*International Conference on Hydropower and Dams Development for Water and Energy Security – Under Changing Climate, 7-9 April, 2022, Rishikesh, India*

# PSP, MODERN TECHNOLOGIES AND LARGE SCALE RE INTEGRATION- AN OVERVIEW

**R.K. VISHNOI**
*CMD, THDCIL, Rishikesh, India*

**L.P.JOSHI AND MADHWI KUMARI**
*EMD Dept, THDCIL, Rishikesh, India*

**ABSTRACT**

*Global concerns towards climate change and commitment for net zero carbon emission in CoP21 and now in CoP26 has brought a paradigm shift in the energy sector. In past decade world has witnessed a drastic transition from conventional fossil fuel to renewable resources to meet its energy needs. India alone has seen a six fold growth in its renewable capacity addition (solar and wind). However, renewable resources have their own challenges and have set forth the need of energy storage. Storage of abundant renewable energy available during low demand time for its usage later is the only answer to manage intermittency. Presently Pumped Storage Technology and Battery Storages are the major commercially viable solutions for long duration and short duration storage. Among these two options, the latter is still under researches to bring in cost competitiveness. Altogether PSPs and Battery storage are two viable solutions which go hand in hand with renewable sources. In this paper PSPs have been discussed with their present status in India, available technology options and configurations.*

***Index Terms*** *: Energy Storage, Net Zero Emission, Pumped Storage Plants, Renewable Energy.*

## I. INTRODUCTION

Pumped storage Plants (PSP) act as an energy storage solution with two reservoirs one at higher elevation and other at lower. PSPs store and generate energy by moving water between these two reservoirs. When the demand for electricity is low and there is abundant renewable energy available from wind or solar sources this excess energy is used to pump water to the upper reservoir. The turbine acts as a pump and generator acts as motor, moving water back to uphill. During periods of high electricity demand or unavailability of solar / wind sources, the stored water is released through turbines and generators in the form of electricity. As per International Hydropower Association's (IHA's) report [1], PSP currently accounts for over 90 per cent of the world's grid-scale energy storage applications, with 160 GW of installed capacity.

The IEA's Net Zero by 2050 report was released in May 2021, modelling how the global energy sector may successfully decarbonize by 2050. As per the report, in the Net Zero Emissions (NZE) scenario, when solar PV and wind are supposed to generate substantial share of electricity, hydropower will steadily grow and double by 2050 thus becoming the largest single source of flexible electricity generation. Further to this, the report also emphasizes that pumped storage hydropower could play an important role, stating that it "offers an attractive means of providing flexibility over a matter of hours and days".[1]

## II. STATUS OF PSPS IN INDIA

The global installed capacity of PSPs in major economies is mentioned in Table I [2].

**Table I** : Installed Capacity of PSP in Major Economies

| Country | Installed Capacity (GW) |
|---|---|
| China | 30.3 |
| U.S | 22.9 |
| Italy | 7.7 |
| Germany | 6.4 |
| France | 5.8 |
| Austria | 5.6 |

Installed capacity of Pumped Storage Plants in India is approximately 4.8 GW. India is bestowed with immense hydro power potential and country wide identified potential is around 145 GW (excluding small HEPs) [3]. As on 31.01.2022, total installed capacity of India is 395 GW where share of Hydro is 46 GW [4], which is 11.6% of total installed capacity in the country. India has many sites suitable for Pumped storage plants as well. Total estimated potential of PSPs is around 96 GW in the country, out of which 88 GW is of size more than 25 MW [5].

Despite having a huge potential for hydro and PSPs we have seen a very abysmal growth in the sector in past decade. Hydro sector has witnessed only approx 3 percent growth whereas total installed capacity of PSPs has been only 4745 MW. Status of PSPs in the country is mentioned in the following Table II in India [5]:

