CEA Committee Report on Requirement of Variable Speed machine vis-à-vis Fixed Speed machine in PSPs

July, 2023

Table of content

1. INTRODUCTION

A round table conference was held at PMI, Noida on the emerging requirement of Energy Storage System such as Pumped Storage Projects (PSPs) and Battery Energy Storage Systems (BESS) due to the increase in penetration of Variable Renewable Energy in the electricity grid. **During the deliberations, a need was felt to have a guiding criteria for the Developers and End Users of PSPs on selection of one of the available options viz. Fixed Speed Machine (FSM) or Variable Speed Machine (VSM) as a type of machine for use in the PSPs.**

A Committee was therefore constituted by CEA in the matter of requirement of VSM vis-à-vis FSM in PSPs vide OM no. 10/3/HE&TD/2023/ dated 15.02.2023 with following Terms of Reference (ToR):

- **i) Review of requirement of variable speed machine vis-à-vis fixed speed machine with respect to economy and efficiency,**
- **ii) Technical considerations and issues,**
- **iii) Practical considerations including technology, availability, sourcing, operation and maintenance issues and impact on tariff,**
- **iv) Make-in-India considerations,**
- **v) Recommendations,**
- **vi) Any other issues/ agenda with the consensus of members.**

The first and second meetings of the Committee were held on 24.02.2023 and 24.03.2023 respectively at CEA Headquarter, New Delhi. The Minutes of these two Meetings (MoM) along with CEA order dated 15.02.2023 for constitution of committee are enclosed at **Annexure-I**.

The various aspects under ToR of the Committee have been discussed hereafter in detail along with conclusions & recommendations at the end of this report.

2. STATUS OF DEVELOPMENT OF PSPs AND DISTINGUISHING FEATURES – SCHEME-WISE PSPs AND MACHINE TYPE-WISE

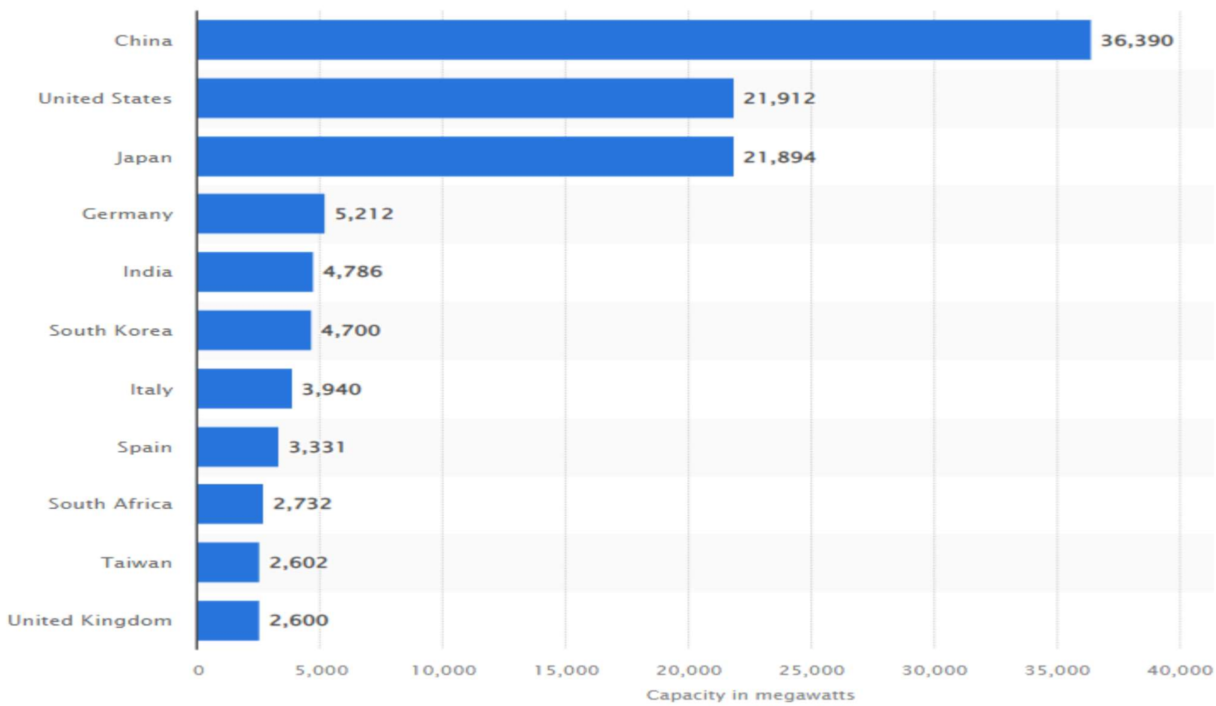
Among the various Energy Storage Technologies, Pumped Storage Plants (PSP), in terms of total installed size, is by far the largest individual contributor with a total worldwide deployment of about 160 GW (almost >90%) and practically makes the entire storage capacity globally to deliver Renewable Energy (RE) Round-The-Clock (RTC) power thereby facilitating "**Long Term Lowest Cost Renewable Energy Round-The-Clock Power**".

PSP is one of the matured and proven techno-commercially viable Long Duration Energy Storage (LDES) solution. Hydro Pumped Energy Storage envisages two water reservoirs at different elevations that can generate power as water moves down from higher one to lower one, while passing through a turbine. PSP requires power to pump water back into the upper reservoir during recharge cycle. PSPs can be generally designed for **daily storage of 4–10 Hours**.

2.1 Status of Development of PSPs

2.1.1 Worldwide

Pumped Storage is by far the largest-capacity form of grid energy storage available, and as of 2020, the United States Department of Energy Global Energy Storage Database reports that PSH accounts for around 95% of all active tracked storage installations worldwide, with a total installed throughput capacity of over 181 GW. Adjustable-speed pump-turbines have been used since the early 1990s in Japan and the late 1990s in Europe.



Pumped Storage Installed Capacity 2021 (Worldwide)

Source: https://www.statista.com/statistics/1304113/pumped-storage-hydropower-capacity-worldwide/

The main reason that adjustable speed pumped storage was developed in Japan in the early 1990s was the realization that significant quantities of oil burned in combustion turbines could be reduced by shifting the responsibility for regulation to pumped storage plants.

The first adjustable speed system, Yagasawa Unit 2, was constructed for the Tokyo Electric Power Company (TEPCO) and became operational in 1990.

However, it is worth noting that only about 5% of the world's installed capacity is equipped with variable speed machines.

2.1.2 India

There is abundant potential for development of PSPs in the country. The status of development of PSPs is as given below:

i) Potential for On-Stream based schemes is 103 GW (89 nos.). Further, the potential assessment for newly identified Off-Stream based schemes in the country is yet to be taken up, however, it appears to be significant. At present, only self-identified Off-Stream schemes by the Developers are either under construction or under survey & investigation (S&I) stage.

ii) Projects* under Construction and S&I Stage:

a) **In operation** – 4745.6 MW (8 nos.) – **All Fixed Speed (Annexure-II)**

b) **Under Construction** – 2780 MW (4 nos.) – **One Project with Variable Speed** and Rest with **Fixed Speed (Annexure-III)**

c) Cleared by CEA and yet to be taken up for construction – **Turga** PSP (4 X 250 MW), West Bengal – (2 **Variable Speed** + 2 **Fixed Speed)**

d) Under Examination in CEA at DPR/ S&I/MoC Stage – 36380 MW (27 nos.) – **All Fixed Speed (Annexure-IV)**

e) Likely additional PSPs by 2029-30 – 10460 MW (8 nos.)

f) Likely additional PSPs by 2030-32 - 26140 MW (19 nos.)

*****This is dynamic and may change. The data is based on information available on CEA Website.

2.2 Types of PSP Schemes

2.2.1 PSPs are classified as On-stream if both the reservoirs (Upper & Lower) are on the stream. Further, Off-stream PSPs can be either Open Loop or Closed Loop types as discussed below:

i. **Closed Loop PSP** – Both Upper and Lower reservoirs are away from natural river course. This envisages one time filling of reservoirs & then make up water on periodic basis for evaporation losses only.
ii. **Open Loop PSP** – One of the existing reservoirs, on the river stream, is used for PSP.

2.2.2 Locations ideal for Off Stream PSPs are widely available across the country. Further, these PSPs can be customized with respect to site conditions, requirements of capacity and storage duration to develop them faster and cheaper. These Projects have multiple advantages as follows:

1. Location & Capacity Range

i. The locations suitable for such projects are widely available across the country.
ii. These Projects can be planned from capacities as low as 100 MW to multiple Giga Watt level.

iii. Customization to the needs of a particular site is very easy and comfortable.
iv. The Project can be made modular by proper site selection.

2. **Design & safety**
   i. Technically, these projects are simpler because they do not require as much Civil Construction as required in the Conventional or Riverine PSPs such as River Diversion works, Desilting & Silt Flushing arrangements, Surge Chambers, etc. Further, Off Stream PSPs have very small water conductor system.
   ii. Hydrology & Power Potential Studies are very simple because of operation at fixed quantum of water and minimal/ negligible catchments.
   iii. Design & Safety aspects are also simple because of no Spillways/ under sluices, no Fish ladders, no flash flood design criteria, no risk of GLOF and small Dam heights.

3. **Ease of Construction**
   i. No limitation of working season.
   ii. No requirement of river diversion works.
   iii. Very compact projects so better project management.
   iv. Gestation Period- 30-36 months.

