Performances achieved to the Grid by a Full Power Converter Used in a Variable Speed Pumped Storage Plant

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Abstract. The growth of renewable energies likes wind and solar requires pumped-storage plants to increase their performances to stabilize grid frequency and voltage. The introduction of a full-power converter constitutes the ultimate step forward to meet the requirement in a safe, reliable and sustainable manner. This article quickly introduces the converter topology and technology before describing the performances it aims to deliver to the grid. Finally, converter bypass is discussed.

1. Introduction
Pumped-storage schemes play a growing role in grid stability to help balance the increasing amount of unpredictable power brought by renewable energies like wind and solar.

However, in Europe — and in many other places in the world — the development of pumped storage is refrained by several counter factors:

- Less available locations to accommodate new schemes.
- Lower hydraulic properties affecting the return on investment.
- Higher environmental pressure from a population that is against the new implementations.
- Decentralization with smaller power generation plants requires decentralized balancing schemes.

Today, most utility companies have some pumped-storage schemes in their portfolios that were constructed in the 1960s and 1970s, housing units of unitary power in the range of 60-200 megawatts (MW).

After large variable-speed, pumped-storage power plant were launched, based on doubly fed induction machines, the next step (coming up) introduces fully fed power converters in new builds or as upgrades to the above mentioned existing schemes to increase their performances.

This article provides an update on converter technology and describes what performances could be achieved by taking the whole electrical part of the plant, from pump/turbine shaft to the connection to the grid, into account.

2. Case Study – 160-MW Pumped Storage
This case study is based on an existing plant having two units of the following optimized main features:

- Rated operating point in pump mode : 160 MVA; 13.8 kV; 55Hz; 550 rpm
- Rated operating point in turbine mode : 155MVA; 13.2kV; 52.6Hz; 526 rpm
- Generator/motor power factor during operation : 1
- Generator/motor number of poles : 12
- Generator/motor subtransient reactance : 22 percent (%) unsaturated
- Generator/motor + pump/turbine inertia : 200 T.m²
- Grid voltage and short-circuit power : 220kV – 10GVA

The single line diagram for one unit is given in figure 1 below:

![Single line diagram](image)

**Figure 1**

The full converter is modular and made of four identical threads connected in parallel through interlacing reactors. It is deionized water cooled with a water-to-water heat exchanger.

The generator/motor static excitation system is closely interfaced with the converter controller.

There is no generator circuit breaker. The whole unit is protected by the line breaker (52L) and a converter feature allows the unit transformer to be softly magnetized, avoiding inrush current on line side every time it is energized.

The speed rotation direction as per turbine or pump mode is naturally achieved by the converter so there is no need for phase reversal switches.
3. Converter Technology

The converter is made of a five level pulse width modulation (PWM) drive utilizing high power injection-enhanced gate transistor (IEGT). The picture 2 below shows a power stack subassembly in which six components are tightened together:

![Figure 2](image1.png)

The converter is four quadrants fully reversible with two identical inverters: one on machine side and another one on grid side — named Active Front End (AFE).

The five-level PWM carriers are shifted from one module to the other through the interlacing reactors, providing 33 levels of PWM phase-to-phase reaction at converter output as shown below:

![Figure 3](image2.png)

Then, a complementary small output filter suppresses the remaining voltage spikes and notches of short amplitude and high frequency. The resulting output voltage seen by the synchronous machine becomes pure sine wave, having less than 0.5 percent harmonic contain.
4. Performances

4.1. General statement:
Variable speed drive (VSD) brings about key benefits to such a plant:
- The unit speed is adjusted so that the pump/turbine operates at its best efficiency, whatever the water head.
- The water head operating range is extended, allowing the plant to capture more power.
- VSD ensures soft start and stop, smoothing hammer effect on draft tubes when spherical valves are open/closed — avoiding inrush current even on transformers and, thus, increasing the operation flexibility of the plant.
- Reactive power exchanged with the grid is fully controlled, and the plant can satisfy the most stringent requirements from the grid, such as fault condition, frequency and power fine tracking.
- The synchronous machine is optimized: Its rating is reduced by 15 percent as it is continuously operating at power factor 1. Its rotor is built with a lower pole number and it no longer needs to provide large inertia for pump/turbine stability.

4.2. Power factor control on the grid side:
The converter takes care of the power factor control as it is able to control reactive power flow and direction independently from the active power flow and direction. Its capability is expressed through the P/Q diagram below (left side):

![P/Q Diagram](image)

**Figure 4**

The converter reactive power capacity is dependent of the grid voltage as shown by the Green curve for rated voltage, the Blue one (+5 percent) and the Red one (-5 percent).

An automatic voltage regulator (AVR) function is implemented inside the converter controller. Reactive power set point is derived from voltage droop (or slope) characteristic. The droop (δ) is defined as the reduction in voltage at the point of connection as the converter output varies from fully inductive to fully capacitive. As a consequence, when the grid voltage is low, the VSD supplies capacitive reactive power. When the grid voltage is on high, the VSD consumes inductive reactive power. This function is illustrated on figure 4 above (on the right).
4.3. **Power control in pump mode**

Power control is the main function devoted to the converter since the pump/turbine could only operate in pump mode with its distributor wide open. Therefore, any power consumption control could only results from speed variation achieved independently of the water net head variation.

4.4. **Starting in pump mode – mode transfer**

With the converter having the same rating as the pump/turbine, dewatering the runner to reduce its resistive torque is no longer needed. Starting could be achieved within a dozen of seconds instead of a couple of minutes, according to the design.

Mode transfer time from pump to turbine, or vice versa, becomes very fast and is illustrated through the curves of figure 5 below:

![Speed variation vs time](image)

![Power variation vs time](image)

**Figure 5**

Notwithstanding what would be the hydraulic constraints, the electrical circuit mainly made of the converter is able to change the mode of operation full power in the pump to full power in the turbine within 32 seconds.
4.5. Fault ride through
The plant can withstand transient fault condition in the power grid without disconnecting. When a short circuit occurs on the grid, for a limited time — and significant voltage dip of up to 100 percent — during 150 to 500 milliseconds (ms) as shown in figure 6 below (left), the converter is able to interrupt active power transfer with the pump/turbine and then resume operation once the voltage is back.

On the grid side, the converter could simply shut down during transient and then restart automatically. When necessary, it also could provide its rated current into the short circuit to contribute to clearing the fault at first instant and then helping the grid to recover.

The figure 6 below (right) shows the converter phase currents on grid side before, during and after a short circuit, having 100 percent voltage dip. After 60 ms transient, the converter provides back its rated current even if the voltage did not recover.

![Figure 6](image)

4.6. Pump/turbine stability – virtual inertia
The converter is decoupling the pump/turbine shaft speed from the grid frequency. The fluctuation or oscillation of one is no longer influencing the other, causing the generator/motor inertia to be enlarged for stability purposes.

The converter could claim providing virtual inertia of infinite value.

5. Conclusion:
The full power converter provides dynamic and stable speed and power variation so that the power plant performs fast grid frequency control in both pump and turbine mode.

Thanks to the converter, the operation is fully flexible; the stored volume of water in the reservoirs is better exploited. The plant can achieve a large number of start/stops per day without additional fatigue and stress for its components.

The converter is add-on equipment compared to a conventional pumped-storage plant, but its presence allows for suppressing of the generator circuit breaker, the phase reversal switches and a huge portion of the isolated phase busbars. The generator/motor is optimized and the protections and control systems are simplified.