**Table II** : Status of PSPs in India

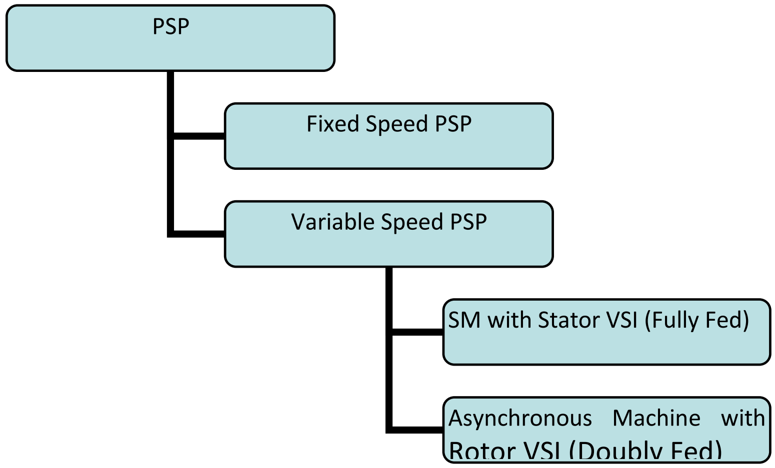
| *Schemes Constructed (Working in Pumping Mode)* | | |
|---|---|---|
| **Sl. No.** | **PSP** | **Installed Capacity (MW)** |
| 1 | Nagarjuna Sagar, Telangana | 705.6 |
| 2 | Srisailam LBPH, Telangana | 900 |
| 3 | Kadamparai, Tamil Nadu | 400 |
| 4 | Bhira, Maharashtra | 150 |
| 5 | Ghatghar, Maharastra | 250 |
| 6 | Purulia PSS, West Bengal | 900 |
| | Sub Total | 3305.6 |
| *Schemes Constructed (Not Working in Pumping Mode)* | | |
| 1 | Kadana, Gujarat | 240 |
| 2 | Sardar Sarovar Project | 1200 |
| | Sub Total | 1440 |
| | Grand Total | 4745.6 |

The two PSPs Kadana & Sardar Sarovar project are not operating in pump mode due to following reasons [5]:

1. Kadana Station I & II, Gujarat (2X60+2X60 MW) is not operational in pump mode because of abnormal vibration in the machine. The matter is under examination.
2. Sardar Sarovar Dam, Gujarat (6X200 MW)) is not operating in pump mode because of non operation of lower reservoir.

In addition to above PSPs, two projects Tehri Stage II, 4 X 250 MW at Tehri, Uttrakhand and Kundah Stage I, II, III & IV, 4 X 125 MW in Tamilnadu are under advance stage of construction and expected to be commissioned by 2022-24. For one PSP, DPR has been concurred & one is under examination by CEA. 17 PSPs are at various stages of survey & investigation and 14 projects are under PFR stage.

## III. PUMP STORAGE TECHNOLOGIES




Based on rotational speed of the machine, PSPs are mainly classified as fixed speed and variable speed PSPs.

**Fixed Speed PSP:**

In fixed speed PSPs, reversible pump-turbine with a fixed speed motor-generator is used. The pump-turbine is conventional francis type and motor-generator is synchronous type. The machine can operate as turbine-generator or pump-motor for generation & pumping operations respectively.

Fixed speed PSP technology is most proven technology almost a century old. For fixed speed machines the rotor of motor-generator is supplied with DC excitation. Static frequency convertors are used on stator side for starting the unit in pump mode.

SFCs are used for starting of pump/turbine sets and provide a source of adjustable frequency/voltage for starting the pumps. Thus they act as source to provide the variable voltage-variable frequency. SFCs usually consist of Convertor circuit, DC link and inverter units. Inverters used are load commutated inverter types wherein commutation of thyristor bridges is enabled with armature induced voltages. The SFC units in fixed speed PSPs are also used for braking.

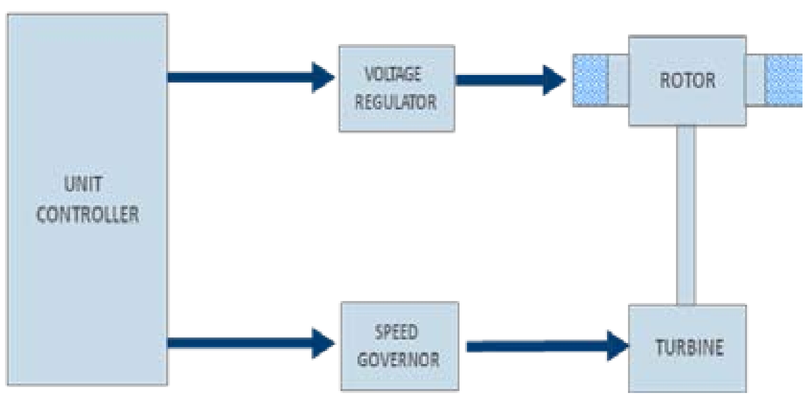



**Fig. 1[6]** : Diagram of Fixed Speed PSP

In a conventional, single-speed pump-turbine, the magnetic field of the stator and that of the rotor always rotate with the same speed and the two are coupled [7]. Therefore,

Stator field speed $n_s = fs / p$

fs : stator frequency

p : poles pairs number

Rotor field speed $n = n_s$.

