Simulation of pump-turbine prototype fast mode transition for grid stability support

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Abstract. The paper explores the additional services that Full Size Frequency Converter, FSFC, solution can provide for the case of an existing pumped storage power plant of 2x210 MW, for which conversion from fixed speed to variable speed is investigated with a focus on fast mode transition. First, reduced scale model tests experiments of fast transition of Francis pump-turbine which have been performed at the ANDRITZ HYDRO Hydraulic Laboratory in Linz Austria are presented. The tests consist of linear speed transition from pump to turbine and vice versa performed with constant guide vane opening. Then existing pumped storage power plant with pump-turbine quasi homologous to the reduced scale model is modelled using the simulation software SIMSEN considering the reservoirs, penstocks, the two Francis pump-turbines, the two downstream surge tanks, and the tailrace tunnel. For the electrical part, an FSFC configuration is considered with a detailed electrical model. The transitions from turbine to pump and vice versa are simulated, and similarities between prototype simulation results and reduced scale model experiments are highlighted.

1. Introduction

The integration of the constantly growing capacity of New Renewable Energies, NRE, mainly composed by wind and solar energies, is a challenging task as far as the power network stability is concerned, due to the intermittent nature of these energy sources. Beside storage and substitution production capabilities, pumped storage power plants can significantly contribute to improve the stability of power network due to their production flexibility, fast response time and large energy storage capability. Variable speed motor-generator solutions enable to provide a variety of new control services to the electrical grid to be carefully considered, [2]. In particular, solution based on synchronous motor-generator with Full Size Frequency Converter, FSFC, offer the possibility to achieve turbine to pump fast transition mode and vice versa [1], [2], [4]. The feasibility of this new ancillary service was deeply investigated in the framework of the HYPERBOLE European Research Project, by means of reduced scale model and numerical simulation [3]. This paper presents experimental and numerical results of fast mode transition from pump to turbine and vice versa performed on a reduced scale model tests as well as simulation results for an existing 2x210 MW pumped storage power plant equipped with a pump-turbine homologous to the reduced scale model, where conversion from fixed speed to FSFC variable speed solution is assumed. The plausibility of fast transition mode is investigated by means of full hydroelectric power plant simulation including both hydraulic system as well as electrical installations.

2. Investigation at reduced scale model

The feasibility of fast mode transition from pump to turbine and vice versa is investigated first at the reduced model scale by means of both experimental and numerical approach enabling a comprehensive survey of the dynamic behavior of the pump-turbine unit and its interaction with the related hydraulic circuit. Figure 1 left presents the reduced scale model of the pump-turbine installed at the ANDRITZ Hydro Hydraulic Laboratory in Linz, Austria. This reduced scale model is quasi-homologous to the prototype unit of the 2x210 MW test case, as both feature the same specific speed of NQE=0.17 (nSQ=207) and the same blade number and main dimensions, [3].

A 1D model of the test rig has been setup using the SIMSEN simulation software developed by the Ecole polytechnique fédérale de Lausanne, EPFL. The model includes the pipes dimensions of the entire test rig; the downstream reservoir; the pump and pump-turbine characteristics. Transitions from pump to turbine and return where carried out on the test rig for transition time of 4s, 8s, 12s and 20s where the rotational speed is varied linearly using specific motor-generator drive. Figure 1 right presents the comparison between the 1-D simulation results and test rig measurements for transition time of 8s and guide vane opening Y=15°. The transition starts at t=3s in 8s. Once in turbine mode, the speed is kept constant during 4s before returning to pump mode with the same transition time. The resulting time evolutions of head and discharge are in good agreement with the measurements, see Figure 1 right.