4. **Environment Friendly**
   i. Very less environmental issues such as, Fisheries, Environmental Flows and CAT Plans etc.
   ii. Lesser R&R and Social issues

5. **Low Risk Perception**
   The reservoirs (either both or any one) of the off-stream PSPs are away from the rivers/ water channels, which makes their development/ construction much easier and faster than the conventional HEPs since the sites are free from river diversion structures, lower or no geological surprises, fewer underground structures, lower gestation period etc. In this view, the risk perspectives of various aspects of construction of PSPs are reduced as listed below:

   i. Components of Project – Very Low
   ii. Hydrological – Very Low
   iii. Construction – Low
   iv. Time Over run – Low
   v. Cost Over-run – Low
   vi. Environmental – Low
   vii. Operational – Very Low

6. **Simple Operation**
   The operation of PSPs are uniform for entire life due to fixed storage as there is no seasonal dependence on operation, i.e. monsoon or lean season, and make up water is needed only for evaporation losses. Further, resources are optimally utilized since water as energy source is of non-consumptive use.

   As the reservoirs (both or any one) are away from the river/ water channel, the silt related issues are not encountered, and due to which the operational life of the machine increases with no de-rating of the efficiencies. Additionally, the provision of Hydraulic Short Circuit enhances the operational flexibility of the plant.

7. **Lowest Storage Cost**
   The projected completed cost for such PSPs as per data available in CEA works out to be approximately **Rs. 4.5-5 Cr/MW** for **6-hours storage** as their construction involves lesser civil components than conventional Hydro, and which further leads to lesser IDC (Interest During Construction) due to faster construction and lower infra cost.

2.3 PSP – Types of Technology & Benefits

2.3.1 **Hydro Pumped Storage** with fixed speed technology is presently more than **85%-90% Make-In-India** solution and provides **over 100 years of mature technology, multi-GW scale, indigenous & lowest cost solution with least life cycle environmental impact**.

2.3.2 This is a mature technology, in operation for more than 100 years now and is well proven, durable, and clean, green, sustainable energy solution.

2.3.3 Based on type of Synchronous and Asynchronous Generator/ Motor, following types of PSP technologies are available:

A. Fixed Speed Machine (FSM)

In fixed speed PSPs, pump-turbine (conventional Francis Type or Ternary Set) with a fixed speed motor-generator (Synchronous Type) is used. Static Frequency Converters are used for starting of pump/ turbine sets and provide a source of adjustable frequency/ voltage for starting the pumps. There are two types of Fixed Speed Machines:

a. **Ternary Set:** Ternary sets consist of a motor-generator and a separate turbine (typically Francis or Pelton) and a pump set. As two separate hydraulic machines, the rotational direction of the motor-generator can be the same in both operational modes. These units normally require deep excavations and complex water conductor system, which eventually leads to increase in cost. Further, such ternary set finds its applicability in an energy market which pays well for ancillary services and for a very rapid change in the mode/ fast response. Currently, we do not have a market for such technology in India.

b. **Reversible Pump-Turbine**: Such type of units are the most compact & simple in design as Motor-Generator is coupled with reversible Pump-Turbine on a common shaft. This PSP technology is widely adopted globally.

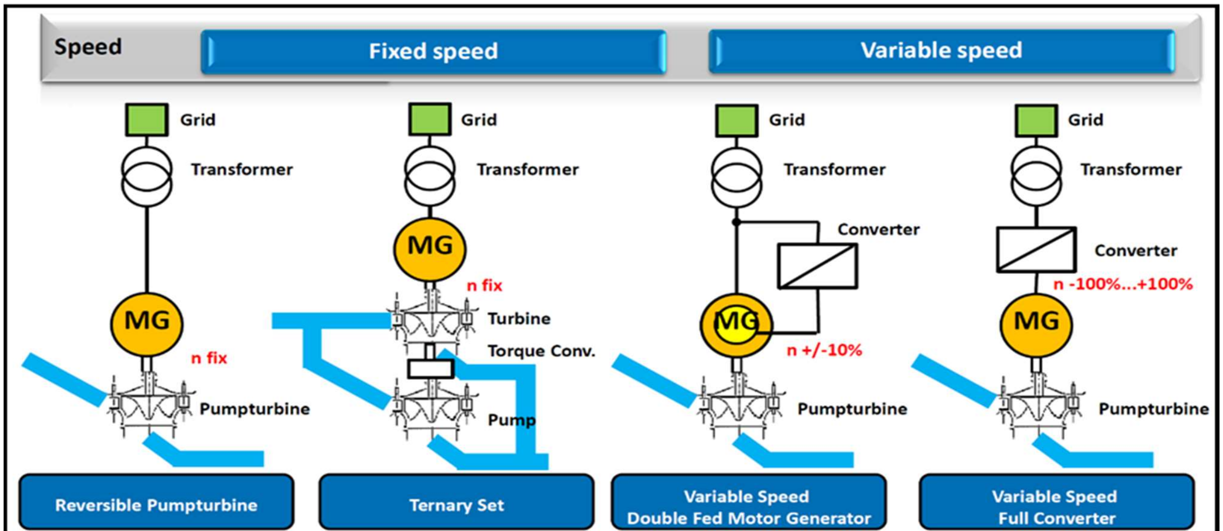
B. Variable Speed Machine (VSM)

With the use of variable speed technology, by use of Asynchronous motor-generator or Synchronous motor-generator with frequency converter, the rotational speed of the pump-turbine can be varied. Thus, the turbine operating range can be extended and the pump capacity can be adjusted to using just the currently available amount of energy. This technology stabilizes the grid efficiently. There are two types of Variable Speed Machines:

a. **Doubly-Fed Induction Machine/ Motor-Generator (DFIM/ DFMG):** The additional requirement of AC excitation system on rotor side increases the volume of power house, thereby resulting in increase in civil cost as well as enhancing geological surprises in underground powerhouse. This technology is expensive and there are few installation of such machines globally.

b. **Variable Speed with Full Converter:** The technology is currently limited to approximately 100MW unit size. Further, there are very few installation across globe due to the complex design and it is an expensive technology.

2.3.4 The various PSP schemes discussed in para 2.3.3 are schematically explained below in Fig. 1 along with their merits & demerits in brief:



Most compact design	Most complex design, requires very deep excavation and with complex water conductor system	Large powerhouse volume required due to AC excitation system	Full size convertor
Most widely employed technology with max. installations globally	Only few installations globally	More than 10 installations across globe	Few installation across globe. Currently, limited to <100MW unit size
Most economical solution	Most expensive solution	Expensive solution	Very expensive

Fig. 1: Technical Comparison of Fixed Speed and Variable Speed

2.3.5 Detailed Technical Comparison of FSMs and VSMs

2.3.5.1 Efficiency:

i. Pump-Turbine (PT) efficiency is lower (~90.5%) & Motor-Generator (MG) efficiency is higher in case of FSM.

ii. In case of DFMG-VSM, PT eff. is better (~92%), however, MG eff. is lower (~97.5%) due to higher AC excitation losses leading to higher overall eff. (~0.5%).

iii. In case of Full Size Converter (FSC) VSM, there are additional 2%-5% losses due to full size convertor leading to lower overall eff.

iv. For projects having high head ratio- a ratio of Gross Maximum Head to Gross Minimum Head (i.e. a ratio of 1.5 & above), the decline in efficiency of turbine at low head may be of the order of 20%.

2.3.5.2 Cycle Efficiency: As per the global practice and the DPRs submitted in CEA by different developers, the cycle efficiency is approximately up to 80% for FSM, which is predominantly impacted by head losses. Whereas, cycle efficiency may be ~1-2% higher for DFMG-VSM owing to flatter pump-turbine efficiency levels across head range, which may be countered by lower machine efficiency at part loads.

2.3.5.3 Wide range of operation: The application of FSM, as indicated by M/s Andritz based on their practice, is generally for head ratio (i.e. a ratio of Gross Maximum Head to Gross Minimum Head) up to 1.3-1.33, whereas, DFMG-VSM is indicated for head ratio of 1.45 – 1.5. Further, in case of FSC-VSM, the technology is limited up to approximately 100MW only and is indicated for head ratio of 1.6. However, M/s Voith, based on their practice, have indicated for FSMs a head ratio of maximum of 1.5. The list of PSPs under various stages (from appraisal to operation) with their respective head ratio & type of machines are placed at Annexure-II to Annexure-V. It is observed from the details therein that majority of the projects have head ratio below 1.3 and that some of the projects, already constructed having FSMs, have head ratio as high as 1.75 for the machines supplied by manufacturers from Japan and are reported to be operational without any problem. This indicates that it is possible to hydraulically design FSMs for head ratios higher than those nominal indicated by some manufacturers based on their practice. As such, for higher head ratios, selection of type of machine, viz. FSM or VSM, may be guided by techno-economic considerations.

