Recent Developments of Hydropower Machines for Pumped Storage Projects

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ABSTRACT

The recent development of the energy market worldwide will increase the demand for peaking power and the request for more flexibility in the electrical grid system. These factors are creating an attractive market for pumped storage power plants.

One of the primary tasks of pumped storage power plants in this era of rapidly growing but less predictable renewable energy sources like wind and solar energy is not only to provide energy storage capabilities, but also to contribute to the stabilization of the electrical grid.

This paper presents three pumped storage power plants, Zhejiang Chang Long Shan, Henan Tianchi and Liaoning Qingyuan, which are equipped with reversible single-stage pump turbines, were developed with focus on pump and turbine stability and low pressure pulsation level. Four additional projects will be illustrated, Kops II and Veytaux II, ternary sets, equipped with a multi-stage pump together with a hydraulic torque converter, and Frades II and Goldisthal as examples for variable speed reversible pump-turbines.

A technical solution which allowed higher flexibility of the units as well as the extension of the operating band of the power plants will be demonstrated for each of these projects. This allows for a quicker reaction to grid requirements with an extended range of operation.

KEYWORDS

Pumped storage power plant, pump-turbine, multi-stage pump, variable speed

1 INTRODUCTION

In recent years, the increasing demands for peaking power strengthened the important role of pumped storage power plants in the electrical supply system. For an adequate answer to these requirements several new developments on pump storage hydraulic equipment solutions were made. The following examples of pumped storage solutions present some latest developments in this field:

- Henan Tianchi and Liaoning Qingyuan: Fixed-speed reversible pump-turbines
- Zhejiang Chang Long Shan: High-head fixed speed reversible pump-turbine
- Kops II and Veytaux II: Ternary concepts with a multi stage pump and turbine units
- Frades II and Goldisthal: Variable-speed reversible pump-turbines

2 FIXED-SPEED REVERSIBLE PUMP-TURBINES: TIANCHI, QINGYUAN

In the Asia-Pacific region several pumped storage plants equipped with fixed-speed reversible pump-turbines are currently in planning and under construction. The demand for energy storage and grid stabilization services keep steadily growing together with the implementation of other energy conversion sources. This trend will continue and keep expanding for the next years. Examples of current large projects in execution are Henan Tianchi and Liaoning Qingyuan in China.

The Tianchi pumped storage plant in the Henan province in China located upstream of the Huangya river near to Nanyang city will be equipped with four 306 MW reversible units operating with heads up to 558 m. The hydraulic model acceptance test was successfully accomplished in December 2018. The Qingyuan pumped storage power station is situated in China in the Liaoning province, on Hunhe river, near to Fushun city. Six units with 306 MW will be operated with heads up to 433 m. In May 2019 its hydraulic model acceptance test was successfully finished. Both plants will integrate the State Grid Xin Yuan electric network. Their main hydraulic data can be found in **Table 1**.

***Table 1**: Henan Tianchi, Liaoning Qingyuan – Main Hydraulic Data*

	Henan Tianchi	**Liaoning Qingyuan**
Head range H [m]	472-558	367-433
Maximum turbine output P_{Tu} [MW]	306	306
Runner inlet diameter D_1 [m]	3.9	4.6
Rotating speed n [rpm]	500	375
Maximum pump input P_{Pu} [MW]	301	315
Rated turbine discharge [m³/s]	66	86
Number of units	4	6

The market in the Asia-Pacific region is highly competitive and demanding, thus requiring highest performance level for reversible pump-turbines under different aspects. Customer expectations are high efficiency, safe cavitation margin, low pressure fluctuation, safe margin towards pump instability and turbine S-shape instability limit, as well as latest technology. High efficiency means higher return for the utilities, while stability and smooth operation mean reduced maintenance and extended service life.

All these performance requirements might appear as conflicting goals for the hydraulic design. High efficiency in pump and turbine mode might be opposing, in the same way as safety margin towards pump and turbine stability. At the same time highest efficiency and smooth stable operation might be conflicting. These impose challenges to the hydraulic design. Compromises have to be found and technology must be pushed. Improved hydraulic design and innovation in relation to traditional and even recent designs are required.

Together with experience and model testing, the numerical fluid flow simulation, i.e. computational fluid dynamics (CFD) analysis, is an important tool to improve the design quality, reliability and performance, through the accurate prediction of the machine characteristics and behavior. The CFD analysis can reduce the development time and increase the number of tested design variants in comparison to the pure experimental development based on model testing.

