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Assessment of power step performances of variable speed pump-turbine unit by means of hydro-electrical system simulation

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Abstract. The paper explores the improvement in ancillary services that variable speed technologies can provide for the case of an existing pumped storage power plant of 2x210 MVA which conversion from fixed speed to variable speed is investigated with a focus on the power step performances of the units. First two motor-generator variable speed technologies are introduced, namely the Doubly Fed Induction Machine (DFIM) and the Full Scale Frequency Converter (FSFC). Then a detailed numerical simulation model of the investigated power plant used to simulate power steps response and comprising the waterways, the pump-turbine unit, the motor-generator, the grid connection and the control systems is presented. Hydroelectric system time domain simulations are performed in order to determine the shortest response time achievable, taking into account the constraints from the maximum penstock pressure and from the rotational speed limits. It is shown that the maximum instantaneous power step response up and down depends on the hydro-mechanical characteristics of the pump-turbine unit and of the motor-generator speed limits. As a results, for the investigated test case, the FSFC solution offer the best power step response performances.

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 [1]. Beside storage and substitution production capabilities, pumped storage power plants can significantly contribute to improve the stability of power network by providing ancillary services, taking advantage of their production flexibility, fast response time and large energy storage capability [2], [3]. The capability of pumped-storage power plant to achieve very fast power injection or absorption assuming a conversion from fixed speed to variable speed technology (see [7]) was investigated in the framework of the HYPERBOLE European Research Project. In the framework of hydro unit refurbishment, such conversion may further increase the unit flexibility thus enable a better integration of NRE. This capability was investigated by means of detailed hydroelectric system time domain simulation to evaluate pump-turbine unit active power step response up and down. The response time of fixed speed units is limited by the maximal rate of opening and closing of the pump-turbine guide vanes, which is optimized to comply with the maximum allowable penstock pressure and the maximum unit over speed during transient regimes. The variable speed motor-generator solutions not only enable efficient off-design operation and pump input control of pump-turbine units, but can also considerably improve active power response time, by decoupling grid frequency from the unit rotational speed, and taking advantage of the fly-wheel effect of the mechanical rotating train. This paper assesses the performances of variable speed pump-turbine units regarding the response time at the grid connection, using numerical simulations of the entire hydro-electrical system of an existing pumped storage plant which is assumed to be converted from fix speed to variable speed. This paper aims at highlighting the performances and limitations of power step performances obtained with two different variable speed technologies, namely the Doubly Fed Induction Machine (DFIM) ([4],[5]) and the Full Size Frequency Converter (FSFC) ([6],[7]). This paper first introduces both variable speed technologies and related control strategies. Then, the 2x210 MW pumped storage power plant case study and the related simulation load cases are presented. Finally simulation results are presented to compare the power step performances achieved with DFIM and FSFC solutions for the considered test case.

2. Variable speed technologies and the control strategy

Figure 1 presents the hydro-electrical model of the existing 2x210 MW pumped-storage power plant case study, modelled with the simulation software SIMSEN, with the hydro-mechanical model (upper part) and electro-mechanical model (lower part). The hydro-mechanical model takes into account the 2 individual penstocks, the 2 reversible Francis pump-turbines with related governors, the downstream surge tanks and the tailrace tunnel. The electro-mechanical layout is shown for both technologies, DFIM (lower left) and FSFC (lower right). For DFIM, the electrical machine is a Wound Rotor Induction Generator with an open terminal rotor, which is fed from a power frequency converter, while for FSFC, the electrical machine is a classical synchronous machine with the stator directly connected to the power frequency converter itself connected to the grid. DFIM solution has one advantage over FSFC which is that the rated power of the frequency converter is only a fraction (typically 10%) of the rated power of the unit. However, for DFIM, the speed range is limited to a given range around the rated speed, typically ≤ 10%, mainly due to thermal limitation of the rotor of the induction machine, while for FSFC, the speed range is not limited by the technology itself.