For starting the motor in pump mode, the AC input from grid is converted to DC and is fed to inverters through DC link to generate variable frequency output to stator of synchronous generator while rotor is fed with DC excitation. The motor starts in synchronism and at nominal speed it is connected to grid.

Although this technology is proven and has worked well for for years, there are limitations to its performance specially in pump mode. Frequency regulation is not possible in the pump mode with single-speed equipment, though design enhancements over the years have improved unit efficiency and power output.[7]

Pump-turbines used in almost all the pumped storage plants installed so far in India are based on fixed speed technology.

**Variable Speed PSP:**

A variable speed pump-turbine can operate at different speeds within a speed range around synchronous speed. Noramally a speed variation of about +10% around synchronous speed is possible. This enables machine operation according to available head and power can be adjusted in pumping mode. This provides an overall better efficiency to the machine and better utilization of larger head variation.

In a variable-speed machine, stator and rotor magnetic fields are decoupled. A frequency converter between the grid and the stator winding, desouples the stator field from the grid, or a multi-phase rotor winding fed from a frequency converter connected to the rotor decouples the rotor field from the rotor body by. [7]

Thus there are two configurations of variable speed PSPs- synchronous generator with full convertor and a double-fed induction generator with converter in the rotor circuit.

**Variable speed Generator – Motor Full Size Converter (FSCS):**

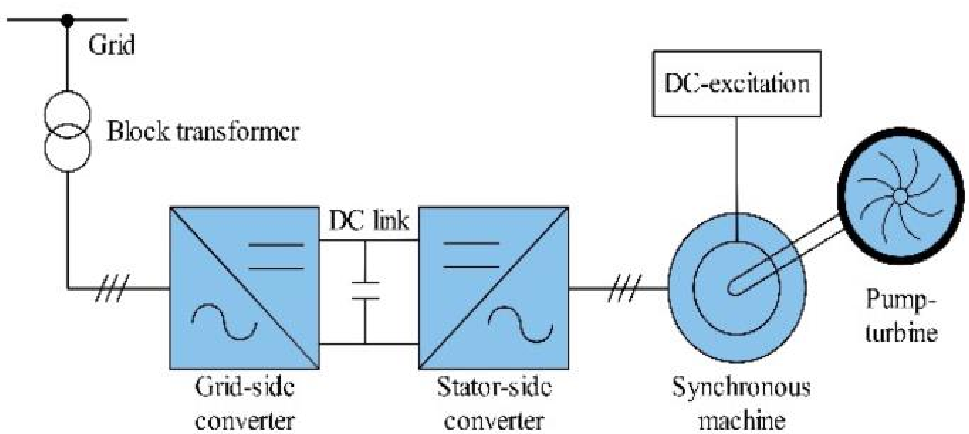



**Fig. 2[8]** : Variable Speed PSP with Full Size Converter

In full size converter based variable speed machines, reversible frnacis pump-turbine is coupled with a synchronouus motor-generator with DC excitation on rotor. However, the variablity in speed is achieved trhough full size converters connected on stator side to decouple the stator & rotor fields. Therefore,

Stator field speed $n_s = fs / p$

fs : stator frequency

p : poles pairs number

Rotor field speed $n_r = fr / p = n_s - n$

n : rotational speed

A fully fed solution has significant advantages relating to flexibility, start-up and transition times. Start-up in pump operation and all transitions can be performed in water, thus reducing the required times substantially [9]. However fully fed converter based variable speed machines can be used upto 100 MW size beyond which size of converter becomes unfeasible. To date, no fully-fed pump turbine is in operation [9].