Different levels of detail and model complexity are possible in the CFD analysis (multi-level CFD). Stationary simulations mainly deliver reliable and accurate results for efficiency and cavitation assessment, being used for daily design work, allowing the decision between different designs. Transient simulations are used for special investigations, for the understanding of basic fluid flow phenomena and to gain insight on design possibilities. They can be applied e.g. for the prediction of pressure pulsation level and assessment of pump and turbine stability.

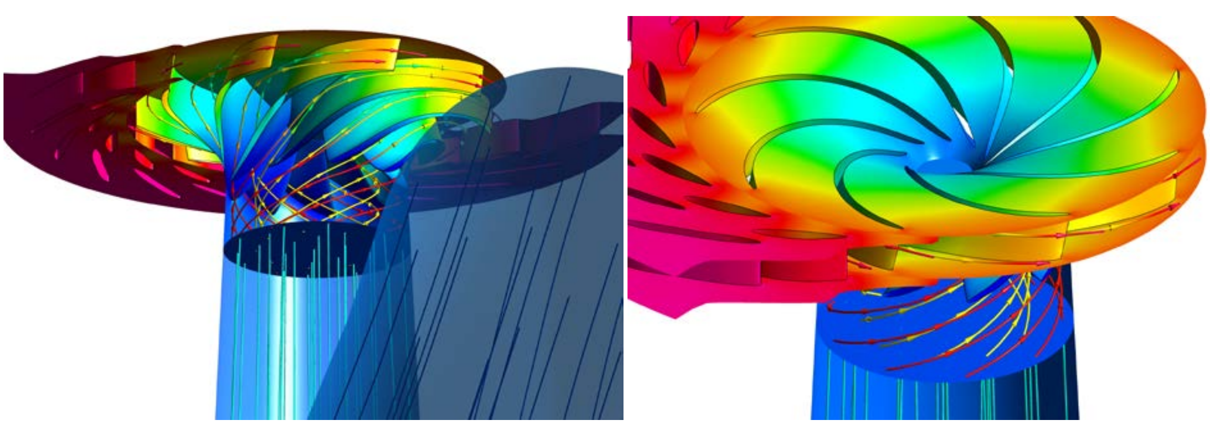


Figure 1*: Visualization of CFD numerical simulation results for a reversible pump-turbine in pump mode showing pressure distribution and velocity streamlines.*

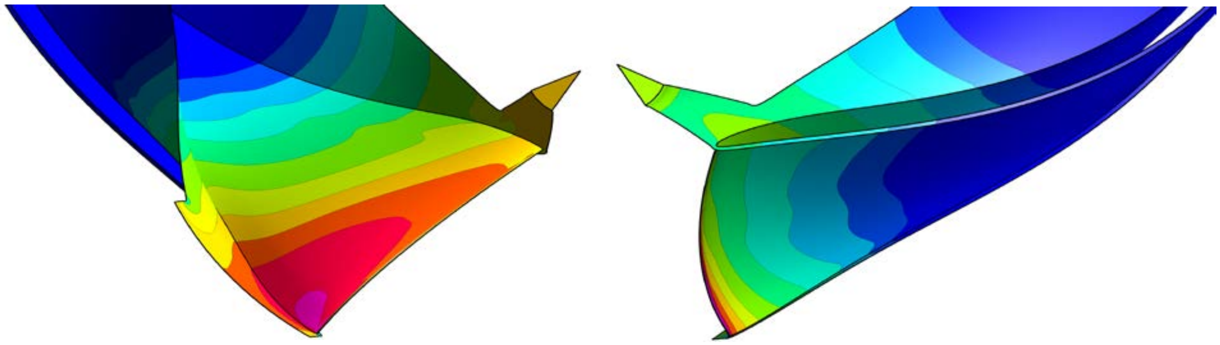


***Figure 2**: Cavitation safety for a reversible pump-turbine in pump mode at the runner blades suction side at high head (left) and pressure side at low head (right)*

For the efficiency evaluation several points are calculated along the pump characteristic curve and distributed through the turbine hillchart. The efficiency level in pump and turbine mode is evaluated based on the calculated integral scalar values. Nevertheless the visualization of the pressure and velocity fields, as seen in **Figure 1**, offers the possibility to identify optimization potential for the hydraulic geometry allowing efficiency increase. For Henan Tianchi and Liaoning Qingyuan the efficiency values were optimized to meet the contractual guarantees making the investment attractive for the utility. Both projects could achieve efficiency values in pump and turbine mode close to the highest currently achievable in the mid-specific speed range for reversible pump-turbines.