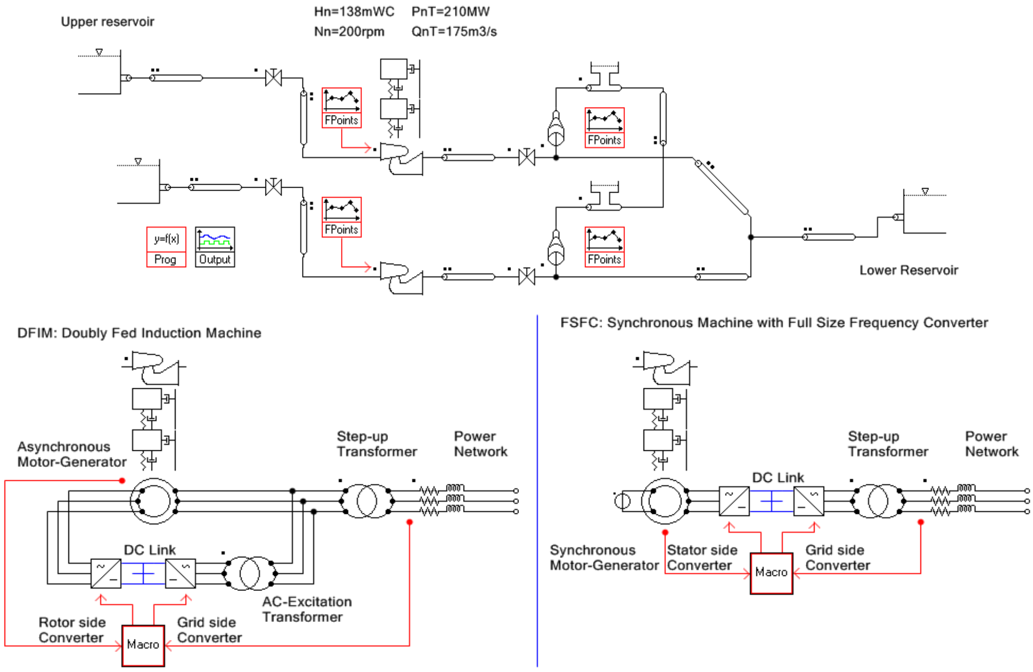

Figure 1 - Hydro-electrical model of a pumped storage power plant, with DFIM and FSFC variants.

For both technologies, the power converter is used to control the active and reactive power that is injected into the grid while the speed of the unit is controlled by the turbine speed governor, acting on the guide vane opening. In pump mode, the pump characteristic imposes the speed for a given power and head, while the guide vane opening is set to an optimal value for maximum pump efficiency. This control strategy allows to use the capability of a power converter to change the operating point very quickly, typically in the order of hundreds of millisecond or smaller [4], [5]. The turbine speed governor response time is much slower due to the hydraulic and mechanical constraints, but the rotational speed is allowed to vary within a given range, thanks to the decoupling between the grid frequency and the units rotational speed. The response time of the turbine speed governor is limited by the opening and closing time of the guide vanes which are set to comply with maximum allowable penstock pressure and unit rotational speed during in transient regimes. The variable speed technologies allow for fast power performance of the converter by exploiting the so called “fly–wheel” effect the rotating inertias of the unit. However, the fly-wheel effect is limited by the allowed speed range of the motor-generator and also by the maximum torque that the turbine can deliver which depends on its torque characteristic. As a consequence, in some cases, the ideal response time that can be expect from a power converter and is restricted and results in a slower power set point ramp.