**Variable speed Generator – Motor Doubly Fed Induction Machines (DFIM):**

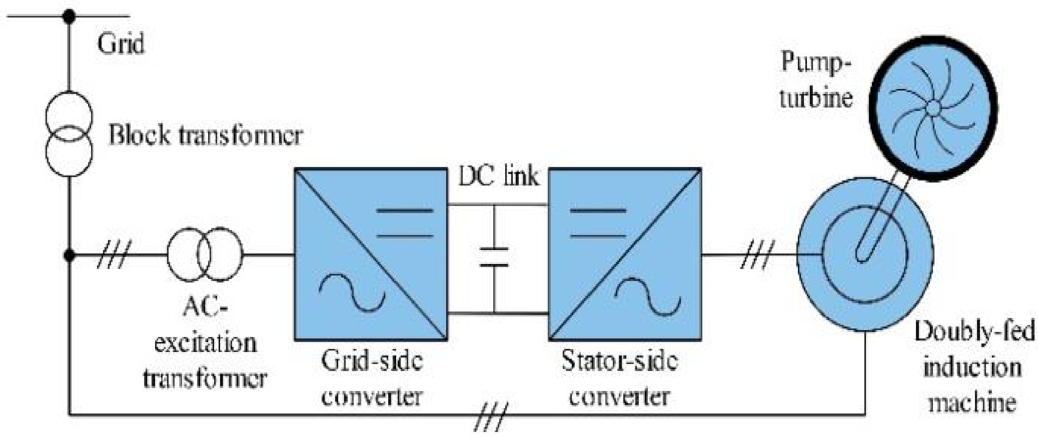



**Fig. 3 [8]** : Variable Speed PSP using DFIM

The synchronous machine-based variable speed PSP has its limitations as power converter with a rating similar to the machine is required, which is unfeasible due to the larger size (space requirement) and cost, especially in the case of an underground power house.[10]

Therefore, to overcome this limitation doubly fed variable speed machines are used where asynchronous motor-generator is used in place of synchrnous one and rotor is fed with AC excitation through slip rings via a converter of reduced size.

A DFIM is generally the preferred solution for large unit outputs (higher than 100 MW). Its main advantage is that it requires lower power converters that use only a fraction of the total output and hence less converter losses [9].

In the beginning DFIM used Cyclo converters to create the rotating field on the rotor to enable variable speed operations. But Cyclo converters absorb reactive power which needs to be compensated by condensers or provided by the generator. Further, the frequency range of these converters is limited and they cannot be used to start the unit in pump mode. Therefore, an additional static frequency converter needs to be used to start the unit. Altogether Cyclo converters using Thyristors are a robust technology proven for many years. [11]

Hitachi's excitation system supplied for adjustable speed pumped storage plant for The Okawachi Power Plant of The Kansai Electric Power is based on cycloconverters. The thyristor-based cycloconverter used as the exciter can operate in torque-producing or regenerative mode. It allows generation at sub-synchronous speed and pumping at super-synchronous speed. Also, this exciter can supply a current component corresponding to the air-gap flux, which produces internal induced voltage to control the reactive power. [12]

Goldisthal Pumped storage plant in Germany is the first cycloconverter based variable speed PSP installed in Europe.

With advancement in semiconductor technologies and improvements in the power ratings of IGBTs and IGCTs, voltage source inverters (VSI) with high power handling capacity are now available in market. These converters do not absorb reactive power and can be used to start the motor in pump mode without any additional device. For VSI based strating in pump mode the stator is short-circuited and a rotating field of increasing frequency is injected into the rotor. These converters provide the frequency or speed variation of 5 to 8% in both direction resulting in pump input power variation of approx. 60 to 100 %.[11]

The concept of variable speed technology is still nascent in India. Tehri PSP is the first project to use VSI based excitation system using a DFIM for variable speed PSP. Advantages of these machines over conventional ones are yet to be practically realized in the country. *Other such installations are Linthal & Nant de Drance in Switzerland.*