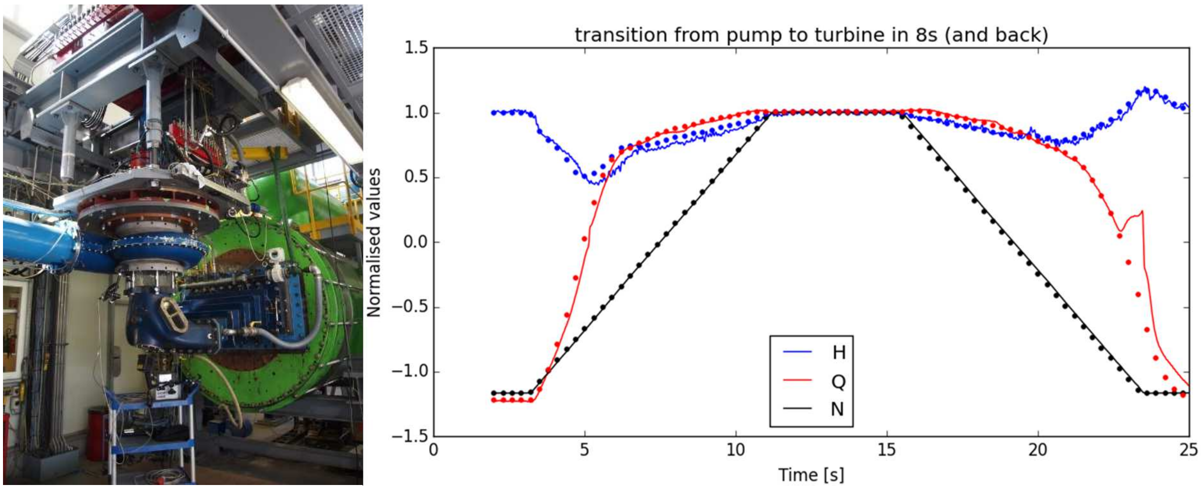

Figure 1. Pump-turbine reduced scale model (left) and comparison between simulation results (dots) and measurements (solid line) of the head, discharge and rotational speed during pump to turbine transitions and vice-versa carried out in 8s and GVO Y=15°.

3. Modelling of prototype pumped storage power plant

The layout of the pump-turbine unit of the 2x210 MW test case is presented in Figure 2 left, while the corresponding main characteristics are provided in Table 1.The SIMSEN model of the pumped storage power plant, see Figure 2 right, includes all hydraulic components and takes into account [3]:

- Water hammer phenomena in piping systems (pipe head losses, water inertia and pipe elastic behavior (fluid compressibility and pipe wall deformation));
- The 4 quadrants transient behavior of the pump-turbine including so-called S-shape unstable characteristics corresponding to the one considered for the reduced scale model tests, and the link with rotating inertias;
- The surge tank mass oscillations phenomena between the lower surge tanks and the lower reservoir taking into account variable cross section area of the surge tanks and asymmetric head losses at the inlet of the surge tank;
- The generating unit rotating train torsion dynamics with turbine and motor-generator rotor rotating inertia linked through coupling shaft with given torsional stiffness corresponding to the first natural torsional frequency of the unit.

Moreover, the SIMSEN model of Figure 1 right included a detailed simulation model of the FSFC set, considering the following elements: a synchronous machine, the machine side and grid side converters and the related control, the unit step-up transformer, a connection to the grid with a given finite short-circuit power and the unit rotating inertia. The model of the synchronous machine is of high order and takes into account the excitation currents and damper currents, see [3].

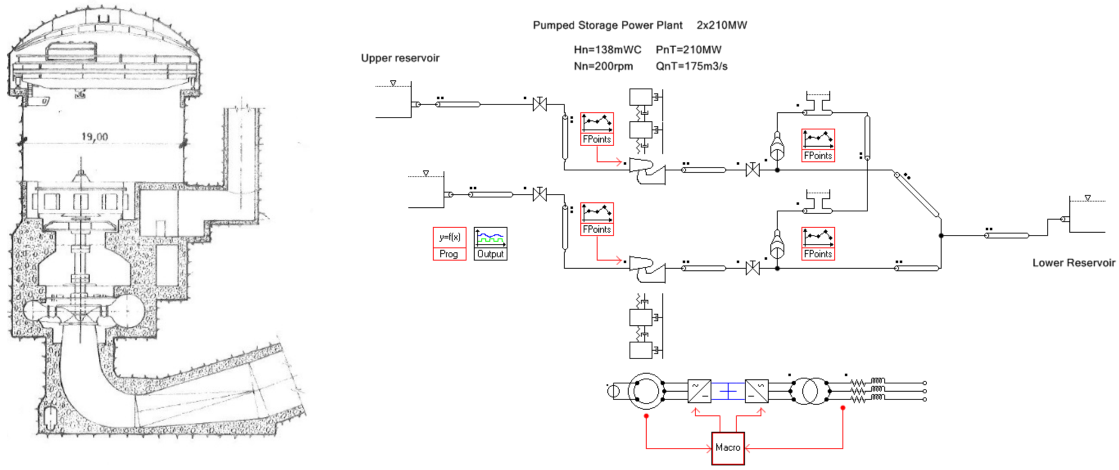

Figure 2. Layout of the 210 MW pump-turbine unit (left) and the SIMSEN model of the pumped storage power plant test case (right).

Table 1. Main characteristics of the pumped-storage power plant test case, see Figure 2 right.