The calculated pressure field also delivers information about the safety margin towards cavitation. **Figure 2** shows the pressure distribution, which is directly related to the cavitation safety, in pump mode at the runner leading edge at the suction side for the maximum head operating point and at the pressure side for the minimum head operating point. These are the critical operating points regarding cavitation in pump mode and they can be precisely evaluated using CFD. This has been an important tool during the hydraulic development of Henan Tianchi and Liaoning Qingyuan. Due to the requirements of large head range in pump mode, with ratios of approximately 1.18 between the maximum and minimum heads in both projects, the hydraulic design was improved to increase the pump operating range without the set-in of cavitation at the runner blades.

The simulation of the pump stability region requires transient fluid flow analysis. The total pressure distribution at runner, guide vanes and stay vanes can be seen in an example at **Figure 3**. When approaching the pump instability region, flow separation with the set-in of vortices take place at the stay vane channels, getting larger and eventually blocking part of them. This kind of analysis offers further understanding of the basic phenomenon involved. This is important as long as for projects such as Henan Tianchi and Liaoning Qingyuan, the safety margin between the maximum lift head and the pump stability limit is part of the contract.

For both of these projects the safety margin between the lowest turbine head and the S-shape stability limit was also specified, with the purpose of assuring smoother synchronization and load rejection in turbine mode. The numerical flow simulation allows the visualization of the flow patterns, velocity streamlines and vortices at low head operating points. The identification of separation regions and consequent set-in of vortex cores, as shown in **Figure 4**, offers valuable information for increased design safety and reliability.

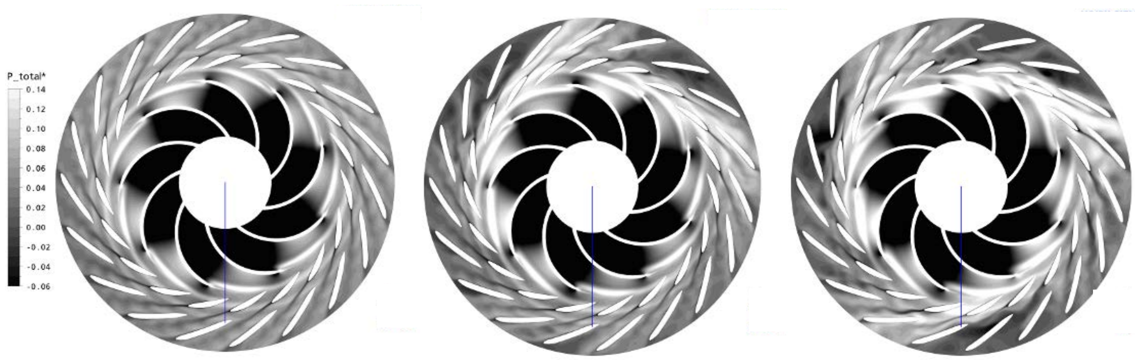


***Figure 3**: Total pressure distribution at runner, guide vanes and stay vanes channels for a reversible pump-turbine in pump mode approaching its stability limit [1]*