**Comparison of Various PSP Technologies**

**Table III** [13] : Comparison Among Various Technologies for PSP

| | **Fixed speed** | **Variable speed** | |
|---|---|---|---|
| **Requirements** | | **Doubly Fed Motor Generator** | **Full Size Convertor** |
| Machine [9] | Synchronous Generator | Induction/Asynchronous Generator | Synchronous Generator |
| Efficiency | Lower Pump Turbine eff. High Motor Generator eff. | Better PT eff. Lower MG eff. due to higher AC exc. Losses. Overall eff. Almost similar to fixed speed. | Lower overall eff. due to convertor losses. |
| Wide range of operation | Limited to a head ratio upto 1.3-1.33. | Operate upto a head ratio of 1.45 – 1.5. | Operate upto a head ratio of 1.6. Technology limited to ~100MW unit size |
| Variation in pump power | Not possible | Power Consumption can vary between 70%-100% | Maximum flexibility in pump mode |
| Fast transition between operating modes | ~7 - 15 min. depends upon inertia and transient behaviour | Longer mode change times than FSCS | Shortest mode change times. |
| | **Fixed speed** | **Variable speed** | |
| Requirements | | Doubly Fed Motor Generator | Full Size Convertor |
| Controllable reactive power | High | High | High |
| Short circuit stability (LVRT) | Low | High | High |
| Grid oscillation damping (PSS) | High | High | High |
| Grid inertia | High | Limited due to wound rotor (limited rotor dia.) | High |
| Immediate step in grid power | Not feasible | Not feasible | Feasible |
| Fast transition in turbine power | Limited by hydraulic transient | Limited by hydraulic transient | Limited by hydraulic transient |
| Black start | Yes | Yes, special requirements - not fully proven. | Yes |
| Cost | $ | $$ | $$$ |
| Space Requirement | Lower | High | Higher |

**Ternary Set PSP:**

In ternary set a motor-generator can be coupled to a separate turbine or pump to work as generator or motor respectively. It consists of a motor-generator, a turbine (typically Francis or Pelton) and a pump. As there are two separate hydraulic machines, the rotational direction in both motor and generator mode can be same resulting in considerable commercial value for the power plant's operation. For switching between turbine and pump operation, a clutch operable at standstill, a starting turbine or a synchronizing tourque converter can be used. Ternary sets can provide very fast grid response, being carried out with the torque converter which allows fast change over between turbine and pump mode. Full regulating capability over 0% to 100% of the unit output can be achieved in both, the turbine and the pump mode operation [14]. It is however more complex and leads to longer shaft arrangements resulting in higher costs, especially if the power station is located in a cavern [11].

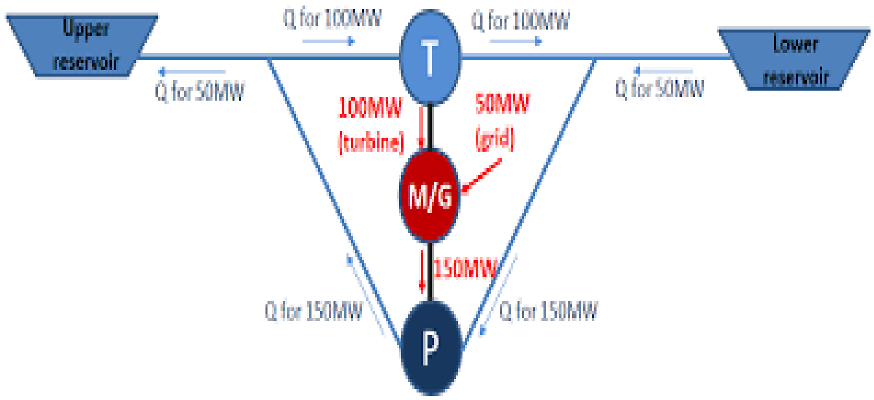



**Fig. 4** : [12]: Ternary Set Unit

**Hydraulic short circuit:**

Hydraulic short circuit means two different units one operating in generation & one in pumping mode at the same time using a water conducting system partially common to both. One unit in the plant operates as pump, while another unit at the same time operates in generation mode (which may or may not be on a common penstock). By using the hydraulic short circuit concept almost the full power range of the plant can be utilized. The principle of hydraulic short circuit operation mode is that only the difference between the constant pump load and the flexible turbine output, both rotating on one common shaft, should come to the grid. [14]