Francis pump-turbine:	
Nominal rotational speed	200 rpm
Turbine nominal power	210 MW
Turbine nominal discharge	175.1 m^3/s
Turbine nominal net head	133.5 mWC
Turbine nominal torque	9.74 MNm
Low pressure side diameter	3.86 m
Total unit inertia including generator and turbine (J=MR2)	4106 $t{*}m^2$
Mechanical time constant ($\tau_m = J_{tot} \cdot \omega_n^{\,2} / P_n$)	8.6 s

4. Simulations of fast transition mode of prototype unit

The Froude similitude has been considered to transpose the transition time from reduced scale model to the prototype scale, by expressing the reference velocity as function of the unit net head H, and then expressing the head H as function of the runner peripheral velocity $U = \omega \cdot R$ with $H = U^2/(2 \cdot g)$ as follows:

$$Fr = \frac{C_{ref}}{\sqrt{g \cdot D_{ref}}} = \sqrt{\frac{g \cdot H}{g \cdot D_{ref}}} = \sqrt{\frac{U^2}{2 \cdot g \cdot D_{ref}}} = \frac{\omega}{2}\sqrt{\frac{D_{ref}}{2 \cdot g}} \qquad (5)$$

According to the dimension ratio of $D^P/D^M = 15.82$ between the prototype and the model, the transition time ratio is given equal to:

$$\frac{T^P}{T^M} = \sqrt{\frac{D^P}{D^M}} = \sqrt{\frac{3.86}{0.244}} = 3.98 \cong 4$$

According to the above transposition, the transition time considered during reduced scale model tests of 4s, 8s, 12s, and 20s, respectively leads to transition time of 16s, 32s, 48s and 80s.

The numerical simulation of the fast transition from pump to turbine mode and vice versa is simulated at the prototype scale with transition time of 32s from pump nominal rotational speed N=-200 rpm to the turbine nominal rotational speed N=+200 rpm, and considering constant guide vane of Y=15° (y=0.375 pu). Figure 3 left presents the time evolution of the dimensionless characteristic quantities of the Prototype pump-turbine resulting from the fast transition and the related transient operating point, see Figure 3 right, to be compared with the simulation and measurement results at the reduced scale of Figure 1 (right). It could be highlighted that despite completely different hydraulic circuits between model and prototype, the qualitative evolution of the dimensionless net head h and discharge q shows remarkable similarities with sudden and sharp net head drop during the pump to turbine transition and a net head rise during the turbine to pump transition. These net head variations result respectively from the discharge acceleration and deceleration. But of course, direct transposition of the transient behavior of the pump-turbine unit from reduced scale model test to prototype is not possible since the related hydraulic systems are not in similitude. Hence transposition can only be investigated by means of numerical simulation. Figure 4 left presents the time evolution of the pump-turbine spiral case and draft tube pressure resulting from the fast transitions which remains within acceptable values. Figure 4 right presents the time evolution of the electromagnetic torque and the related active power. As expected, the transition from pump to turbine does not lead to large values of the electromagnetic quantities as the transition induces a discharge reversal supported by the gravity forces. However, during the transition from turbine to pump, extreme values of electromagnetic torque and active power are reached due to discharge reversal against gravity forces leading to 1.7 times the nominal torque at t=115s and a maximum active power of 240 MW at t=132s representing 114% of the nominal power of the unit. The maximum torque occurs during the zero rotational speed cross over, while the maximum active power occurs at the end of the fast transition.

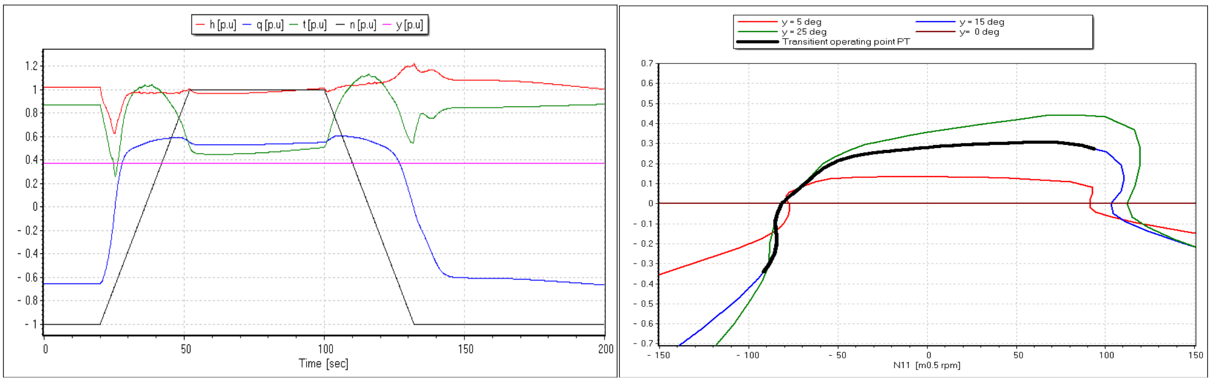

Figure 3. Simulation results of the time evolution of the pump-turbine key quantities (left; h: head, q: discharge, t: torque, n: rotational speed, y: guide vane opening) and related transient operating point (right) in case of fast transition mode from pump to turbine achieved in 32s and vice-versa.