2.3.5.4 Hydraulic Short Circuit & Flexibility of Operation in Pump Mode:

i. The hydraulic short circuit could be adopted through the reservoirs (long hydraulic path) or through the penstock bifurcation (short hydraulic path). It is preferable to have a shorter water conductor system which avoids higher hydraulic losses during hydraulic short circuit operation. The scheme is self-explanatory at Fig. 2.

ii. Under hydraulic short circuit, one or more units operate in pump mode while other units operate in generating mode at the same time at full or partial load to offer. These units may or may not be on the same penstock.

iii. The hydraulic short circuit operation does not require any additional infrastructure. It is achieved through powerhouse control system. Several pumped storage projects globally operate in hydraulic short circuit whenever required.

iv. **Fixed speed units do not provide flexibility in pump mode of operation due to constant power consumption. However, combination of different unit sizes (Higher & Lower Capacities) and the provision of**

Hydraulic Short Circuit may be employed to achieve the intended objective.

v. **Hydraulic short circuit can be employed to gain higher degree of flexibility in the pump mode even with fixed speed units**.

vi. In order to quantify the advantages of such hydraulic short circuit in pumped storage projects, Frades 2 PSP, Grand Maison PSP, Alqueva PSP and Alto Lindoso PSP have been taken under the XFLEX HYDRO Project introduced in Europe as part of COP25 initiative.

vii. **DFIM-VSM** can operate at +/-10% speed variation with which **power consumption can be varied from 70% - 100%** of the rated capacity.

viii. **Full size convertor units provide maximum flexibility** in pump mode – can vary **from about 50% - 100%** of the rated capacity.

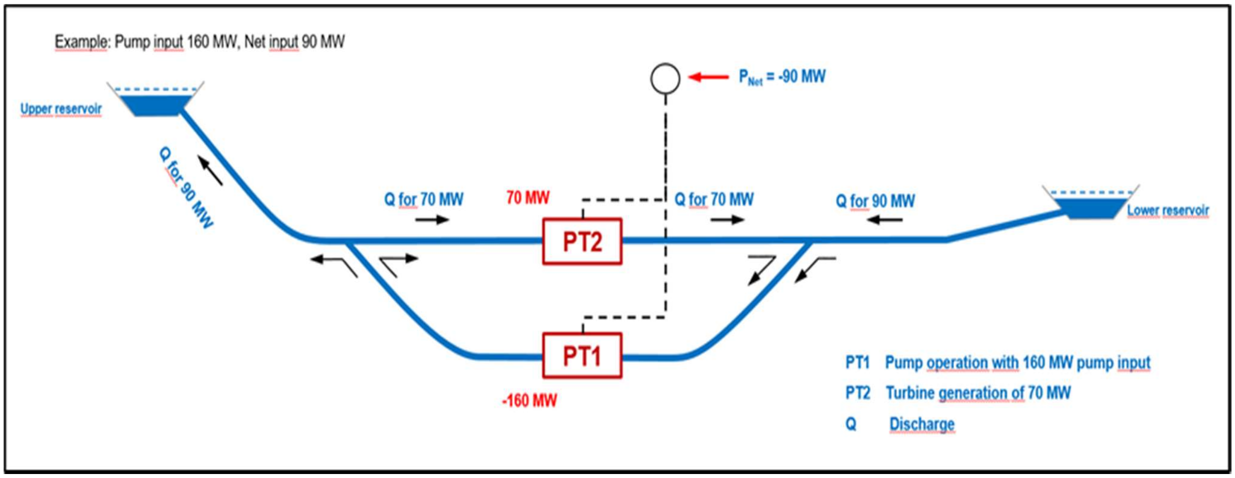


Fig. 2: Flexibility of Operation

2.3.5.5 Part Load Operation (Flexibilization) in Generation Mode: The FSM can operate up to a part load of 50%-60%, whereas, deeper part load operation for DFMG-VSM is feasible up to 35%-40% depending upon the head range of the machine, and which is limited by AC excitation sizing. In case of FSC-VSM, up to 10% part load operation is feasible.

2.3.5.6 Other Performance Comparison of FSMs and VSMs:

A. Functional/ Technical Characteristics-wise

	Fixed Speed	Variable Speed	
Requirements		**Doubly Fed Motor Generator**	**Full Size Convertor**
Fast transition between operating modes	~7 - 15 min, depends upon inertia and transient behaviour	Faster mode change times: ~7 – 10 mins	Shortest mode change times. ~5 – 8 mins
Controllable reactive power	High	High	High
Short circuit stability(LVRT)	Low	High	High

	Fixed Speed	Variable Speed	
Requirements		**Doubly Fed Motor Generator**	**Full Size Convertor**
Grid oscillation damping (PSS)	High	High	High
Grid inertia	High	Limited due to wound rotor (limited rotor dia.)	High
Fast transition in turbine power (min.-Full load)/ (Full–min. load)	<30 s. Limited by hydraulic transient	<30s. Limited by hydraulic transient	<30s. Limited by hydraulic transient
Black start	Yes	Yes, special requirements - not fully proven	Yes
Synchronous Condenser Mode	Yes	Yes	Yes

B. Construction & Operation Aspects

	Fixed Speed	Variable Speed
Availability of Vendors	Sufficient	Very few vendors limited by the no. of suppliers for Convertors. Currently only 02 nos. namely GE & Hitachi
Civil works: Reservoirs for similar storage capacity	Larger surface area required to limit the head variation	Reservoirs can be optimised since higher head range operation is feasible
Civil works: Unit setting	Deep setting required	Setting can be optimised. May bring an advantage with surface powerhouse. In a PH with combination of fixed speed – no specific advantage
Civil works: Powerhouse volume	Most compact design	Need at least 20% more volume to cater to AC excitation system space requirements
Procurement Lead Time of Machine	Lesser	May be greater by about an year
Flexibility	Can be brought about with powerhouse operation in hydraulic short circuit	Flexibility is enhanced with hydraulic short circuit
Maintenance*	Least cost of maintenance	Higher maintenance required – High voltage and high current slip rings need frequent maintenance due to faster wear of carbon brushes

	Fixed Speed	Variable Speed
Reliability*	Higher reliability due to simpler overall design Synchronous motor generator used. Availability of above 95% on annual basis.	Complex design of the motor generator rotor (3 phase winding of the rotor) – rotor winding fixation arrangement and slip rings require frequent checks. Difficult to have Availability of minimum 95%.
Cost**	100%	150% - 160% on overall electro-mechanical value
Speed Variation	-	10% (Maximum)

*Refer Annexure VI
**Detailed Cost Benefit Analysis by BHEL is enclosed as Annexure VII.

C. In view of above comparison brought out between FSM and VSM, only fixed speed reversible units and variable speed with doubly fed motor generator are technical options at present for the Indian market. Further, it is intimated by M/s GE that globally, there are almost 270 PSPs either operating or under construction. This represents a combined generating capacity of over 220,000MW. Of these total installations, more than 60 units consist of variable-speed machines, out of which more than 30 units are currently in operation and rest are under construction. All of these units are located mostly in Europe, China, India and Japan.

D. It has been observed that the provision of FSMs has been proposed by the developers in all the DPRs under examination whether at S&I/ DPR stage required for concurrence by CEA, or under construction, or under operation projects except for Tehri PSP (under-construction) and Turga PSP (concurred by CEA and construction yet to be taken up).

E. The value for services provided by a PSP may vary from project to project depending on its end users/ business-end propositions, and with lapse of time as the realization & appreciation for its increasing requirement would be increasingly felt with increasing penetration pace of variable energy based sources, viz. solar & wind in the grid. Also, the cost for civil works may be site specific and dependent on parameters such as head ratio etc. Further, the cost of VSMs may decrease with increasing sale volumes and technology of E&M component becoming older over the period.

F. It may, therefore, be prudent to base selection of type of machine, viz. FSM or VSM, for the head ratio above 1.35 based on techno-economic consideration/ levelised cost of storage (LCoS) while considering the initial CAPEX and estimated O&M cost over its useful life for both type of machines.

3. CONCLUSION AND RECOMMENDATIONS:

3.1 *The existing PSP technologies, namely Fixed Speed & Variable Speed, in current Indian market scenario have been compared on various techno-economic parameters such* *as efficiency, responsiveness, reliability, associated civil and future O&M cost etc. From this comparative study, it was observed that FSM may be usually well suited at present for the Indian Scenario being cost effective, lesser outage, responsive to the Grid requirement (as the switching time from one operation to another is comparable to those in other technology), lesser outage due to breakdown, local availability of spare parts, easy to install, operational flexibility with different unit sizes & hydraulic short circuit, comparable overall efficiency etc.*

3.2 *It is generally assumed that the PSP will use the entire head range in every charge-discharge operation. However, since a PSP operation may also require multiple part charge-discharge operation every day, it may not always be reasonable to assume that a very wide head variation will be consumed during each operation cycle. A PSP may thus also operate within a very narrow operating head range in the daily operating cycle irrespective of the head ratio at the site.*

3.3 *With plants operating in the narrow head range, there is no unit setting advantage by virtue of variable speed operation (as per USBR Report). Only in extreme cases of very large head variation, variable speed may lead to any minimal advantage in setting.*

3.4 *However, the* ***Variable Speed Technology may find its application in specific conditions*** *as discussed below:*

a. ***High Head Ratio/ Head Variation:*** *It is evident that extremely large operating head range leads to a quite high variation in the power absorbed by the pump and high risk of cavitation, i.e. limitation of zone of operation. Further, in case of FSM, often in pump-turbine performance, the best efficiency point when turbining is out of the operating head range. The efficiency would deteriorate sharply (in the range of -20%) as soon as the head is away from the rated head particularly in case of low delivery head in pumping. In such cases, VSM may be suitable by the virtue of having uniform efficiency across wider range of head.*

b. ***High Submergence:*** *The condition of extremely high submergence may be observed in certain projects having extremely high head variation and huge discharge in order to achieve the net positive suction head for pumping operation, as in the case of Tehri PSP. In such cases, the VSM may be required to handle such huge variations, to reduce civil cost due to submergence and to have overall better performance on across the varying heads after detailed techno-economic analysis & business aspect/ revenue generation model of the developer*

c. ***Highly Intermittent Pumping Power:*** *Variable-speed technology may be well suited to accommodate variable renewable generation to provide stability and frequency regulation especially in an isolated grid, typically for wind at night or during large ramping periods due to its inherent characteristics of wider operating range, faster start and turnaround times.*