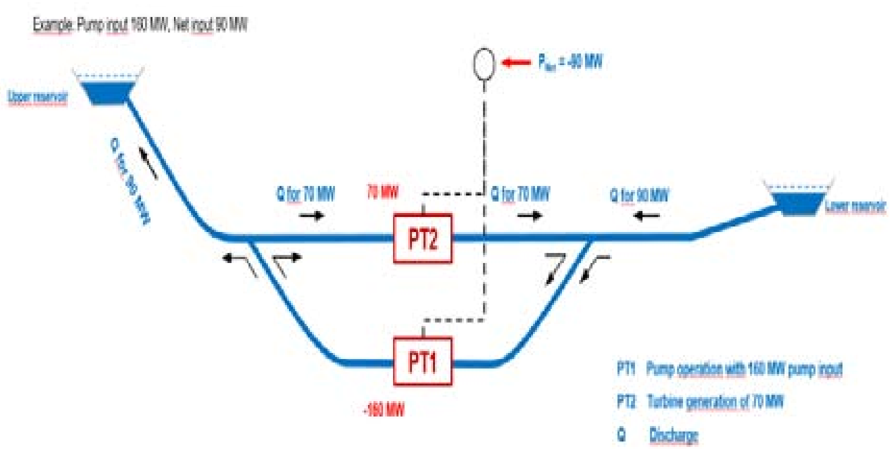



**Fig. 5** [12] : Hydraulic Short Circuit

**Off Stream PSPs:**

Off stream PSPs are defined as the projects where reservoirs are not lying on any river stream or water system. These PSPs can be open loop and closed loop PSPs. In closed loop PSPs both the reservoirs are away from water stream whereas in open loop PSP one reservoir can be away from water course. Off stream PSPs offer advantages in terms of faster and easier execution, less number of clearances required, minimal R&R issues and lower cost.

## IV. LARGE SCALE RE INTEGRATION- NEED OF STORAGE

Global need for grid scale energy storage has become imperative due to large scale integration of VRE technology in energy mix. The ambitious commitment of GoI in CoP26 at Glasgow to make its energy grid greener and reduce carbon emission to net zero by adding 500 GW of non fossil fuel Generation Capacity by 2030 has further necessitated the need of energy storage.

PSPs are the most mature and established technology available for storage as on date. PSPs offer following advantages for integration of RE into the grid:

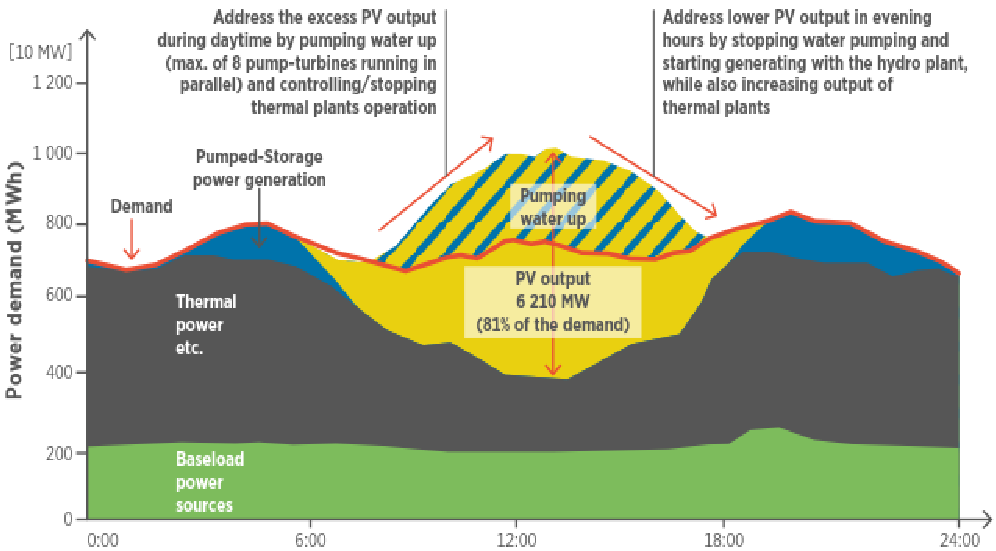



**Table IV** : Relevance of PSP in RE Integration

| **Application** | **Particulars** |
|---|---|
| Time shifting/ storage | Storage of surplus power during off-peak hours and supply during peak demand hours. |
| Ramping Capability | Quick-start and ramping capability of ~200 MW/ min, taking just a few minutes.<br>Savings in start-up and shutdown costs of thermal plants and steadier operations. |
| Peak Shaving | PSPs can meet peak demand in a short period due to their high ramping capability. Can enable supply-demand balancing. |
| Black Start | Utilization of PSPs for energizing the Grid in case of cascaded tripping. Power supply can be made available within few seconds of blackout. |
| Frequency Response | Can follow frequency within the given margins by continuous modulation of active power and meeting moment-to-moment fluctuations in the system's power requirements. |
| Spinning Reserve | PSP can support in maintaining grid stability in case of unexpected load changes or sudden outages or failure of any generator by facilitating stored energy. |
| Reactive Power & Voltage Control | Can provide voltage control through reactive power balancing. Can also operate in synchronous condenser mode. |