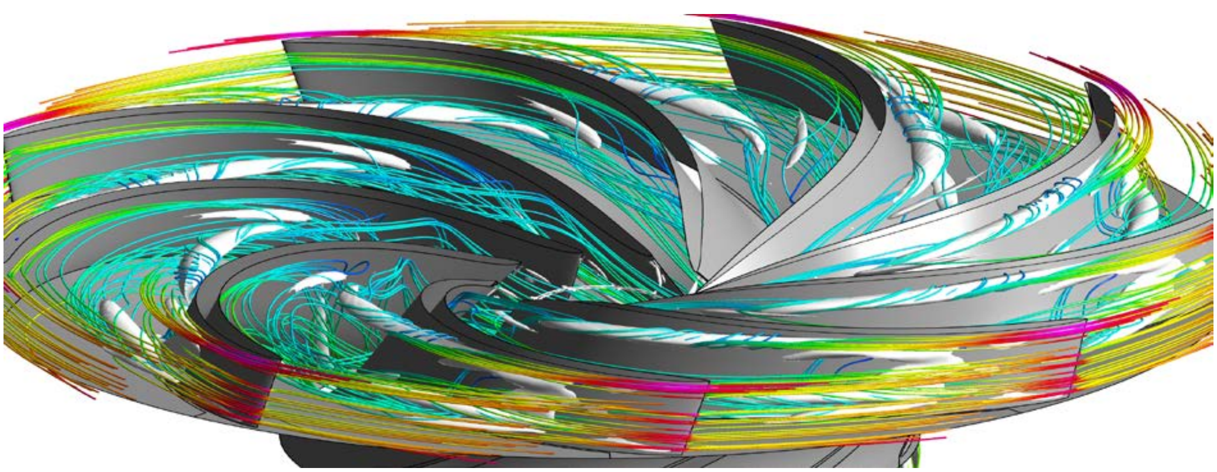


***Figure 4**: Velocity streamlines and vortices in the runner channels for a reversible pump-turbine in turbine mode approaching the S-shape stability limit.*

3 HIGH HEAD FIXED-SPEED REVERSIBLE PUMP-TURBINE: CHANG LONG SHAN

After performing an extensive competitive witness model test at the independent laboratory **IWHR** (China Institute of Water Resources and Hydropower Research) in Beijing, China (**Figure 5**), the contract was awarded by China Three Gorges Corporation in 2017. The contract for Voith Hydro included the development and supply of two 350 MW units for the Zhejiang Chang Long Shan pumped storage power station. The final model acceptance test was successfully completed in September 2017. The delivery of the reversible pump turbine generator units once again highlights the competence in equipping large pumped storage plants, as recently also proven in Jiangxi Hongping, a further Chinese pumped storage project. The Chang Long Shan power station is located in the Zhejiang Province's Anji County between the cities of Tianhuangping and Shanchuan. With a total capacity of 2,100 MW the station will rank number three in terms of capacity among pumped storage plants built or being built within the Chinese mainland. Additionally, its 756 m head (rated head 710 m) makes it the highest in China and second highest in the world. Commissioning is scheduled to be 2020.

The development of the Chang Long Shan pump-turbine was basically driven by the very high heads and performance level combined with good dynamic and transient behavior considering pressure fluctuations, pump stability and turbine S-shape safety margin. For the Chang Long Shan pump-turbine the 11-blade runner has proven to be the most efficient one with more compact machine design and consequently civil construction results with the best performance and most cost effective solution. The selected design for the pumped storage arrangement was chosen as an optimum technical solution that in the context of expected operation modes and grid regulation demands results in the best possible return for the operating utility.

***Table 2**: Chang Long Shan – Main Hydraulic Data*

Head range H [m]	681-**756**
Maximum turbine output P_{Tu} [MW]	357
Runner inlet diameter D_1 [m]	3.65
Rotating speed n [rpm]	600
Maximum pump input P_{Pu} [MW]	353
Rated turbine discharge [m³/s]	56
Number of units	2

***Figure 5**: Competitive model testing at IWHR laboratory in China*

4 MULTISTAGE TERNARY PUMPED STORAGE UNITS: KOPS II, VEYTAUX II

Large hydro pumps in combination with Pelton or Francis turbines or as standalone units are used mostly for high-head applications, where quick and frequent changes between pump and turbine mode and quick start-up times are a key point. These boundary conditions make these types of projects rare worldwide, with only a few installations per decade. These units show high efficiencies and reliability. Future operation needs to be already considered in the hydraulic and mechanical design phase as the absolute number of such projects and the high variety of possible design variants (number of stages, single units versus ternary sets, stay vanes only versus tandem cascade) results in a comparable low standardization level.

Other than reversible pump-turbines, for heads of about 700 m and higher a ternary set combined with a Pelton turbine is a rediscovered solution. This certainly increases the total costs of the hydraulic machine but it provides a clear benefit compared to the reversible pump-turbine units for fast starting times in both operation modes, for fast load up and down ramping, as well as fast mode changes. Since the unit operates as turbine or as pump with the same direction of shaft rotation, it needs not to reverse its rotation direction when the operating mode is changed from generating to pumping or vice versa. Therefore, the time required for the mode change of a ternary unit is much shorter compared to the time needed for a reversible pump-turbine. **Figure 6** shows a ternary type unit in comparison to a reversible pump-turbine. A tandem type unit consists of a motor-generator, turbine and pump coupled with a common shaft [1].