3.5 *It has been observed that the identified sites in India predominantly have nominal head ratios, i.e. project sites with high head ratios are very rare, and therefore, considering this aspect as well, FSM may be considered as an optimal solution at present for machine selection for sites having head ratio below 1.35 without investing additional time and cost in deciding the type of machine to be deployed. Accordingly, an exercise for selection of type of machine, i.e. FSM or VSM, may be made only in such cases where head ratios are high, i.e. say above 1.35 considering constructional & operational performance aspects discussed at para 2.3.5.6 A & B above, and based on the cost inputs provided by vendors and estimated revenue streams for the various applications/ business uses of the project as discussed below.*

As such, the decision of type of machine (i.e. FSM or VSM) for head ratio above 1.35 may be taken by the developer while also considering the cost on various aspects as given below and based on inputs provided by vendors:

	Increase in Cost	***Decrease in Cost***
A. Initial Investment		
i. Civil Cost	*VSM*	*FSM*
ii. E&M Cost	*VSM*	*FSM*
iii. IDC (Interest During Construction)	*VSM*	*FSM*
iv. Other Costs		
Net Cost (Initial Investment)	*VSM*	*FSM*
B. Recurring Annual Cost *(O&M Cost)*	*VSM*	*FSM*
C. Levelised Cost of Scheme *(LCoS) based on Total Cost (considering Initial Investment + O&M Cost over Useful Life) and Design Energy or Capacity with No. of Operation Cycles on Daily/ Annual basis*	*LCoS*	*LCoS*
D. Value of Revenue Stream *from the Project*		
E. FSM or VSM considering D ≥ C		

Further, a typical example of selection of Variable Speed type of machine in case of Tehri PSP, as provided by THDC representative & Member of the Committee is placed at ***Annexure-V****.*

File No.CEA-HY-17-145/1/2018-HETD Division **Annexure-I**

भारत सरकार/Government of India
विद्युत मंत्रालय/Ministry of Power
केंद्रीय विद्युत प्राधिकरण/Central Electricity Authority
जल विद्युत अभियांत्रिकी व प्रौद्योगिकी विकास प्रभाग
Hydro Engg. & Technology Dev. Division
सेवा भवन, आर. के. पुरम-1, नई दिल्ली-110066
Sewa Bhawan, R. K. Puram-1, New Delhi-110066

टेलीफैक्स/Telefax:
011-26732789
ईमेल/Email:
hetdcea@nic.in
वेबसाइट/Website:
www.cea.nic.in

10/03/HE&TD/2023/ Date: 15/02/2023

OFFICE MEMORANDUM

Subject: Constitution of the Committee for requirement of variable speed machine vis-à-vis fixed speed machine for Pumped Storage Projects -reg.

A round table conference on the requirement of Energy Storage System such as, PSPs and BESS with the increase of penetration of Variable Renewable Energy Capacity addition in the grid was recently at PMI, Noida. In the deliberations, it was felt that there must be a defined criteria for the preference of selection between Fixed Speed Machine and Variable Speed Machine for Pumped Storage Projects in view of the large head variation.

In this regard, a Committee comprising following members is hereby constituted:

1.	Member (Hydro), CEA	Chairman
2.	Chief Engineer (HE&TD)	Member & Convener
3.	Representative of BHEL	Member (not below the rank of ED/GM)
4.	Representative of THDC	Member (not below the rank of ED/GM)
5.	Representative of M/s Voith	Member
6.	Representative of M/s Greenko	Member

Further, the Committee may co-opt any other member, if required.

The Terms of Reference (ToR) of the Committee shall be as given below:

1. Review of requirement of variable speed machine vis-à-vis fixed speed machine w.r.t. economy and efficiency.
2. Technical considerations and issues.
3. Practical considerations including technology, availability, sourcing, operation and maintenance issues and impact on tariff.
4. Make-in-India considerations.
5. Recommendations
6. Any other issues/ agenda with the consensus of members.

The Committee shall submit its report within eight weeks of issue of this OM.

Reetesh Tiwari

(Reetesh Tiwari)
Deputy Director

File No.CEA-HY-17-145/1/2018-HETD Division

To:

1. Chairman & Managing Director, BHEL, BHEL House, August Kranti Road, Siri Institutional Area, Siri Fort Institutional Area, Siri Fort, New Delhi, Delhi 110049.
2. Chairman & Managing Director, THDC, THDC India Limited, Corporate Office, Rishikesh, Pragatipuram, By Pass Road, Rishikesh- 249201 (Uttarakhand).
3. CEO, Voith, A-20 & 21, A Block, Sector 59, Noida, Uttar Pradesh 201301- with a request to nominate a representative of M/s Voith (senior officer with sufficient experience/ holding relevant portfolio).
4. CEO, Greenko, House, 18, Hindustan Times, 15th Floor, 20, KG Marg, New Delhi, Delhi 110001- with a request to nominate a representative of M/s Greenko (senior officer with sufficient experience/ holding relevant portfolio).
5. SA to Chairperson, CEA.
6. SA to Member (Hydro), CEA.
7. Office file.

File No.CEA-HY-17-145/1/2018-HETD Division-Part(1)

Azadi Ka Amrit Mahotsav

भारत सरकार/Government of India
विद्युत मंत्रालय/Ministry of Power
केंद्रीय विद्युत प्राधिकरण/Central Electricity Authority
जल विद्युत अभियांत्रिकी व प्रौद्योगिकी विकास प्रभाग
Hydro Engineering & Technology Development Division
सेवा भवन, आर. के. पुरम-1, नई दिल्ली-110066
Sewa Bhawan, R. K. Puram-1, New Delhi-110066

टेलीफेक्स/Telefax:
011-26732789
ईमेल/Email:
hetdcea@nic.in
वेबसाइट/Website:
www.cea.nic.in

10/03/HE&TD/2023/ Date: 21 /03/2023

Subject: Minutes of the First Meeting of Committee under chairmanship of Member (Hydro), CEA on requirement of Variable Speed machine vis-à-vis Fixed Speed machine in PSPs held at 10:30AM on 24th February, 2023 at Central Electricity Authority, New Delhi - reg.

Please find enclosed herewith the Minutes of the First Meeting of Committee on subject matter for your kind perusal and necessary action.

Enclosure: as above

(Shyam Singal)
Asst. Director

To:

1. Shri M A K P Singh, Member (Hydro), CEA
2. Shri Rakesh Kumar, Chief Engineer (HE&TD), CEA
3. Shri V. Shrinivas Rao, GM (Hydro), BHEL.
4. Shri Neeraj Verma, GM (E&M), THDC.
5. Shri Sanjai Dhar Dwivedi, Voith.
6. Shri Y. K. Sehgal, ED, Greenko.
7. SA to Member (Hydro), CEA.
8. Office file.

Minutes of Meeting (MoM) of the Committee under chairmanship of Member (Hydro), CEA on requirement of Variable Speed machine vis-à-vis Fixed Speed machine in PSPs held at 10:30AM on 24th February, 2023 at Central Electricity Authority, Sewa Bhawan, New Delhi

1. A meeting of the committee under the chairmanship of Member (Hydro), CEA on requirement of Variable Speed vis-à-vis Fixed Speed Machine in PSPs in view of the large head variation was held at 10:30 AM on 24th February, 2023 in Conference Hall "Manthan" of Central Electricity Authority, Sewa Bhawan, New Delhi. List of Participants is given at Annexure-1.
2. Member (Hydro), CEA welcomed all the participants from BHEL, THDC, Greenko, Voith Hydro, NHPC and enlightened in detail the objectives of the Committee constituted vide CEA Office Memorandum dated 15.02.2023 on requirement of Variable speed machine vis-à-vis Fixed speed machine for PSPs.
3. The committee members, while drawing references from the need of Energy Storage Systems such as PSP, BESS etc. with the increase in penetration of Variable Renewable Energy (VRE) capacity in the gird welcomed the initiative taken by Member (Hydro), CEA and unanimously agreed that there must be a defined criteria for the preference of selection between fixed speed machine and variable speed machine for the PSPs in view of large head variation and other factors/parameters.
4. CEA gave a brief presentation highlighting the major technical comparisons between fixed & variable speed machines. Technical parameters of the machine viz. head ratio, black start capability, variation in/ switching-in between pump & generation mode, cycle efficiency, synchronous condenser mode operation etc. of fixed & variable machine were discussed in detail during the presentation.
5. During the presentation, the Turbine type (Fixed/Variable) installed in different PSPs in India were also deliberated and it was found out that amongst all, the fixed speed turbine had been installed except in Tehri PSP. Director (HE&TD), CEA requested the forum to share technical inputs so that a Report guiding the developer or manufacturer to select the type of machine judiciously. He also requested to submit data/details/exercise, if any, for selecting the variable speed machine under commonly stated indicative/ thumb rule of Head ratio being above 1.3. In this regard, M/s Greenko and M/s Voith stated that the said thumb rule ratio is not the only deciding factor.
6. The issue of limited number of global OEM's for the power electronics items including AC excitation system required for variable speed machines and also the possibility of non-responsiveness of these respective global OEM's in future in the event of maintenance

requirements was discussed. Further, this issue was also deliberated in light of 'Atmanirbhar Bharat' and 'Make in India'.