## V. TEHRI PSP- A CASE ANALYSIS

Tehri PSP is a constituent of Tehri Hydro Power Complex (2400 MW) located in District Tehri, Uttrakhand, India. The complex comprises of 4X250 MW Tehri Hydro Power Plant (THPP), 4X100 MW Koteshwar Hydro Electric Plant (KHEP) and 4X250MW under construction Tehri Pump Storage Project (TPSP). A 260.5 m high earth & rock fill dam built on the confluence of the river Bhagirathi & Bhilangana creates upper reservoir with live storage capacity of 2615MCM. Koteshwar Dam, located at about 22km downstream of Tehri Dam, a 97 m high concrete dam with live storage capacity of 35MCM, serves as the lower reservoir for the PSP. Tehri HPP is a conventional plant consisting of four synchronous generators coupled with Francis turbines whereas Tehri PSP has four variable speed pump-turbines coupled with double fed induction motor-generator. KHEP also has four conventional synchronous generator coupled with Francis turbines.

The major characteristics of variable speed pump-turbine of Tehri for Turbine mode are as mentioned in Table V:

**Table V** : Turbine Characteristics

| No. | Characteristics | Value |
|---|---|---|
| 1 | Turbine Axis | 568 m |
| 2 | Rated Design Head | 188m |
| 3 | Gross Head Range in Turbine Mode | 127m-227m |
| 4 | Rated Speed at Rated Power & Rated Head | 230.77 rpm |
| 5 | Maximum Reservoir Level | 830m |
| 6 | Minimum Drawdown level of reservoir | 740m |
| 7 | Maximum Tail Water Level | 612.5m |
| 8 | Minimum Tail water level in Turbine mode | 603m |
| 9 | Operating Speed Range in Turbine Mode | 206rpm-250rpm |

**Integrated Operation of Tehri Power Complex**

**Table VI** : Operating Characteristics for Integrated Mode

| Characteristics | Value |
|---|---|
| Capacity of balancing Reservoir for Tehri PSP (Operating range EL 606m to 612m) | 612-606= 6 m |
| Capacity of reservoir / mtr | 2.6 MCM |
| Gross Capacity Available | 15.6 MCM |
| Pumping Discharge of Tehri PSP/Machine | 110 Cumecs (109.5 Cumecs at nominal net Head) |
| Generation mode Discharge of Tehri PSP/Machine | 150 Cumecs (146.9 Cumecs As per Design) |
| Discharge of Koteshwar HEP/Machine | 155 Cumecs (157.93 Cumecs As per Design) |
| Discharge of Tehri HPP/Machine | 150 Cumecs (146 As per Design) |

**Case I : Emptying Balancing Reservoir**

Time Required for emptying balancing reservoir while 04 Machines of PSP in Pumping mode and 01 unit of KHEP in Generating mode:

Let the time required is 'T'

Volume of water pumped back by Tehri PSP

= Tx (4x110x3600)/10^6 =T x 1.584 MCM

Volume of water release by KHEP

= Tx(1x155x3600)/10^6 = Tx 0.558 MCM

Net volume of Water evacuated from balancing reservoir

= Tx(1.584+0.558) MCM = Tx 2.142

Time Required to evacuate the reservoir

Tx2.142=15.6 MCM

**T = 7:16:58 hrs**

**Case II: Refilling Balancing Reservoir**

Time Required to refill balancing reservoir while all 08 Machines of Tehri HPP & PSP and 01 unit of KHEP in Generating Mode :

Let the time required is 't',

Volume of Water Release in t hrs from Tehri HPP and PSP

= t x (8x150x3600)/10^6 = t x 4.32 MCM

Volume of Water Release in t hrs from Koteshwar HEP

= t x (1x155x3600)10^6 = t x 0.558 MCM

Net Volume = t x (4.32-0.558) = t x 3.762 MCM

Time Required

t x 3.762 = 15.6

**t = 4:08:48 hrs**

**Case III : Refilling Balancing Reservoir**

Time required for refilling balancing reservoir while all 08 Machines of Tehri HPP & PSP and 04 unit of KHEP in Generating Mode:

