Pump Storage Power Plants’ Flexibility
Supporting India’s Electrical Grid Stability

Jean-Marc Henry
Renewable Energy - Hydro
GE
France

Chandrakant Jain
Renewable Energy - Hydro
GE
India

Arash Shoarinejad
Global Growth
GE
Iran

Abstract—This paper brings about a cost effective solution which helps reduce power fluctuations and stabilize the grid with the integration of other renewable energy sources such as wind. The Indian power system is discussed as an example using GE’s latest technologies with pumped storage power plants.

Keywords—renewables, pumped storage power plants, GE, power fluctuations, hydro, grid stability

I. INTRODUCTION

Forthcoming Indian energy system will be heavily dependent on wind and solar energy inputs, which need to be compensated with a more flexible balancing energy system.

With the continued growth of renewable and nuclear energy in Indian power grid, more energy storage, faster power regulation and increased regulation capacity are needed. Currently, pumped storage power plants (PSP) provide the most cost effective, means of storing large amounts of energy, while at the same time compensating large power fluctuations into the grid, resulting from renewable energy sources such as wind.

While conventional Hydro Power Plants rely on the best use of site water resources, pumped-storage power plants require considering additional parameters, mainly operating, to ensure the necessary income in relation to the Power Grid requirements. This has an impact on the design requirements of the electro-mechanic equipment.

While not relying on site water resources, various sites could be considered involving various heads in pumped storage power plants and various head ranges within these plants.

The conventional reversible pump-turbine, with its constant speed, cannot always adjust the absorbed pump power to the grid requirement, when a large number of intermittent sources, such as wind and solar are used. Variable speed pumped storage plants offer additional network flexibility compared to conventional fixed speed pumped storage plants.

GE will show through examples, with the operating units of Alqueva II, Huizhou and the variable speed projects of Linthal and Nant de Drance in Switzerland, that pumped-storage power plants have various constraints, which drive the technology of the Units:

- depending on head and head range,
- depending on the grid, operation and maintenance requirements,
- expanding to variable speed.

An appropriate solution has been adopted to suit these requirements.

II. LOW HEAD PUMP-TURBINES : ALQUEVA PSP PROJECT

Portugal’s wind power generation is growing rapidly, with an installed capacity of 4713 MW as of December 2013. To provide sufficient stability with regards to this volatile source of energy, EDP has launched a large program to develop new pumped storage power plants. Most of them are located in the north of Portugal because most of the wind power generation is in the north and the topography is favorable for pumped storage, as well.
However, the Alqueva site is located in the southeast of Portugal on the Guadiana River. It is on the largest artificial lake in Western Europe and has quite a low head.

The Alqueva PSP consists of two power plants, each with two units of 130 MW: Alqueva I and Alqueva II. A similar concept was used in both plants [1]. In both cases, GE is the supplier of the complete electromechanical package and hydro-mechanical equipment.

Salient features of Alqueva I and II are provided in Table 1 with a cross section in Figure 1.

![Alqueva pump-turbine crosssection](image)

**TABLE I. ALQUEVA I & II MAIN DATA**

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Nº Units</th>
<th>Head (m)</th>
<th>Power (MW)</th>
<th>Speed (rmp)</th>
<th>Stator Voltage (kV)</th>
<th>Power Factor</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al. I</td>
<td>2</td>
<td>45-73</td>
<td>130</td>
<td>136</td>
<td>15</td>
<td>0.9</td>
<td>2004</td>
</tr>
<tr>
<td>Al II</td>
<td>2</td>
<td>53-73</td>
<td>130</td>
<td>136</td>
<td>15</td>
<td>0.9</td>
<td>2012</td>
</tr>
</tbody>
</table>

**A. Mechanical Aspects**

The turbine design includes a ring gate with 6 servomotors. In order to guarantee reliable and safe operation of the ring gate, it is necessary to synchronize the displacement of each servomotor even in emergency cases. This synchronization is made mechanically as applied on many GE units [2, 3]. Despite this successful application of mechanical synchronization, a new hydraulic synchronization has been developed [4]. The skill level of maintenance technicians drives this need as well as the time currently taken for the maintenance of mechanical synchronization arrangements. Such hydraulic synchronization system could, then, be applied on future pump-turbines equipped with ring gates.

The ring gate allows optimizing the civil works while keeping the safety and operational benefits of inlet valves:

- Suitable for pit arrangement
- The overall efficiency of the plant is improved by the reduction of the power absorbed during the phases when the machine works in condenser mode, as a result of a reduced water ring
- Compared to butterfly or lattice valves, it does not produce heat losses, thus leading to a significant saving in energy

The shaft line includes 3 bearings with a combined thrust bearing below the motor-generator.