7. Member (Hydro), CEA stressed that the list of issues which may impact the selection of machine type in case of PSPs may be explored, finalised, elaborated for preparation of questionnaire for decision-making process, and which will facilitate the developer while having discussion with design consultants for finalisation of machine type i.e. fixed or variable speed machine.

   He further stated that the technical issues considering electro-mechanical & civil aspects in case of variable speed machine such as high unit cost, convertor losses, high maintenance/ downtime period & cost, civil excavation quantity required, required size of VSI, machine tripping probability, submergence required, replacement time of VSI system in case of fault, rotor winding damage etc. may be studied in a collective manner.

   Member (Hydro), CEA also stated that the monetary aspect in case of variable speed such as payback period of VSI convertors, present cost of VSI convertor as a percentage of total cost of the machine, cost benefit analysis in terms of gain in energy/efficiency to the capital invested may be suitably analysed while finalising the specifications of the machine.

8. M/s Greenko representative said that regarding the guarantee of the availability of variable speed machines, the vendors in general are reluctant to give machine availability above 90% and when insisted upon, they try to load the contract accordingly.
9. The representatives of M/s Voith and BHEL, during the meeting were requested to highlight the key issues from OEM perspective and the representative of M/s Greenko present during the meeting was requested to highlight issues from fulfilment of their business objective.
10. Member (Hydro), CEA directed the participants to study the best industry practise followed by project developers in Asian and European countries while finalising a variable speed machine or fixed speed machine in case of a pump storage projects.

The meeting ended with a vote of thanks to the chair.

Annexure -I

List of Participants

CEA

1. Sh. M. A. K. P Singh, Member (Hydro)- in Chair
2. Sh. Pankaj Kumar Gupta, Director (HE&TD)
3. Sh. Reetesh Tiwari, Deputy Director (HE&TD)
4. Sh. Shyam Singal, Asst. Director (HE&TD)

BHEL

5. Sh. V. Shrinivas Rao, GM (Hydro)

M/s Greenko

6. Sh. Y. K. Sehgal, ED
7. Sh. P. S. Ahluwalia, Sr. Vice President
8. Om Prakash, Sr. GM

M/s THDCIL

9. Sh. O. P. Samwal, DGM
10. Sh. Shailendra Singh, DGM
11. Sh. Rahul Joshi, Manager

M/s Voith Hydro

12. Sh. Sanjai Dhar Dwivedi, AVP

Azadi Ka Amrit Mahotsav

सत्यमेव जयते

भारत सरकार/Government of India
विद्युत मंत्रालय/Ministry of Power
केंद्रीय विद्युत प्राधिकरण/Central Electricity Authority
जल विद्युत अभियांत्रिकी व प्रौद्योगिकी विकास प्रभाग
Hydro Engg. & Technology Dev. Division
सेवा भवन, आर. के. पुरम-1, नई दिल्ली-110066
Sewa Bhawan, R. K. Puram-1, New Delhi-110066

टेलीफेक्स/Telefax:
011-26732789
ईमेल/Email:
hetdcea@nic.in
वेबसाइट/Website:
www.cea.nic.in

No.10/03/HE&TD/2023/ Date: 24.07.2023

Subject: Minutes of Second Meeting of Committee on "Requirement of Variable Speed machine vis-à-vis Fixed Speed machine in PSPs" held at 10:30 AM on 24th March, 2023 at Central Electricity Authority, New Delhi - reg.

Please find enclosed herewith the Minutes of Second Meeting of Committee on the subject matter for your kind perusal and necessary action.

Enclosure: As above

Signed by Shyam Singal
Date: 24-07-2023 15:04:11
Reason: Approved

(Shyam Singal)
Asst. Director

To:

1. Shri M A K P Singh, Member (Hydro), CEA
2. Shri Rakesh Kumar, Chief Engineer (HE&TD), CEA
3. Shri V. Shrinivas Rao, GM (Hydro), BHEL.
4. Shri Neeraj Verma, GM (E&M), THDC.
5. Shri Sanjai Dhar Dwivedi, AVP, Voith.
6. Shri Y. K. Sehgal, ED, Greenko.
7. SA to Member (Hydro), CEA.
8. Office file.

<u>Minutes of Meeting (MoM) of the Committee on "Requirement of Variable Speed machine viz-a-viz Fixed Speed machine in PSPs" held at 10:30AM on 24th March, 2023 at Central Electricity Authority, New Delhi</u>

1. The second meeting of the Committee on the **"Requirement of Variable Speed machine (VSM) viz-a-viz Fixed Speed machine (FSM) in PSPs"** was held at 10:30 AM on 24.03.2023 at CEA, Sewa Bhawan, R. K. Puram, New Delhi under the Chair of Member (Hydro) to review the **Draft Report**. The list of Participants is given at **Annexure-I**.
2. At the outset, Member (Hydro), CEA welcomed all the Committee members/ participants from CEA, BHEL (through VC), THDC, M/s Greenko (through VC), M/s Voith Hydro and sought their observations/ comments/ inputs on the Draft report circulated to them before the meeting.
3. Representative from M/s Voith stated that against Point no. 6 of cl. no. 2.2.2.6, the settling time of sedimentation should be considered in the report. However, Representative from BHEL apprised that the sedimentation does not play any role in the overall operation of the machines. Further, Member (Hydro) opined that the MDDL is always kept at higher level from reservoir surface and the silt can be settled easily in one cycle operation. In case of multiple cycles, effect of sedimentation for "On River" and "Off River" PSPs would be different. Further, the number of Operation Cycles would depend on business use cases such as, ancillary services, balancing, etc. provided by the developer, and therefore the type of operations should be decided by the developer itself taking into account all the possible scenarios of sedimentation, if any.
4. Representative from M/s Voith stated that the Gestation period (point no. 2.2.2.3 of draft report) of 30-36 months may be reviewed as in the case of fresh development of PSPs in civil aspects, the gestation period may be longer i.e. 30-38 months. Further, representative of M/s Greenko observed that the gestation period of PSPs having VSM viz-a-viz those having FSM would be longer by at least one year.

   The Chair directed to re-consider the gestation periods as following:
   i) In case of the already existing hydraulic module/ modular approach with FSM, it could be 30-36 months whereas for VSM, it could be 42-48 months;
   ii) In case of new hydraulic module with FSM, it could be taken as 32-38 months whereas for VSM, it could be 44-50 months.
5. Representative from M/s Voith further stated that in case of the Ternary Set, the type of turbine, i.e. Pelton or Francis could be considered in the report as there are separate pump and turbine in Ternary set machine, and therefore, Pelton turbine can be deployed for high head (above 800m) in case of generation mode.
6. During discussion on point no. 2.3.5.3, Representative from M/s Voith opined that head ratio criteria for selecting FSM could be maximum up to 1.5. On this issue, Member (Hydro), CEA opined that the data has been collected from the market - M/s Andritz recommends head ratio to be 1.32 to 1.33, whereas, M/s Voith recommends Head Ratio of 1.5 for FSM. However, the genesis/ supporting studies behind selecting head ratio have not been provided by both, and the cost data also

has not been provided by the suppliers. Only THDC has provided some details for techno-commercial comparison of FSM and VSM and justified the selection of VSM over FSM for Tehri PSP (4x250 MW). Member (Hydro), CEA further stated that the head ratio given in the Draft report may be considered as general guideline taking into account the present practice. However, the developer is free to conduct the detailed study for selecting one of the options viz. FSM or VSM, and may adopt the machine which is techno-commercial beneficial to them.

7. Chief Engineer (HE&TD), CEA apprised that the Draft report would be a general guideline for guiding & facilitating the developers in making an informed choice by making them aware about the various Pros and Cons of Fixed Speed Machine and Variable Speed Machine and other related project aspects. Therefore, project/ machine specific parameters, which are beneficial to the developer, should be studied in detail by the developers themselves while keeping market dynamics and business propositions in view before making the final selection of the type of turbine i.e. FSM or VSM.
8. Representative from M/s Greenko stated that higher Head Ratio in case of Variable machine can be beneficial in pumping mode. He further added that the same benefit of high head variation can be taken by deploying different capacity of fixed speed machine in the same project. The cost incurred in both options can be compared and accordingly machine can be selected.

The meeting ended with a vote of thanks to the chair.