3. Simulations model and load cases

The SIMSEN simulation of Figure 1 comprises high order models of the hydraulic system, taking into account for penstock water hammer effect, downstream surge tanks mass oscillations and pump-turbine 4 quadrant characteristics including the unstable S-shape characteristic, and the PID turbine governor with guide vane rate limiter. The rated apparent power of the unit is 210MVA, under a voltage of 15kV and the frequency of the electrical grid is 50Hz. The nominal rotational speed is 200rpm. The limitations for the speed deviation from rated speed, for DFIM, has been set to +-7%, which is a typical value. For FSFC, there is no lower limit for speed but upper limit corresponds to maximum allowable over-speed of the unit. Simulation are performed considering three different active power set point decrease of respectively 0.1, 0.2 or 0.4 pu, from nominal power and 100s latter an active power set point increase back to the nominal power. For each power set point decrease and increase, the minimal duration of the set point transition is determined by successive trial, starting with an ideal instantaneous transition and progressively increasing the ramp time until the resulting transients are stable and respect the constraints on rotational speed and penstock’s pressures. The constraints on pressures are in fact ensured by the closing time of the guide vane, which has been determined beforehand also by simulations on specific dimensioning load cases. In variable speed technologies, the speed of the mechanical shaft is usually set to optimize the pump-turbine efficiency and hence depends on the operating point. In this study, it is chosen to let the speed set point to the nominal speed in order to benefit from the maximal speed range for both over-speed and under-speed deviations.

4. Simulation results

Table 1 summarizes the response time achieved by the pump-turbine unit of interest, for both DFIM and FSFC technology, for the three different magnitudes of power step and for power set point decrease and increase. The simulation results are shown in figures 2a and 2b for the DFIM and FSFC technology respectively. In figure 2, the speed of the unit and the guide vane opening are shown, as well as the active power at the grid connection point. Power decrease results in a speed rise that is later restored to the nominal speed set point by the action of the turbine speed governor. Similarly, for power increase, a speed decrease first happens followed by the recovery of the nominal speed set point.

Table 1- Response time of power set point decrease and increase, for DFIM and FSFC

Set point initial value (MW)	Set point final value (MW)	(pu)	Power step magnitude (MW)	(pu)	ramp time decrease (s)		ramp time increase (s)	
					DFIM	FSFC	DFIM	FSFC
210	189	0.9	21	0.1	< 0.1	< 0.1	< 0.1	< 0.1
210	168	0.8	42	0.2	7	< 0.1	7	4
210	130	0.6	80	0.4	14	< 0.1	14	11

From table 1 it could be noticed that for power decrease, the response time are improved significantly when FSFC is used as compared to DFIM, because the upper speed limitation is higher for FSFC than