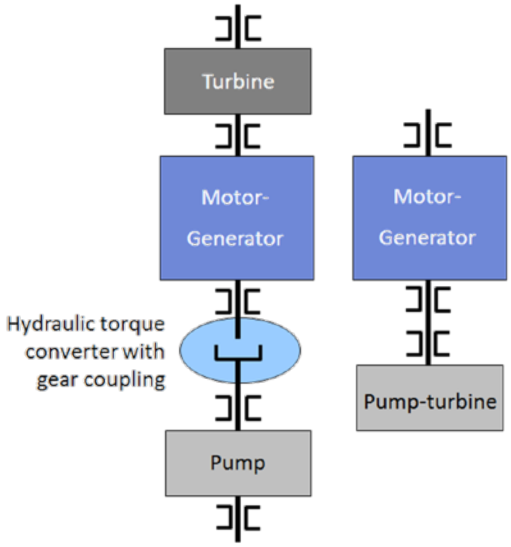


***Figure 6**: Comparison of ternary pump storage arrangement (left) and reversible pump-turbine (right)*

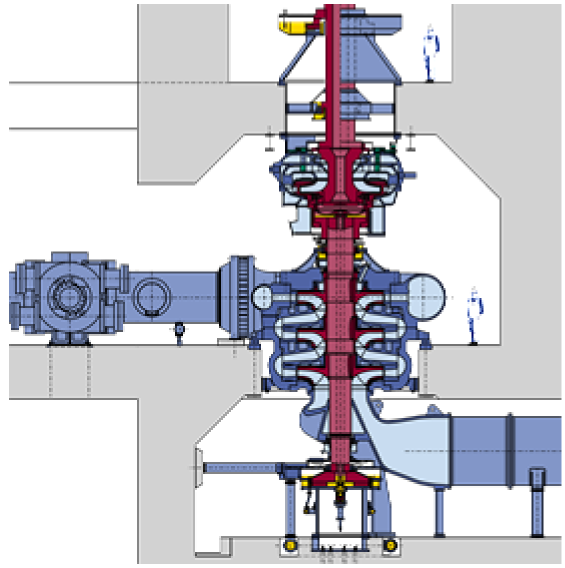


***Figure 7**: Cross-section of Kops II arrangement*

Examples for ternary pump storage units:

The **Kops II** pumped storage power plant (**Figure 7**: cross section, **Figure 8**: 3D view) was erected parallel to the existing power plant Kops I. In 2004 Voith Hydro was awarded the contract to supply three-stage pumps, spherical valves and hydraulic torque converters for the three machine sets of Kops II pumped storage project in Austria. The model acceptance test was successfully completed in 2005. The Kops II plant went into commercial operation in 2008.

The **Veytaux II** (VEHO) pumped storage power plant (**Figure 9**) is located close to the city of Montreux, Switzerland and will add two ternary sets of about 120 MW each to the existing Veytaux I PSPP after its completion. It will be equipped with two vertical shaft ternary sets consisting of a five-stage radial storage pump, a coupling, a motor-generator and a Pelton turbine. The model acceptance test was successfully completed in 2011 and the thermodynamic efficiency test at the Veytaux hydro power plant, which was conducted in December 2016, confirmed that all performance guarantees are fulfilled.

***Table 3**: Multi-Stage Pumps – Main Hydraulic Data*

	Kops II	Veytaux II
Head range H [m]	818-723	884-837
Rotating speed n [rpm]	500	500
Runner inlet diameter D_1 [m]	2.8	2.2
Maximum pump input P_{Pu} [MW]	162	118
Pump mode unit discharge [m³/s]	18.5	12.5
Power range turbine output P_{Tu} [MW]	150-173	-
No. of stages	3	5