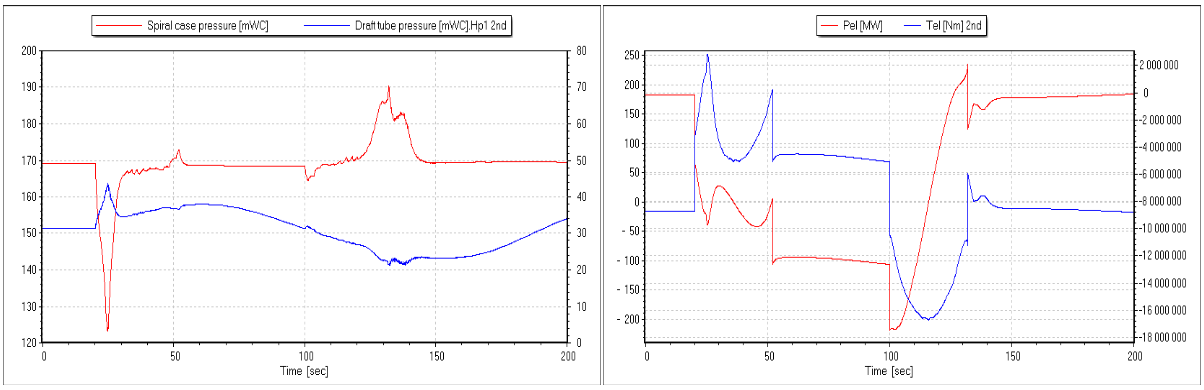

Figure 4. Simulation results of the time evolution of the pump-turbine spiral case and draft tube pressure (left) and active power and air-gap torque (right) in case of fast transition mode from pump to turbine achieved in 32s and vice-versa.

Figure 5 presents simulation results of the time evolution of the motor-generator air gap torque obtained for different transition time varying from 16s to 80s considering a specific guide vane closing and reopening sequence defined to mitigate extreme values of electrical quantities, pointing out the potential for fast transition optimization.

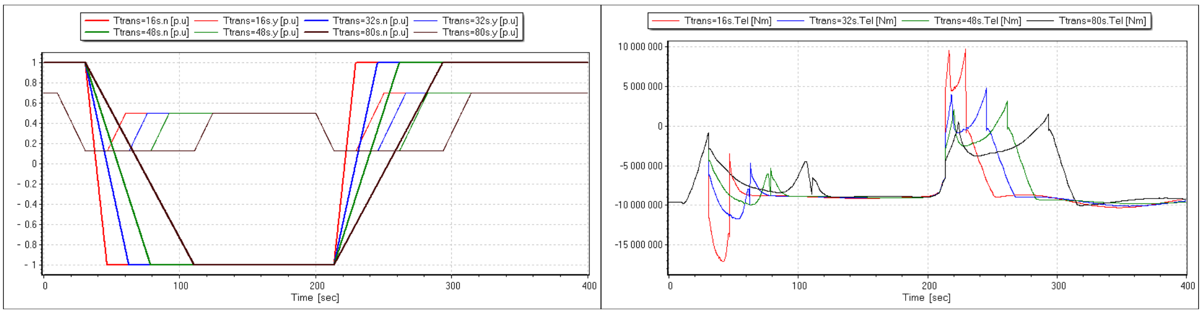

Figure 5. Simulation results of the time evolution of the pump-turbine guide vane opening and rotational speed (left) and resulting air-gap torque (right) in case of fast transition mode from pump to turbine and vice-versa achieved for different transition time.

5. Conclusions

The lean integration of intermittent New Renewable Energies requires additional power control services capabilities to ensure electrical grid stability. In this context, pumped storage power plants operating flexibility combined with recent development of power electronics enable to envisage new ancillary services such as fast active power injection or absorption and inertia emulation which can significantly contribute to secure power network operation. Full Size Frequency Converter synchronous machine unit offer new perspectives such as fast transition from pump to turbine and vice versa enabling to take full advantage of the entire pumped storage capacity from consumption to generation mode. Such opportunity was deeply investigated in the framework of the European Research Project HYPERBOLE in order to assess the feasibility of fast mode transitions. Therefore, reduced scale model test investigations were carried out by means of both experimental and numerical approaches while the transposition to prototype was investigated by means of numerical simulation for an existing power plant whose pump-turbine is quasi homologous to the reduced scale model, demonstrating the feasibility of fast mode transition at the prototype scale.

6. References

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