With the large size of the unit, a thrust bearing supported by a cone connected to the head cover is adopted. Compared to a thrust bearing supported by a bracket, this arrangement has the following advantages [5]:

- Shorter shaft line
- Lower loads on concrete around the pump-turbine pit
- Shaft line higher axial stiffness
- Partial balancing of the forces acting on the head cover leading to head cover lower deformations
- Good access to thrust bearing for maintenance operations

Associated with the ring gate technology, this design leads to significant savings on civil costs.

The thrust bearing integrates membrane technology developed by GE, which allows equal load distribution on each pad regardless of the supporting frame deformation, shaft line deflection or misalignment in every operating condition. This result is obtained without any adjustment (maintenance free) and ensures a reliable long-term operation.

The turbine guide bearing is of the shell type with a rotating sump in water. The bearing is self-cooled as oil circulation is achieved by use of internal viscosity pumps and cooling by the water around the rotating sump tank. Therefore, a minimal maintenance is needed.

The rotating sump in water allows the location of the shaft seal above the rotating sump of the guide bearing so that the access to the shaft seal is very easy.

**B. Extension of the Operating Range**

The high volatility of wind energy requires an increased pumped storage plant flexibility and an increased partial load operation. The sensitivity to a part load of high specific speed design with large runner blade profiles led to a specific program [6] to extend the operation range of the Alqueva power plant.

Thanks to a combination of a mechanical model test, unsteady numerical simulations and special field tests with onboard measurements, the operation range has been extended as shown in Figure 2.
The fatigue evaluation is repeated for each load step recorded during the special field test. The results are given in term of relative damage. It corresponds to the absolute damage per hour of operation divided by the damage calculated at the optimum point. The continuous operation threshold is defined as the limit below which the damage generated by a continuous operation during the expected lifetime of the runner is negligible. Above this line, the number of hours in operation has to be controlled in order to avoid premature damage to the turbine. This representation enables to optimize the operating range by considering its impact on the lifetime of the structure.

Fig. 2. Extension of operation based on relative damage vs. load factor

III. HIGH HEAD PUMP-TURBINE: HUIZHOU PSP

Huizhou is the second pumped storage power plant of the Guangdong Pumped Storage Corporation in China, after Guangzhou PSP, of same capacity which was built in two stages. The four units of Guangzhou stage 1 have been supplied by GE and were fully commissioned in 1994.

Huizhou and Guangzhou stage 1 have a similar head, unit output, and speed, whereas Huizhou exhibits different features such as intermediate dismantling and individual servomotors, quite suitable for units of this kind.

Huizhou is a power plant with 2 caverns, each with 4 units. The operational installed capacity of the power station has reached 2,400 MW, which makes Huizhou the second most powerful pumped storage power plant in the world. Main data of Huizhou pump-turbines are provided in Table 2 with a cross section of the unit in Figure 3.

<table>
<thead>
<tr>
<th>TABLE II. HUIZHOU MAIN DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max Shaft Output</strong></td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>340 MW</td>
</tr>
<tr>
<td>Dismantling TB Position</td>
</tr>
<tr>
<td>Sideway Upper bracket</td>
</tr>
</tbody>
</table>

The high head leads to a high rotating speed and consequently reduced dimensions. The moderate rotor weight, upper bracket dimensions and hydraulic thrust allow placing the thrust bearing on the upper bracket. With this location, a good access is provided and due to a reduced thrust collar dimension, the thrust bearing losses are reduced, despite the high rotating speed.

High head machines are highly stressed, due to the head, the high rotating speed, and the low specific speed. It may become of interest to have a fast dismantling facility to access any part of the machine. The reduced size of the unit, the location of the thrust bearing on the upper bracket allows the dismantling of the pump-turbine, sideway through an intermediate gallery of moderate dimensions [7].

Fig. 3. Huizhou cross section
The individual servomotors control [8] is well adapted to high head pump-turbines with:

- Removal of a heavy added weight of operating ring regarding vibration.
- Avoiding the safety breaking mechanism (shear pin failure) limiting the risk of failure in the operating system.
- Less and smaller components between the wicket gates and the servomotor, and as a consequence:
  - Less operating gaps, improving the operation of the unit and therefore reducing risks of pressure fluctuation, which could create vibrations in the wicket gate mechanism.
  - Easier access to the head cover, that facilitates maintenance operations on the bearing and shaft seal.
  - Easier maintenance of the servomotors themselves using complete servomotor set as spare parts.