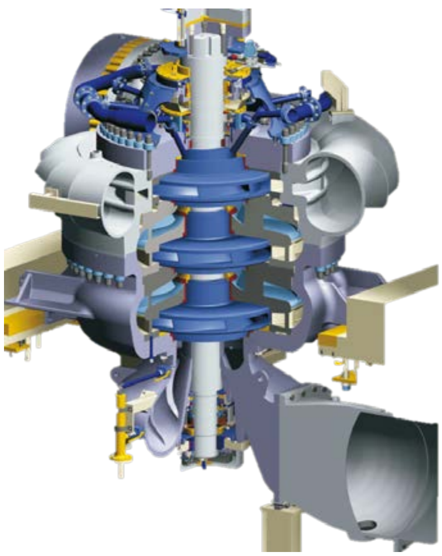


***Figure 8**: 3D view of Kops II arrangement, 3 stages*

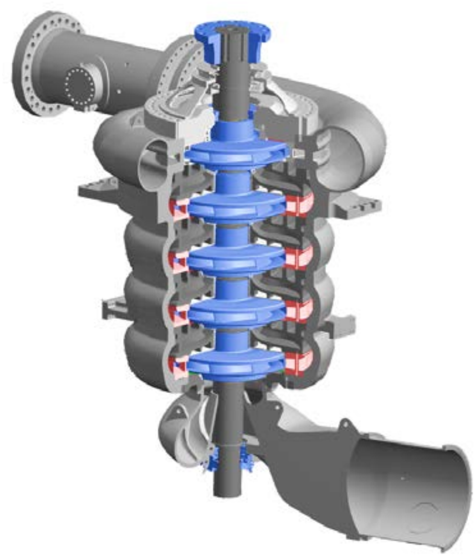


***Figure 9**: 3D view of Veytaux II arrangement, 5 stages*

5 HYDRAULIC TORQUE CONVERTER

For the turbine start no extra facilities are necessary, the start-up in pump mode requires special features. The water filled pump can be started with the help of stored energy in headwater pond released through the turbine. The key to short transition times, with shortest response to the grid, is the hydraulic torque converter (**Figure 10**) based on the principle of Hermann Föttinger. It is located between the rotating synchronized motor generator shaft and the non-rotating pump shaft. When the converter is filled with water during the start and stop sequences, full power can be transmitted and the pump shaft is accelerated or decelerated moderately in seconds. When main shaft and pump shaft have the same rotational speed a gear coupling is switched without mentionable wear. When the converter is empty, the created power losses are low.

The most important advantages of hydraulic torque converters are [3]:

- Short start-up time, the power consumption of the supply net starts by filling of the converter with water, after 10 seconds approximately 60% of the storage pump power is available for the supply net and the valve can start to open.
- Operation of the motor independently from the pump.
- Minimal no-load losses (less than 0.05% of the nominal power).
- Self-regulating to the synchronism, no external governor is used.
- Minimal water consumption, water is taken out of the tail water reservoir, no costly water of the penstock is used (in opposite to a start-up turbine).

In order to ensure stable and reliable electricity availability new pump-turbine units are being employed. Typical mode switching times for reversible pump-turbines and ternary units with torque converters are as follows (**Figure 11**):

The most flexible arrangement regarding primary power control tasks for both operation modes is the ternary set (with HTC and short circuit operation). More interesting details on the special feature "Hydraulic Short Circuit Operation" can be found in [4]. The reversible fixed speed unit partly fulfils the requirements for primary control while variable speed provides higher flexibility. All mentioned arrangements are very suitable for secondary and tertiary control [5].

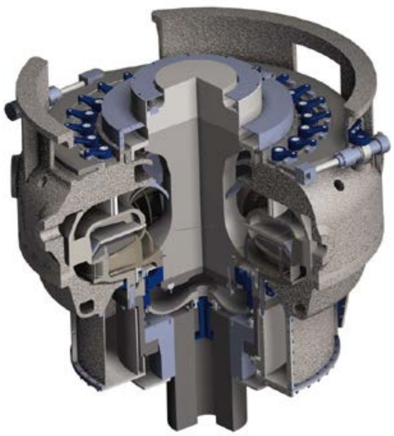
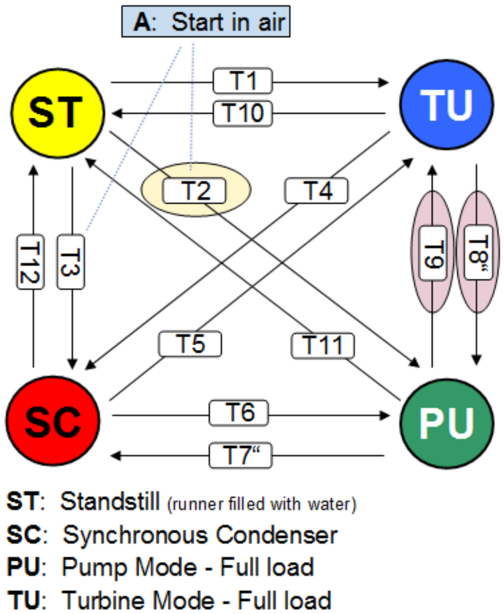