Annexure-I

List of Participants

CEA

1. Sh. M. A. K. P Singh, Member (Hydro) - in Chair
2. Sh. Rakesh Kumar, Chief Engineer (HE&TD)
3. Sh. Pankaj Gupta, Director (HE&TD)
4. Sh. Reetesh Tiwari, Dy. Director (HE&TD)

BHEL

5. Sh. V. Shrinivas Rao, GM (Hydro)- via VC

M/s Greenko

6. Sh. P.M. Nanda, Sr. Vice President - via VC
7. Sh. Om Prakash, Sr. GM

M/s THDCIL

8. Sh. Neeraj Verma, GM (EM-Design)
9. Sh. O. P. Semwal, DGM (EM-Design)
10. Sh. Anil Raghuwanshi, Sr. Manager (EM-Design)

M/s Voith Hydro

11. Sh. Arun Gupta, VP
12. Sh. Sanjai Dhar Dwivedi, AVP

Annexure-II

Head Ratio of Projects (which are already constructed)

(Head Ratio = Gross Maximum Head/ Gross Minimum Head)

Sr. No.	Name of Project	Type of Machine	Head Ratio
A. Working in Pumping Mode			
1.	Nagarjuna Sagar (7x100.80MW), Telangana	Fixed Speed	1.32
2.	Srisailam LBPH, (6x150 MW), Telangana	Fixed Speed	1.75 Turbine Supplier- M/s Hitachi Generator Supplier- M/s Melco, Japan
3.	Kadamparai PSP (4x100 MW), Tamil Nadu	Fixed Speed	1.19
4.	Bhira (1x150 MW), Maharashtra	Fixed Speed	--
5.	Ghatgar (2x125 MW), Maharashtra	Fixed Speed	1.10
6.	Purulia HEP (4x225 MW)	Fixed Speed	1.38 Turbine Supplier- M/s Toshiba Generator Supplier- M/s Toshiba Ltd.
B. Presently not working in Pumping Mode			
1.	Kadana (4x60 MW), Gujarat	Fixed Speed	1.68 Turbine Supplier (Unit 1 & 2) - M/s Skoda Turbine Supplier (Unit 3 & 4)- M/s BHEL Generator Supplier (Unit 1 & 2) - M/s Skoda Generator Supplier (Unit 3 & 4)- M/s BHEL
2.	Sardar Sarovar Project (6x200 MW), Gujarat	Fixed Speed	1.42 Turbine Supplier (Unit 1 to 4) - M/s Hitachi Turbine Supplier (Unit 5 & 6)- M/s BHEL Generator Supplier (Unit 1 to 4) - M/s Toshiba Generator Supplier (Unit 5 & 6)- M/s BHEL

Annexure-III

Head Ratio of Projects (which are under Construction)

Sr. No.	Name of Project	Type of Machine	Head Ratio
A. Under Active Construction			
1.	Tehri Stage-II (4x250 MW), Uttrakhand	Variable Speed	1.78
2.	Kundah (Stage I, II, III & IV), (4x125 MW), Tamil Nadu	Fixed Speed	1.18
3.	Pinnapuram (4x240 + 2x120 MW), Andhra Pradesh	Fixed Speed	1.30
B. DPR Concurred by CEA			
1.	Turga PSP (4x250 MW), West Bengal	Fixed Speed (2M/c)+ Variable Speed (2 M/c)	1.47

Annexure-IV

Head Ratio of Projects (which are under Examination in CEA of 36380 MW Capacity)

Sr. No.	Name of Project	Type of Machine	Water level (FRL_U/ $MDDL_U$/ FRL_L/ $MDDL_L$)	Head Ratio
1.	Shahpura PSP 1800 MW (5X300 + 2X150MW) , Rajasthan	Fixed Speed	U- 507.0, 490.0 L- 349.0, 328.0	1.26
2.	Paidipalem East PSP (200X6 MW), 1200 MW, Andhra Pradesh	Fixed Speed	U- 570.0 m , 540.0 L- 310.0 m , 270.0	1.30
3.	Sukhpura PSP (2560 MW) (7X320 + 2X160 MW), Rajasthan	Fixed Speed	U- 605.0, 586.0 L- 410.0, 393.0	1.20
4.	Singanamala PSP (4X200 MW), 800 MW, Andhra Pradesh	Fixed Speed	U-485.0, 465.0 L-335.0, 317.0	1.29
5.	OWK PSP, (4X200 MW), 800 MW, Andhra Pradesh	Fixed Speed	U- 392.0, 373.0 L- 227.0, 215.0	1.15
6.	Chitravathi PSP (2X250) MW, Andhra Pradesh	Fixed Speed	U- 495.0, 460.0 L- 298.0,282.55	1.31
7.	Gandikota PSP, (4X250 MW), 1000 MW, Andhra Pradesh	Fixed Speed	U- 481.0, 464.0 L- 212.0, 202.9	1.10
8.	Kurukutti PSP, (5x240 MW), Andhra Pradesh	Fixed Speed	U -899.0, 861.0 L- 306.0, 281.0	1.08
9.	Karrivalasa PSP, (4X250 MW) = 1000 MW, Andhra Pradesh	Fixed Speed	U- 825.0, 771.0 L-306.0, 281.0	1.16
10.	Pinnapuram PSP (480 MW), Andhra Pradesh Under MoC Stage	Fixed Speed	U-463.0, 445.50 L- 337.0, 321.80	1.30
11.	MP30 Gandhi Sagar PSP (5X240 +2X120 MW) = 1440 MW, Madhya Pradesh	Fixed Speed	U- 522.20, 508.0 L- 399.90, 381.0	1.30
12.	Upper Sileru (9x 150 MW), Andhra Pradesh	Fixed Speed	U- 414.50, 406.75 L-316.0, 306.0	1.19
13.	Sillahalla PSP (4 X250 MW), Tamilnadu	E&M chapter awaited	U- 1950.0, 1940.0 L- 1560.0, 1520.0	1.13
14.	Saundati (4x252 + 2x126 MW), Karnataka	Fixed Speed	U- 855.0, 825.0 L-633.83, 623.93	1.20
15.	Bhavali (6x250 MW) PSP, Maharastra	Fixed Speed	U- 737.0, 711.0 L-300.0, 270.0	1.13

16.	Paidipalem North PSP (1000 MW), Andhra Pradesh	E&M chapter awaited	U- 540.0, 518.0 L-310.0, 270.0	1.29
17.	Sirohi PSP (4x300 MW) = 1200 MW, Rajasthan	Fixed Speed	U- 888.0, 832.0 L-388.0, 335.0	1.24
18.	Narihalla PSP (300 MW), Karnataka	Fixed Speed	U- 700.0, 673.0 L-542.315, 530.0	1.30
19.	Veeraballi PSP (1800 MW), Andhra Pradesh	Fixed Speed	U- 690.0, 664.0 L-323.0, 305.0	1.12
20.	Pane PSP (1500 MW), Maharashtra	Fixed Speed	U- 747.0, 696.0 L-213.0, 193.0	1.14
21.	Gujjili PSP (6x250 MW) = 1500 MW, Andhra Pradesh	Fixed Speed	U- 950.0, 930.0 L-303.0, 279.0	1.07
22.	Vemapalli PSP (6x250 MW) = 1500 MW, Andhra Pradesh	Fixed Speed	U- 586.0, 570.0 L-322.0, 302.0	1.14
23.	Tarali PSP (5X300)=1500 MW), Maharasthra	Fixed Speed	U- 1101.0, 1060.0 L-711.3, 675.0	1.22
24.	UP01 OCPSP (3660 MW), Sonbhadra,Uttar Pradesh	Fixed Speed	U- 590.0, 567.0 L-223.0, 209.0	1.10
25.	Kandhaura PSP (1680 MW), Uttar pradesh	Fixed Speed	U- 568.0, 535.0 L-220.0, 205.0	1.15
26.	Raiwada Pumped Storage Project 850 MW, Andhra Pradesh	Fixed Speed	U- 563.0, 530.0 L-138.0, 133.0	1.09
27.	Sharavathy Pumped Storage Project (8X250 MW) 2000, Karnataka	Fixed Speed	U- 522.12, 520.59 L-55.0, 48.50	1.01

Annexure-V

Selection of Machine for Tehri PSP as made by THDC

Design constraints on rated characteristics: Very large operating head range (approx. 50% of the average net head) leads to a quite high variation in the power absorbed by the pump, large area of performances and high risk of cavitation. In this view, the following factors are considered in selection of pump turbine:

In pump mode:

a) A better efficiency curve.
b) Reduced power and discharge ranges, lower maximum discharge, less severe transient flows.
c) The lowest cavitation factor.
d) A significant margin relative to instability zone, permitting operation at low frequency and high head.
e) A lower inlet diameter.

In Turbine mode:

a) Best optimization between pump and Turbine Design, from the electric machine point of view.
b) A lower maximum discharge and less severe transient flows.

As Tehri PSP has a wide head range (130m to 230m) of operation, therefore, fixed speed and Variable Speed pump turbine had been studied.

