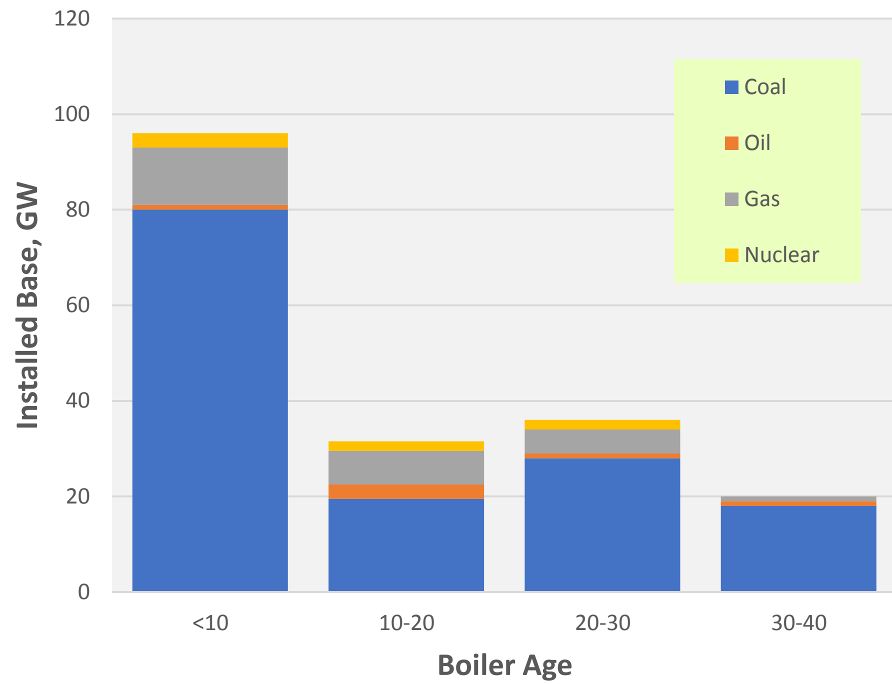
- 500 MW_e Plant
  - Main impact is on:
    - Water consumption
    - Forced draft fan
    - Induced draft fan
  - AdvX™
    - Higher FD fan power consumption
    - Lower ID fan power consumption
    - Reduced water consumption
  - No net difference in operating cost



AdvX

SUMMARY

- India has a sizable coal fleet which can enjoy tremendous savings
  - Single 500 MW_e plant $16M
  - Boilers <10 years $2.6B
  - Entire Fleet $4.6B
- AdvX™ SGR can also be used on new plants
  - Reduce ESP size and cost
  - Improve boiler efficiency
- AdvX™ Stack Gas Reheat is available now!



PATH FORWARD

AdvX™ Technology can quickly be demonstrated in India in a pilot project.

LJUNGSTRÖM is ready to support.

LJUNGSTRÖM | ARVOS GROUP

www.ljungstrom-global.com

General Network Access-The Concept

Shilpa Agarwal
Jt. Chief (Engg.), CERC
shilpadce@yahoo.com

Agam Kumar
Research Associate (Engg.), CERC
agamkumar115@gmail.com

Abstract

The paper proposes to understand the changes in power sector over years, challenges faced with prevailing Regulations and the need of a new concept. The paper aims to develop basic understanding of the new concept, the proposed benefits and the expected challenges in implementing the concept. The power sector in Indian context has moved from a deficit scenario to surplus scenario which has been possible with progressive reforms taken with the Electricity Act, 2003 and the advent of merchant generation. The advent of market has brought challenges with respect to planning carried out with identified location & capacity of Inter-State Generating Station (ISGS) and their identified beneficiaries. Further, the areas requiring attention are the integration of renewable and the need of regulatory reforms it demands along with. The benefit of the scheme for planners is that the concept is aimed at getting appropriate inputs for optimal transmission planning. Generating Stations shall have to apply for GNA corresponding to its Installed capacity less auxiliary consumption. STUs shall apply for quarterly GNA for five year period on behalf of all intra-state entities. This shall provide the data of expected ISTS drawal of a State to the transmission system planner. It has also been proposed to consider variable cost of generating stations while planning the system. The benefits of the scheme for States is that States shall be able to schedule power under long term or medium term or short term contracts based on its own assessment of merit order on day ahead basis. The curtailment of power shall be carried out in line with existing provisions of short term transactions to be curtailed first followed by medium term transactions and then long term transactions. Regulatory oversight has been proposed to make the process transparent and ensure due participation of stakeholders.