***Figure 10**: Cross-section and photo of the Kops II hydraulic torque converter*



A - Reversible PT

B - Ternary set (HTC + Pelton Turbine)

	MODE CHANGE	A	B
1	Standstill → TU – Mode	90	60
2	Standstill → PU – Mode	340	120
3	Standstill → SC – Mode	120	60
4	TU – Mode → SC - Mode	80	20
5	SC – Mode → TU - Mode	70	20
6	SC – Mode → PU - Mode	70	30
7	PU – Mode → SC - Mode	140	30
8	TU – Mode → PU - Mode	420	30
9	PU – Mode → TU - Mode	190	30
10	TU – Mode → Standstill	200	110
11	PU – Mode → Standstill	160	50
12	SC – Mode → Standstill	200	100

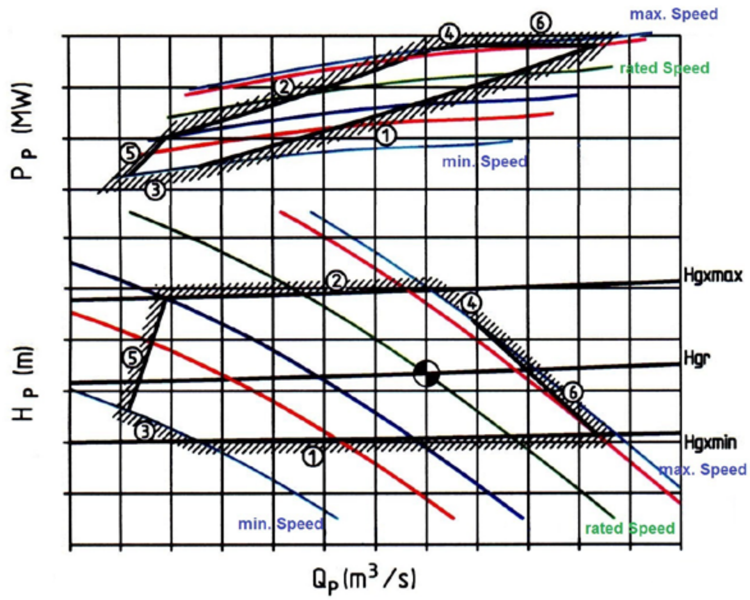
***Figure 11**: Mode switching times for reversible pump-turbines and ternary units*

6 VARIABLE-SPEED PUMP-TURBINES: FRADES II, GOLDISTHAL

Adjustable speed pumped storage equipment is a major option for many projects during the planning and optimization phase these days. Besides a substantial increase in efficiency at turbine part load operation, the main advantage is the possibility of power variation during pump operation. Machines operating at constant synchronous speed have a fixed power input that is determined by the actual pumping head and the resulting discharge according to the pump characteristic of the machine. The operation range for pump mode is shown in **Figure 12**. Variable speed machines are therefore providing much higher operating flexibility and improved plant efficiency by covering a wider operation range than fixed speed machines [6].

The variable speed technology enhances the positive contribution to the grid, the three main advantages of variable speed units are [7]:

- In turbine mode, an increase of the head range and better efficiency, especially at partial loads.
- In pump mode, the possibility to control the input power.
- Potential to contribute to the stability of the grid by injecting active and reactive power.



In pump mode the operation range is defined by:

(1) minimum gross head

(2) maximum gross head

(3) minimum speed

(4) maximum speed

(5) pump instability

(6) maximum pump input

Figure 12*: Characteristics for adjustable speed in pump mode*

Frades II in Portugal (former "Venda Nova III – Venda Nova Power Increase"), the largest variable speed pump storage plant in Europe, is in operation since April 2017. There were supplied two variable speed pump turbines each with a rated output of 390 MW, two asynchronous motor-generators with a rated output of 440 MVA each, the frequency converter and control systems as well as the hydraulic steel components. The generator (DFIM – Double Fed Induction Machine) sets are the largest and most powerful of their kind in Europe. The plant operator is the Portuguese utility company Energias de Portugal (EDP) [8].