Parameters of Tehri PSP

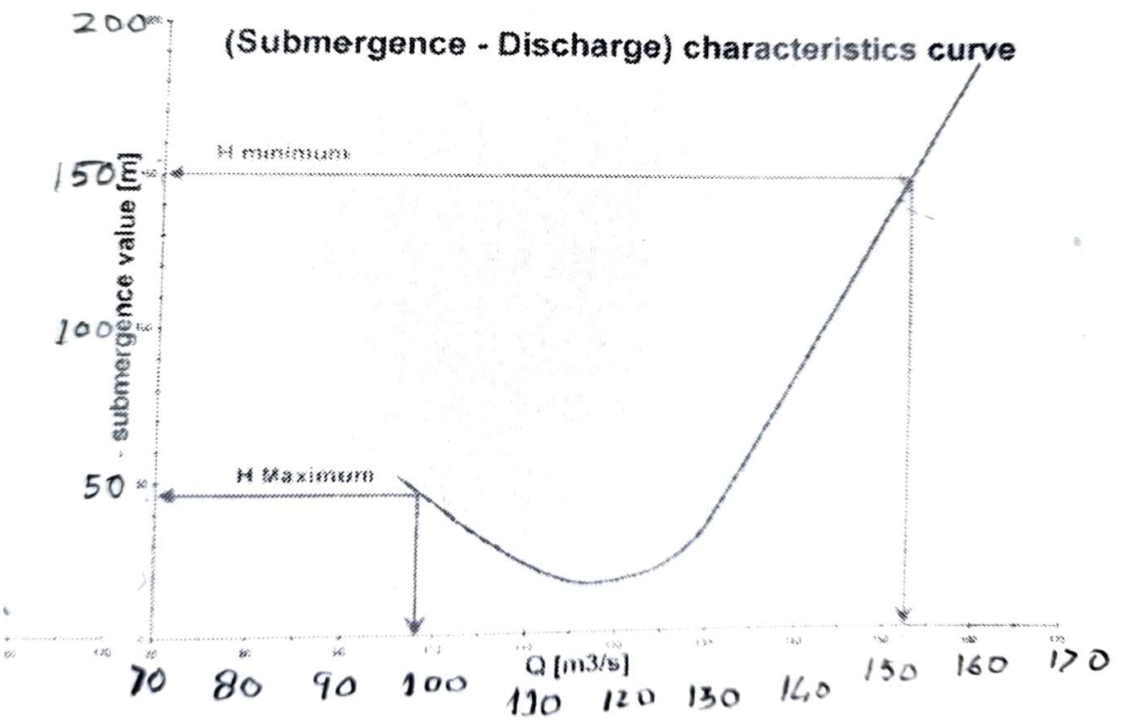
	Upper Reservoir	**Lower Reservoir**
Live Storage (Mm3)	2615	17.6
Water Level in Turbine Mode (m)	EL.830 to El.740	EL.612.5 to EL.603
Water Level in Pump Mode (m)	EL.830 to EL.740	EL.612.5 to EL.606
	Maximum	**Minimum**
Design Gross Head (m)	227	127.5
Net Head (m)	222.8	120.4
Delivery Head (m)	229.5	130.5

Technical parameters such as Specific Speed, Rotational Speed, Rated Power, Discharge and Submergence for different speed and cost analysis were studied in detail. Overall lower cost of the project has been kept in mind.

Technology Comparison in respect of Tehri PSP:

i) Fixed Speed Machine: The required submergence calculated in Fixed speed is equal to (-) 150m. The submergence value is deduced from the Net Positive Suction

Head (NPSH) in pumping mode taking into account the atmospheric pressure. NPSH value is usually estimated with laboratory scaled models during cavitation tests and is one of the pump-turbine characteristics, with the Head-Discharge, Input power and Efficiency curves.



As in Tehri PSP, head range is very large which implies that the pump operates while NPSH becomes high at extreme heads. Although, lower value of submergence could be obtained by specific ways of closing of wicket gates, but this would mean dissipation of energy in the machine at low heads and then resulting the sharp decrease of efficiency, a bigger runner and also risk of excessive vibration zone and thus was not accepted.

Moreover, with such a Fixed Speed turbine mode option, the best efficiency point is always outside the operating range. That means 100% of relative efficiency is not reached when turbining always with single speed Pump-Turbine Machine. However, fixed speed machine is technologically simpler as one runner is coupled with a single speed synchronous motor generator.

Following are the drawbacks of Fixed speed machine:

a) As often in pump-turbine performance, the best efficiency point when turbining is out of the operating head range. The efficiency would deteriorate sharply (in the range of -20%) as soon the head is away from the rated head particularly in case of low delivery head in pumping.
b) This would imply difficulty in designing and manufacturing reliable shaft seal and a risk of counter thrust has to be also considered.
c) As often in pump-turbine performance, the best efficiency point when turbining is out of the operating head range.

d) The submergence (-150 m) is extremely high but is needed to avoid the cavitation.
e) Imply greater diameters of the upstream and downstream guard valves.

It is clear from the above that high submergence is difficult and costly to implement and best efficiency points are out of operating head range. Therefore option of Fixed speed machine is rejected during appraisal report study.

ii) Variable Speed:

In variable speed machine pump can work maximum to minimum head by adjusting the speed continuously. At each operating head, the optimum of the machine performance could be achieved in terms of efficiency and cavitation limits. This is possible if each reversible unit is composed of single stage Francis pump-turbine coupled with an asynchronous motor-generator equipped with a wound rotor fed by a cyclo-converter. Moreover, much lower submergence (-40 m) is required for a pump-turbine operating at normal head range with such hydraulic characteristics. It is clear that this option is the most appropriate for an efficient pumping, working either at the best efficiency throughout the year or either on a narrow range of head-discharge. This option enables to adjust the required Input Power by adjusting the required speed, which is not possible in other option. Thus, this option provides a new possibility of optimizing the Head-Discharge characteristics towards the network capacities, in other words, this alternative is able to regulate frequency in pump mode. In this option, possibility to run at minimum speed enables to reach the best efficiency point within the operating range, when turbining. However, this option is costly due to the necessity of cyclo-converter and technically more complex rotor. This option has also the drawback of a lower motor generator efficiency (98%), which is again slightly reduced by the VSI/Cyclo converter energy loss. In case of Tehri PSP, the cumulative generator efficiency including losses in the variable speed drive and IPB in PUMP mode and TURBINE mode is 97.79% and 97.56% respectively.

Merits and Demerits of Variable Speed Machine are as under:

Demerits	**Merits**
i) Additional equipment costs for variable speed; ii) Extra space requirement for additional equipment thus increasing the Civil Cost iii) Lack of recognition for the additional services provided by the equipment upgrades (i.e., ancillary service market development); iv) High-tech Solution might give technical risk and result in forced outages and higher O&M cost; v) Higher Auxiliary power consumption. vi) Dependence majorly on foreign OEMs for spare parts.	i) Reduction in excavation cost due to low submergence requirement; ii) Fixed speed machine has limitations in performance, whereas variable speed control is advantageous; iii) Better unit efficiency, power output and frequency regulation while in the pump mode is not possible with Fixed speed machine; iv) Fixed speed Machine cannot operate at peak efficiency during part load (in turbine mode). Modifying the speed in variable speed machine allows the turbine to operate at peak efficiency

	over a larger portion of its operating band; v) Variable-speed machines enable the power consumed in the pumping mode to be varied over a range of outputs; vi) Improves the flexibility of VREs; vii) Extending the head operating range in pumped mode making feasible to increase the storage possibilities.

(i) Unit and Main Dimensions comparison for Tehri PSP for different machines:

Dimensions of main generating equipment in all two options were studied during DPR stage and found that weight of stator & rotor is less in Variable Speed which would need lesser capacity EOT crane and ease in handling. See the table below.

	Fixed Speed	Variable Speed
Outlet Pump Runner diameter (m)	4.92	5.18
Maximum Spiral case width (m)	13	13
Stator Frame Outer Diameter (m)	9	11
Core length (m)	3	2.9
Stator Weight (Tons)	240	321
Rotor Weight (Tons)*	560	490
Speed	272.73	206 - 250

(ii) Characteristics comparison for two options:

Comparing the characteristics, it was found that least submergence is required in variable Speed option. Submergence of 150 m required in fixed speed would have increased the civil cost of excavation and construction due to longer penstock and TRTs. Approximate Cost of penstock is 30.7 lacs per RM. Cycle efficiency is least in Fixed speed and in variable speed. Input energy required for pumping is 16.6% less than Fixed speed machine. Energy generated in Variable speed machine is 13.3% more than the Fixed speed machine.

	Machine Characteristics	Fixed Speed	Variable Speed
1	Submergence (m) *	-150	-40
2	Speed Value (RPM)	272.8	206-250
3	Energy absorbed in pumping per year per unit (mu)	495.2	412.92

4	Energy Produced in turbine per year per unit (mu) **	291.5	330.45
5	Turbine/ Pumping energies Ratio (%)	77.3	80.01
6	Average energy ratio in pumping (Kwh/m3)	0.59	0.583
7	% reduction in energy drawls in Pump operation taking the reference of Single speed (%)	0	-16.6
8	% excess energy generation in Turbining in taking reference of Fixed speed	0	13.3
9	% Total energy saving taking reference of fixed speed machine	0	29.9

Economic comparison

The economic comparison between Fixed, and Variable Speed machine has been carried out in this section taking into account some specific equipment that are different in all kind of machine selection option. The cost comparative analysis is as under:

	Fixed Speed	**Variable Speed as per DPR**
Turbine, Governor & Valves	Low	High
Generator (Incl. Thrust & Upr Bearings)	Low	High
Excitation	Low	----
VSI	----	High
Pole Changing Switchgear	----	----
Extra Civil cost due to submergence in Fixed speed (Approx.)	High	Medium
Cost of Extra excavation for VSI & VSI Transformer (Approx.)	0	Medium

As per the economic analysis in DPR cost the variable machine is nearly 32.85 % higher than fixed speed.

Annexure VI

Higher Maintenance and Lower Reliability of Variable Speed Machines

One of the major disadvantages of variable speed machines is higher maintenance requirements and lower reliability.