### IV. WIDE HEAD RANGE: NANT DE DRANCE AND LINTHAL VARIABLE SPEED PSP

As Switzerland has many hydro power plants, it could be advantageous to use the existing reservoirs of these power plants to get significant savings on the construction of new PSP. This has been done on Nant de Drance and Linthal. In both cases, the re-use of existing reservoirs led to a very wide head range. Such a wide head range required using variable speed to match with the operating points and the submergence of the units [9].

#### TABLE III. NANT DE DRANCE AND LINTHAL PSP FEATURES

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>No Units</th>
<th>Head (m)</th>
<th>Power (MW)</th>
<th>Speed (rpm)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nant de Drance</td>
<td>6</td>
<td>250-390</td>
<td>157</td>
<td>428.6±7/-10%</td>
<td>2017</td>
</tr>
<tr>
<td>Linthal</td>
<td>4</td>
<td>560-724</td>
<td>250</td>
<td>500±6/-7.7%</td>
<td>2016</td>
</tr>
</tbody>
</table>

The development of these variable speed units has raised the attention in deploying variable speed pumped storage as an efficient solution for power regulation in Europe.

Following the characteristic of the variable speed units, the assets can provide several opportunities towards the grid and advantages to the plant operator, as:

- Operation of the units in turbine mode at the optimal efficiency point for different hydraulic conditions by shifting the pump-turbine efficiency hill chart).
- Smoother operation (for example at partial load) by shifting the turbine efficiency hill chart towards the optimum efficiency area and decreased pressure fluctuation area.
- Operation in a wider head range by allowing the head/flow and cavitation/flow curves to move together towards higher and/or lower heads.
- Fast dynamic response to support the network due to instantaneous power output adjustment capability.

The hydraulic design of the pump-turbine defines the speed range and the operating limits of the entire machine set. Therefore, the specific design of the hydraulic machine is essential [10] for the development of a variable speed PSP project.

The maximum head of the Linthal pumped storage plant is above 700 m which is the highest head for a single stage PSP in Europe. Wide experience and recent measurements on commissioned units, with heads higher than 500 meters as presented for Huizhou in China and Afourer in Morocco, have been incorporated in the design stage.

In the Linthal and Nant de Dance PSPs, the necessary speed variation is enabled by using double-fed induction machines (DFIM) in combination with AC excitation systems based on static converters.

The rotor of a double-fed induction motor-generator consists of a three-phase rotor winding wound into a cylindrical rotor, which differs significantly from salient pole rotors, used in most hydro power plants. Motor-generator design developments, such as the winding overhang concept, as well as necessary adaptations to the insulation system due to the voltage pattern of the AC excitation system have been widely discussed in other publications [11, 12].

![Fig. 4. Linthal unit 1, stator frame installed in the pit](image-url)
Significant efforts on design and industrialization were done to address the design challenges for large double fed induction machines. This was followed by the manufacturing and assembly of a full-scale rotor between October 2011 and January 2014 in the GE factory in Birr, Switzerland.

The voltage source inverter is a key element in the dimensioning and optimization process of a variable speed unit. The main operation and design parameters e.g. speed-range, voltage variation, and reactive power define directly the size of the electrical machine, as well as its AC excitation system. Hence, the specified operation points have been carefully optimized, evaluating the needs of the plant owner and the cost impact on the entire unit.

In pumped storage plants with variable speed units, the integration of the motor-generator, the AC excitation, as well as the control and protection system requires special attention. Rotor protection and control systems have been tested on dedicated test benches that allow real-time testing of the corresponding hardware with online models of the hydraulic and electrical machines.

Linthal unit 1 is presently under commissioning. Figure 4 shows the installation of the stator frame. For Nant de Drance, the main components of the generating units are being manufactured and installed.

These previous developments and experiences will benefit to Tehri power plant in India, where the units to be supplied by GE are presently under construction. The gross head varies between 127.5 and 227 m which was the reason for the selection of a variable speed solution. Tehri is a power plant located in the state of Uttarakhand. The power station will be equipped with four variable speed units with a unit output of 250 MW. The rated speed is 230.77 rpm with a speed range of ±7.5%. Project completion is currently forecasted for 2019.

V. CONCLUSION

This paper showed that various constraints can affect pumped-storage power plants, which require different approaches. Such different approaches have a strong impact on the technology.

In any case, this technology should be specifically adapted to the developed project. The variety and complexity of the solutions require a close collaboration between customers and experienced manufacturers to find the most optimized solution.

As shown by the variable speed projects highlighted in this paper, individual equipment such as pump-turbines, motor-generators, and frequency converters are not enough to define the solution, but requires manufacturers to handle the overall system as a global entity.

REFERENCES