The variable speed of the DFIM machine has two main advantages. Firstly, the new systems allow a fast and flexible response to active and reactive demand from the power grid; the supply can be varied to meet demand. Secondly, they offer additional stability in cases of voltage drop, reducing the likelihood of blackout and enabling the system to resume operation much faster if one occurs. When the voltage drops by significantly more than 5% below normal, the turbines and DFIM motor-generators at Frades II can retain stability for up to 600 milliseconds, four times longer than a fixed-speed power unit.

Ultimately, DFIM technology delivers optimal operation in both turbine and pump modes, while fulfilling stringent TSO (Transmission system operator) grid code requirements (role assumed in Portugal by REN – Redes Energéticas Nacionais) for grid fault behavior by fast injecting active and reactive power when needed in both modes. The variable speed motor-generator technology at Frades II provides enhanced flexibility, which increases the plant's total number of operating hours [9].

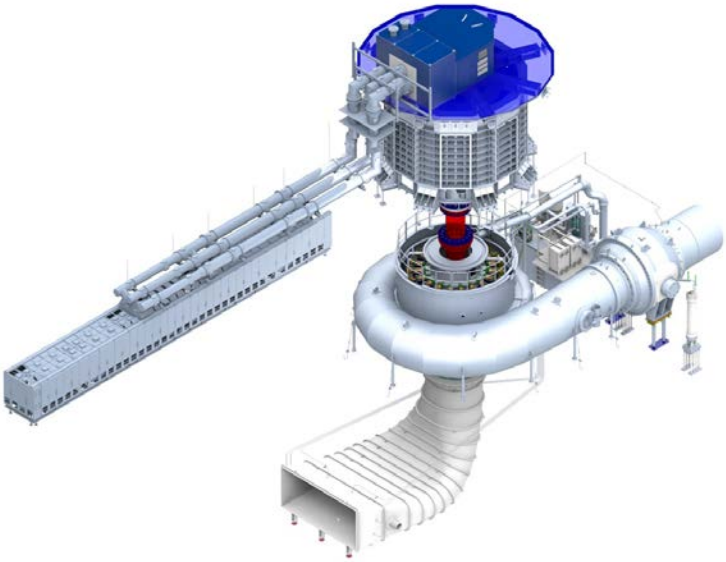


Figure 13*: 3D view of Frades II arrangement*

Figure 14*: Frades II commissioning*

Table 4*: Variable-speed pump-turbines – Main Hydraulic Data*

	Frades II		**Goldisthal**	
Head range H [m]	414-432		279-334	
Rated / maximum turbine output P_{Tu} [MW]	383 / 400		269 / 325	
Runner inlet diameter D_1 [m]	4.5		4.6	
Rotating speed n [rpm]	375	350-381 -7% / +2%	333	300-347 -10% / +4%
Pump input P_{Pu} [MW] at min. / max. delivery head	363 / 380	320-380	262 / 247	168-291 / 186-289
Minumum input variation ΔP [MW] at each lift head	-	> 60		> 100

The model tests to verify the specified guarantees and the general operation behavior were internally carried out and the final model acceptance test was successfully completed in October 2011. Frades II is now in operation since 2017.

Goldisthal pumped storage plant in Germany is equipped with four radial, single stage, reversible pump-turbines rated at 269 MW and 301.6 m gross head. Each of the two penstocks are connected to one machine operating at constant synchronous speed and one machine operating at variable speed assigned for a pump input variation range of at least 100 MW at each individual pump head. The contract for the pump-turbines including governors was awarded in October 1997. Model acceptance tests were successfully completed in 1999. The power plant went into commercial operation in 2003 and since then has proven a very stable and quiet operation [10].

SUMMARY

The power demand increases permanently with the expansion of the economy and improvement of living standards. The focus on renewable electricity production increases the demand for energy storage. Pumped storage power plants are the only state-of-the-art option of grid energy storage, which essentially contributes to peak load balancing and to the stabilization of the electrical grids. Pumped storage power plants with their extremely short starting and transition periods and outstanding regulation characteristics provide mandatory ancillary services (frequency and voltage regulation, black start ability, among others) for the grids. Different concepts (ternary versus reversible units, single versus multistage, torque converter and closed circuit operation, variable speed) have been discussed in this paper. With the rich experience in the development of pumped storage power plant equipment gained over the last century, these concepts provide answers to the requirements of power producers in all areas of equipment for pumped storage power plants.

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