Miodrag Basid et. Al, Power Electronics Laboratory, EPFL, Switzerland have noted that "several drawbacks exist for the DFIM configuration. The wound rotor is complex in design, introduces slip rings as an additional maintenance issue, and has a limited power according to cooling capabilities of the machine. In practice, rotor power is roughly limited to 15% of rated machine power, limiting available speed range and starting torque. Limited starting torque, in return, may be insufficient when switching between generation and pumping, requiring a dewatering procedure, a time-and-resource-consuming task.

During grid faults resulting in short circuit, low voltage ride-through (LVRT) proves to be challenging for DFIM. High rotor currents in short circuit conditions reach values well above rated, overloading the converter. In case rotor supply converter enters protected mode, rotor windings are short-circuited, and DFIM acts as a consumer of reactive power, negatively contributing to LVRT situation. Special requirements for DFIM during LVRT thus require the machine to be controlled for some time during the fault. In practice, this means that converter must be oversized to withstand the requirement. The degree of oversizing depends heavily on required length of operation, and can reach values 3-4 p.u. higher than rated ones."

Further, Anto Joseph et. Al.have concluded that the Mean Time to Failure (MTTF) in case of variable speed units is much much lower than that for fixed speed units.

Table 8. Availability of pumped-storage power plants.

S.No	Particulars	Pumped-Storage Power Plant Unit (250 MW)		
		Variable-Speed Unit		Fixed-Speed Unit
		Without Redundancy	With Redundancy	
1	MTTF (years)	0.295	0.934	2.63
2	Availability	0.9775	0.9916	0.9964

Further, there is a limited number of vendors in the global market for the power electronics items required for variable speed machines. This may not only increase the lead time for procurement of goods (including spares) & services, but may also lead to problems during O&M.

References:

1. High Power Electronics Innovation Perspectives for Pumped Storage Power Plants, M. Basic, P. Silva, and D. Dujic, Power Electronics Laboratory, EPFL, Switzerland, Hydro 2018.
2. Reliability of Variable Speed Pumped-Storage Plant, Anto Joseph, Thanga Raj Chelliah, Sze Sing Lee and Kyo-Beum Lee, 2018.

Annexure VII

1.0 Variable Speed Technology: Cost-Benefit Analysis

1.1 Initial Investment

Variable speed machines call for a much higher initial investment in the Electro-mechanical equipment. **Variable speed machines (EM equipment for PSP) are 30-40 % costlier than fixed speed machines.**

The rotor of a variable speed motor-generator is itself 2-3 times costlier than the rotor of a fixed speed motor-generator owing to its complicated design & construction. This high cost of AC excitation system & generator rotor alone results in a hike of around 30-40 % in the cost of Electro-mechanical equipment. For reference, normally in fixed speed motor-generators, DC excitation system costs only about 5% of the cost of fixed-speed generator.

Further, the C&I package (Controls & Instrumentation) of a variable speed machine is also costlier than that of a fixed speed machine. However, there is no change in the design of the reversible pump-turbine with a variable speed motor-generator.

Since this is a huge increment in the initial cost of the Pumped Storage plant, this additional investment may not be economically justifiable for all market conditions and has to be considered judiciously on a case-to-case basis.

Recent Case: Comparison of Fixed speed and variable speed machines' cost

Cost Comparator: Fixed Speed Technology vs Variable Speed Technology

Pinnapuram (2 x 120 MW)

Package Name	Fixed Speed Technology (Cr)	Variable Speed Technology (Cr)
Turbine + MIV + Governing (per unit)	39.6	44
Motor-Generator (per unit)	26	55.3
Static Excitation Equipment (per unit)	1.3	Not Required
AC Excitation System + GCB(per unit)	Not Required	33.2
Other Packages (Transformer, GIS, Switchyard, Erection & commissioning, BOPs like Cranes, HVAC, Lifts, Illuminations & PA systems etc.)	--	--

Pinnapuram (4 x 240 MW)

Package Name	Fixed Speed Technology (Cr)	Variable Speed Technology (Cr)
Turbine + MIV + Governing (per unit)	75.9	84.68
Motor-Generator (per unit)	44.24	96.85
Static Excitation Equipment (per unit)	1.6	Not Required
AC Excitation System + GCB(per unit)	Not Required	76
Other Packages (Transformer, GIS, Switchyard, Erection & commissioning, BOPs like Cranes, HVAC, Lifts, Illuminations & PA systems etc.)	--	--

E&M equipment Cost for Variable Speed PSS is approximately 30-40% higher than Fixed speed PSS

1.2 Limited Vendor Base & Longer Lead Time

The AC excitation system of variable speed generators is highly complicated. There are **limited suppliers (2-3) of this AC excitation system in the world** leading to high cost, higher lead time. This dependence on international vendors also defeats the objective of energy security for the country. **This also goes against the principles of 'Atmanirbhar Bharat' and 'Make in India'.**

1.3 Actual speed variation

As suggested by its name, variable speed technology seems to be capable of infinite variation of speed from zero to rated speed. However, the truth is rather contrary. Variable speed technology permits speed variation of only around 6-7% (10% at max) from the rated speed. This fact alone offsets most of the advantages advertised by the promoters of variable speed technology.

1.4 Adjustable pumping power

Variation in pumping power is another advantage being portrayed by proponents of variable speed technology. The foremost aspect that needs to be clarified that there is no significance of adjustable power with regards to turbine mode operation since the output power in turbine mode is already adjustable by virtue of adjustable guide vanes. It is only in the pumping mode where adjustable speed allows some variation in input power. However, the following points need to be considered for judicious decisions in this regard:

1.4.1 Pumping Flexibility

Sufficient grid flexibility already exists within the country's electrical grid that can easily cater to pumping requirements. Micro adjustment of pumping input might not really be required considering the size and scale of our country's electrical grid. **The successful operation of BHEL's mega Lift Irrigation pumps (biggest single stage pumps in the world) of unit capacities up to 140 MW in the state of Telangana is testimony to the fact that we do not require micro level adjustment of pumping input for ensuring grid stability.**

In fact, whatever little advantage that variable speed machines have to offer can be realized only in the case of a small sized isolated grid. On the contrary, in our country's case, where we have a huge grid and the pumped storage plants are going to be coupled in the national grid instead of an isolated island, making huge additional investment in variable speed machines may not make much sense.

1.4.2 Number of units

Since any pumped hydro scheme would be consisting of a multiple number of units, any 'major' fluctuation in grid requirements can always be taken care of by increasing/ decreasing the operational number of units as is the case with the conventional hydro power plants also. This means that grid stability can be achieved at no extra cost as compared to a huge additional investment that would be required for variable speed machines.

1.4.3 Hydraulic Short Circuit Operation

Most of the benefits envisaged from variable speed operation of pump can be achieved without incurring any major extra investment or additional lead time through Hydraulic Short Circuit mode operation by operating a combination of the number of units in operation in turbine/pump mode so as to match the available grid power with the net input power of the plant.

1.5 Efficiency improvement in turbine mode

Again, it is submitted that there is no real gain in efficiency with respect to **pumping** mode operation by virtue of variable speed operation. Whatever gain in efficiency is expected, is in the **turbine mode** only. There too, there is only a marginal improvement in turbine efficiency by virtue of variable speed operation since operating points still remain significantly away from the best efficiency point despite of variable speed because the possible variation in speed is only 6-7% (10% at max) of the rated speed and not continuous variation from zero to rated speed.

Also, the gain in turbine efficiency is subjective and not across board. The actual gain in efficiency depends upon site conditions, difference between turbine & pump heads and between max & min operating heads.

Further, a finely tuned and optimized pump-turbine will have pumping and turbine mode characteristics defined such that the turbine operating points will not be very far from the best efficiency zone, thus alleviating the essentiality of variable speed for better efficiency.

The minimal gain in efficiency alone might not justify the higher initial cost (30-40% higher investment)

1.6 Design, Manufacturing and Maintenance Issues

The design of the generator rotor and the control scheme of the machine are highly complicated. This leads to cumbersome and longer manufacturing of the generator-motor. The experience of European operators also suggests that these variable speed machines are prone to frequent break-downs and maintenance requirements. The reasons include complicated design consisting of at least one slip ring per phase, higher mechanical stresses and heating issues.

Above considerations have been summarized in the table below:

Variable Speed Technology: Cost Benefit

Features	Inhibitors
Variable Speed Operation • Variation in Speed of 6-7% normally (max 10%, not continuous variation from zero to rated speed) • Complicated Control Scheme	**Initial Investment** • Cost of variable speed machine is 30-40 % higher than corresponding fixed speed machine **AC excitation System** • Only one or two vendors worldwide for AC excitation system leading to tech. dependence, higher costs & longer lead time • Against the spirit of Atmanirbhar Bharat **Manufacturing, Operation & Maintenance** • Manufacturing and O&M of variable speed motor-generator is cumbersome, time-consuming & costlier. (May extend project timelines)
Power Variation • Applicable for Pumping Mode only • Owing to limited variation in speed, power variation is limited to only maximum 25-30 %.	**Turbine Mode** • No significance for turbine mode **Flexibility** • Micro adjustment not required (BHEL's large LIS pumps running successfully) • No. of units • Hydraulic Short circuit operation
Efficiency • Weighted average Efficiency Improvement in generation mode by 1%-1.5% (max)	**Cost-Effectiveness** • Only a marginal improvement in turbine efficiency since operating points still remain significantly away from the best efficiency point • Efficiency gain can be offsetted by 0.5 %, if design is properly tuned for turbine mode