Let the time required is t',

Volume of Water Release in t' hrs from Tehri HPP and PSP

= t'x(8x150x3600)/10^6 = t' x 4.32MCM

Volume of Water Release in t' hrs from Koteshwar HEP

= t'x(4x155x3600)10^6 =t'x 2.232 MCM

Net Volume =t'x(4.32-2.232) = t'x2.088MCM

Time Required

t'x2.088 = 15.6

**t' = 7:28:17 hrs**

From the above time analysis it is clear that the Tehri PSP can be operated for 1.5 or 2 cycles of reservoir emptying through pumping and refilling through generation every day depending upon the grid requirements and availability of RE at lean time. In the above analysis nominal head conditions have been considered. However depending upon the head at upper and lower reservoirs the time cycles may vary.

## VI. WAY AHEAD FOR DEVELOPINMENT OF PSPS FOR BUILDING STORAGE CAPACITY

Major economies globally such as China, U.S, Germany, Japan have adopted various measure to promote the Pumped Storage Power. Policy push for carbon neutral grid through bundling of RE with storage, identification of legal status of storage, different Time of Usage (ToU) tariffs, Building ancillary services market, energy arbitrage and strict norms against curtailment of RE are some special measures granted in different countries.

India still has to go too far in building its storage assets. As per CEA's report on "Optimal Generation Capacity Mix for 2029-30" India will need storage capacity of 10GW from PSPs and 27 GW from Battery storage by 2030. Considering the revised RE capacity addition targets set forth in CoP26 we have a long way to go ahead.

Some hand holding for storage technologies is essentially required such as:

(a) Defining legal status of PSP as generation/ transmission/distribution/ grid asset.

(b) Developing Ancillary Services Market.

(c) Regulatory framework for tariff for ancillary services provided by storage.

(d) Differential tariffs for peak and off peak supplies.

(e) Off stream PSPs be defined as separate category with simplified clearance process.

(f) Single window clearance mechanism for storage projects.

Pump Storage plants offer solution for energy storage as cost optimization in battery storage technologies is still in progress. With aforementioned supporting steps we hope to build a sustainable green grid with RE supplies balanced by storage for our future generation and reduce the burden of our socio-economic activities on the environment.

**REFERENCES**

[1] Hydropower Status Report Sector trends and Insights 2021, International Hydropower Association.

[2] Hydropower Status Report Sector trends and Insights 2020, International Hydropower Association.

[3] Status of Large Hydro Electric Potential Development- Basin Wise (In terms of Installed Capacity Above 25MW) As on 31.01.2022. https://cea.nic.in/wp-content/uploads/hepr/2022/01/hydro_potential_basin_1-1.pdf.

[4] All India Installed Capacity (in MW)of Power Stations As on 31.01.2022. https://cea.nic.in/wp-content/uploads/installed/2021/03/installed_capacity.pdf

[5] Status of Pumped Storage Development in India As on 31.01.2022. https://cea.nic.in/wp-content/uploads/hepr/2022/01/pump_storage_1-1.pdf.

[6] Presentation on "PSP Vriable Speed Control Concept" by GE to THDCIL.

[7] https://energystorage.org/why-energy-storage/technologies/variable-speed-pumped-hydroelectric-storage/

[8] Regulation Characteristics and Load Optimization of Pump-Turbine in Variable-Speed Operation https://www.mdpi.com/1996-1073/14/24/8484/htm.

[9] CONVERTING CONVENTIONAL PUMPED-STORAGE PLANTS TO VARIABLE SPEED https://www.researchgate.net/publication/329268493

[10] https://www.mdpi.com/2079-9292/7/10/265/htm

[11] https://www.uniassignment.com/essay-samples/engineering/optimal-operation-of-wind-psp-engineering-essay.php

[12] Hitachi's Adjustable-speed Pumped-storage System Contributing to Prevention of Global Warming. https://www.hitachi.com/rev/pdf/2010/r2010_03_107.pdf.

[13] Presentation by / ANDRITZ HYDRO / SUB GROUP - 3, MOP / 20211011

[14] Pumped storage machines Reversible pump turbines, Ternary sets and Motor-generators – Voith. https://voith.com/corp-en/11_06_Broschuere-Pumped-storage_einzeln.pdf