1. Introduction

Power Sector has moved from a peak deficit of 9% in the year 2012-13 to 2% in year 2017-18 (up to December, 2017 (Provisional): CEA). The 12th plan forecasted for demand/load growth of 68 GW (from 130 GW to 198 GW) whereas the actual has been 165GW. Similarly, in the 12th Plan, the generation capacity additions was targeted as 88,537 MW against which generation capacity additions achievements are 92,209.47MW which is 12.05% more than the target. Transmission planning for inter-state transmission system (ISTS) has historically been done on the basis of identified beneficiaries for Central Sector Generating plants. CERC introduced the concept of "target region" with CERC (Grant of Connectivity, Long-term Access, Medium-term Open Access in inter-State Transmission and related matters) Regulations, 2009 ("Connectivity Regulations") effective from 1.1.2010. With the advent of merchant generation and thereby availability of generation where customers can exercise a choice depending on price, there emerges a need to relook at traditional transmission planning methodology. Further, the inter-State transmission system has become stronger and it should be possible to do planning with fair degree of certainty without prior knowledge of pairs of injection and drawal as power in a meshed network would be transferred by displacement.

2. Challenges upcoming in the Sector

Presently ISTS is being planned on the basis of Long Term Access (LTA) requirements in accordance with the Connectivity Regulations where as Medium Term Open Access (MTOA) and Short Term Open Access (STOA) sought by beneficiaries are accommodated in the margins available in the system planned for LTA requirement. The Connectivity Regulations also provide liberty to the Independent Power Producers (IPPs) to seek LTA in ISTS less than their installed capacity and sell remaining power through MTOA/STOA as and when need arises. Further, the monthly transmission charges and losses in respect of ISTS are being shared by Long Term Customers and MTOA/STOA customers pay ISTS transmission charges and losses when they transact power through medium/short term open access. Hence, IPPs were seeking LTA for quantum less than their installed capacity and that too with target region and selling remaining power through MTOA/STOA. Also, many IPPs were seeking only connectivity to ISTS and selling power through MTOA/STOA. This resulted in the sub-optimal planning of inter-State transmission system and congestion was faced in inter-Regional corridors.

The IPPs are also facing challenge as they had sought LTA in a particular target region but they have been able to sign PPA with DISCOMs in region other than target region. Further, the country has moved from a deficit scenario to a surplus scenario and States are backing down their own generation/costly generation in pursuit of cheaper power from other regions. DISCOMs are also facing financial stress and consistently seeking open access in inter-State transmission system to get cheaper power from other regions. Also, the existing system of transmission planning does not account for variable cost of generation i.e merit order despatch which needs to be reviewed in view of availability of cheaper power in the country.

Generation capacities based on solar/wind resources are coming in huge numbers in certain parts of the country and the same will be utilized by all non-renewable rich states to meet their Renewable Purchase Obligation (RPO). Also, solar/wind sources are intermittent in nature which needs support from conventional sources for smooth grid operation. Therefore, integration of renewable energy sources with the grid is another major challenge being faced by the transmission planner.

Further, there is information asymmetry between transmission planners and other stakeholders which results in lack of confidence among stakeholders generating a need to make the system more tranaparent.

In order to counter all the aforementioned challenges, a need was felt to relook into the existing methodology of transmission planning.

3. Proposed Mechanism

To address the challenges faced by transmission planners, system operators and IPPs, the Commission proposed the methodology of transmission planning based on the General Network Access (GNA) through the Draft CERC (Transmission Planning and other related matters) Regulations, 2017 ("Draft Transmission Planning Regulations") and the Draft CERC (Grant of Connectivity and General Network Access to the inter-State transmission system and other related matters) Regulations, 2017 ("Draft GNA Regulations").

In accordance with the proposed GNA methodology, inter-State transmission system will be planned on the status of generating station as provided to Central Repository to be maintained at CEA, drawal GNA requirements of States and variable cost of existing /upcoming generating stations. The transmission system planner will carry out system studies for various generation and load scenarios during peak, off-peak and other than peak/off-peak hours for different seasons considering low, moderate and high renewable capacity addition, scheduling of various generating stations which do not have any PPAs based on the relative merit order and GNA applied by the Generating Companies and the load projections of the

States. The variable cost of new generating stations should be estimated by CTU in consultation with CEA and the generating stations based on likely source of fuel, normative heat rate as per CERC Regulations, variable charges of existing generating stations in a state based on pit head/load center based stations.

Now, States have options to procure cheaper power from different regions/source and their drawal patters vary quarterly/seasonally, therefore, they will be required to submit quarterly drawal requirements from ISTS as per the format prescribed in the Draft GNA Regulations for 5 years hence. Each STU will also furnish node wise details of drawal/injection. In case if, node wise details are not furnished by STUs, it would lead to assumption of loads at different nodes by planner which can results into congestion in some corridors and underutilisation in some other corridors. In case the projected import/export requirement from ISTS is not provided by STU, CTU should, in consultation with CEA and POSOCO, assess the import /export requirement of the State for the purpose of transmission planning and upload the same on CTU's website for comments from stakeholders. The same shall be discussed at Regional Study Committee level. In the absence of any response to the same from the STU, the projected import/export requirement assessed by CTU should be taken for transmission planning.

The progress of generating station will be ascertained from quarterly progress report submitted by generating stations in the Central Repository of Generators and the injection data of generating stations will be taken from applications seeking GNA to ISTS. The purpose of these regulations is to enhance participation of stakeholders in the process of transmission planning and increase transparency in sharing data between transmission planners and beneficiaries.

The ISTS is crucial for India's renewable energy sector. With large no. of wind and solar based renewable generating station getting connected to ISTS in the coming year, the proposed regulations will provide guidance for the optimal utilization of available transmission network and strengthening of grid when need arises. MNRE may suggest likely location of renewable generating stations 4-5 years in advance to facilitate transmission planning.

The transmission system finalized by the Standing Committee on Power System Planning will approach CERC for regulatory approval where stakeholders will get another chance give their views on the requirements of the transmission system. The transmission system will be implemented after approval of the Commission. Hence, the Commission has proposed to make the system transparent and participative.

4. Major benefits of the GNA Mechanism

Following are the benefits of the GNA mechanism

(a) States shall have the flexibility to purchase power through long / medium / short term transactions/agreements on day ahead basis depending upon their need and economic considerations free of term of contract except in case of congestion.
(b) New transmission corridors could be planned based on GNA requirement, which would help in a great way to remove congestion in transmission corridors
(c) Generators shall have access to ISTS grid with flexibility for point of drawal subject to conditions laid down at the time of grant of GNA

5. Conclusion

This paper intends to highlight the major challenges faced by transmission planners, system operator, States and IPPs and their possible solutions in the form of change in the transmission planning methodology. There may be situations of congestion where a state may not be able to schedule as desired on day ahead basis depending on difference in planning scenarios vs actual operational scenario. States have also raised difficulties in assessing their GNA requirements 5 years hence moreso due to open access customers and envisaging their GNA requirements. However, in order to achieve overall economy in procurement of power by State, to facilitate generating stations to sell power in any region and for optimal planning of inter-State transmission system, time is ripe to adopt the proposed transmission planning based on GNA. We have to recognize the fact that short/ medium term market can no longer be restricted to “spare margins” on the lines, which was the basic premise of the first open access regulations introduced in 2004 when long term PPAs were predominant. As of now fresh investment in transmission is permitted only for providing LTA or system strengthening. It needs to be recognized that in the current scenario if short term/ medium/PX transactions are curtailed it results in significant bottling up of generation and distress to DISCOMs. The new transmission corridors could be planned based on GNA requirement, which would help in a great way to remove congestion in transmission corridor. With the implementation of GNA based transmission planning, the generating stations will have access to ISTS grid with flexibility for point of drawal subject to conditions laid down at the time of grant of GNA, Drawing Utilities shall also access to ISTS to the extent of their GNA and get the system created for power transfer over ISTS from anywhere in the grid and variability of renewable energy sources can be handled in a better way. This will give them flexibility to purchase power through long / medium / short term transactions/agreements depending upon their need and economic considerations and without any transmission restrictions.

Disclaimer:

The paper is based on Draft Central Electricity Regulatory Commission (Grant of Connectivity and General Network Access to the inter-State transmission system and other related matters) Regulations, 2017 which was notified on 14.11.2017. The Regulations are yet to be finalised and the last date to submit comments is 28.2.2018. The views expressed in the instant paper are personal and gained while working as staff of the Commission and does not have any bearing with the Organisation.

Bibliography:

[1] "Draft Central Electricity Regulatory Commission (Grant of Connectivity and General Network Access to the inter-State transmission system and other related matters) Regulations, 2017." Available: http://www.cercind.gov.in/2017/draft_reg/GNA.pdf

[2] "Draft Central Electricity Regulatory Commission (Transmission Planning and other related matters) Regulations, 2017." Available: http://www.cercind.gov.in/2017/draft_reg/NOTIFICATION_220.pdf

[3] "Report of the Committee to Review Transmission Planning, Connectivity, Long Term Access, Medium Term Open Access and other related issues." Available: http://www.cercind.gov.in/2016/whatsnew/OA.pdf

[4] "Central Electricity Regulatory Commission (Grant of Connectivity, Long-term Access and Medium-term Open Access in inter-State Transmission and related matters) Regulations, 2009." Available:

[5] "Central Electricity Regulatory Commission (Indian Electricity Grid Code) Regulations, 2010." Available: http://www.cercind.gov.in/Regulations/Signed-IEGC.pdf