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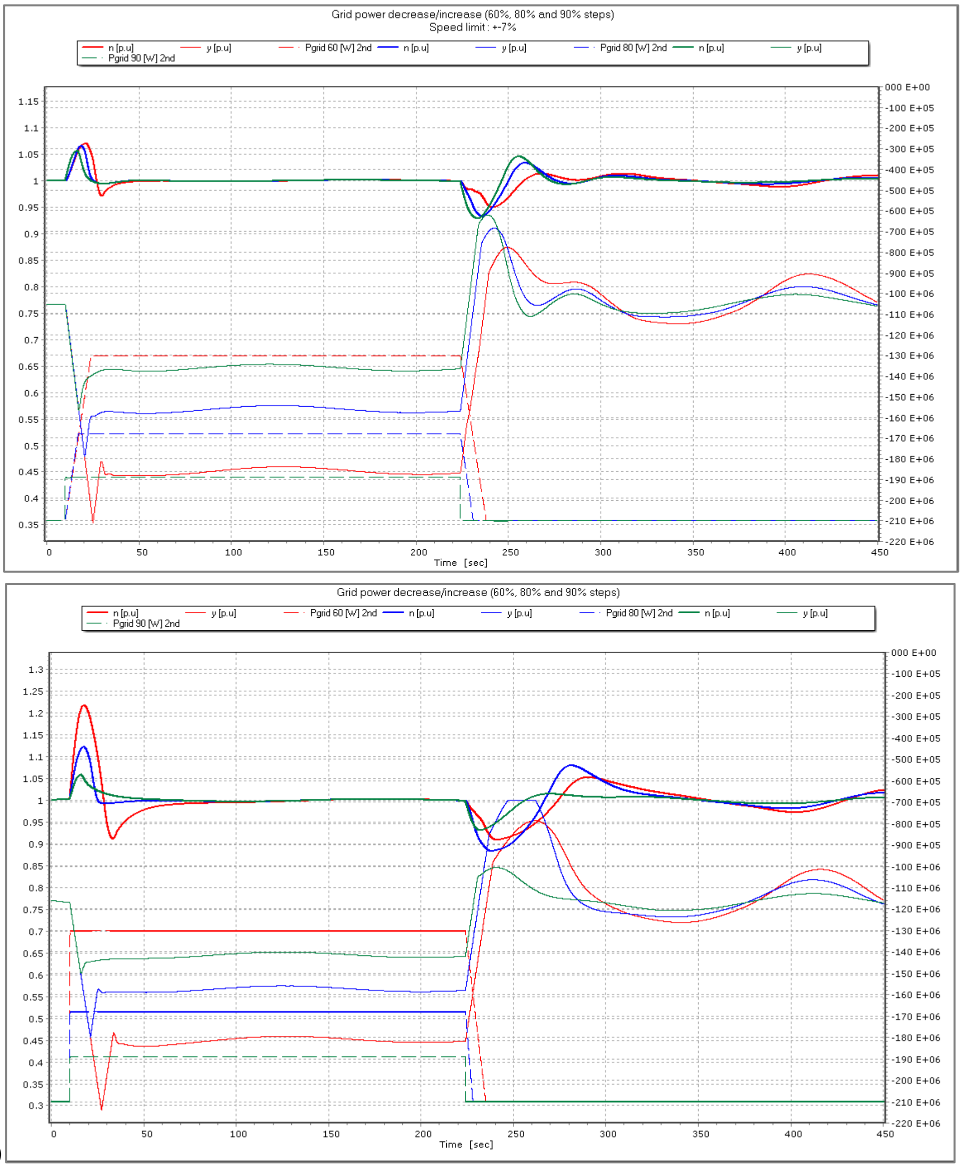
for DFIM. Hence, for FSFC, the power decrease considered here, up to -0.4pu, can be performed instantaneously. A power set point ramp is considered instantaneous when it is in the order of hundreds of millisecond or below, when this is the power converter that imposes this minimal ramp time, which depends on its current controller's dynamic and on its maximum output voltage. For DFIM, only small steps (~ -0.1 pu) can be performed instantaneously. Larger step decrease in DFIM mode require to ramp the power set point change to comply with the upper limit of rotational speed, which is approximately linearly dependant on the power step size, as it can be observed in table for DFIM for the step magnitude -0.2 and -0.4 pu. For DFIM, it can be seen that the response time for a given step size is similar for the power decrease as for the power increase for the three load case considered, mainly because the speed range is symmetrical.



a)

b)

Figure 2 - Simulated transient responses of power set point decrease/increase, for DFIM (a) FSFC (b), unit's speed, guide vane opening ad converter output power

For power set point increase, the situation is still better with FSFC than for DFIM but not as good as for power step decrease. Indeed the improvement in the response time of FSFC compared to DFIM is about 2/3 faster. Although there is no lower limit for the speed in FSFC mode, the fly-wheel effect cannot be fully exploited in power increase because of the maximum torque that the turbine can deliver. Indeed, for a given constant power at the grid, the lower the speed decreases, the higher the torque to apply in order to recover the speed set point. Hence, the maximum torque that the turbine can deliver is quickly reached, which can be clearly observed in figure 2, where the guide vane opening reaches the maximum value and stays saturated for a few seconds. Imposing a quicker power ramp would lead to unstable behaviour of the pump-turbine unit, as the speed governor will not be able to recover the speed set point. The stronger oscillations observed on the speed transient for power set point increase than the one observed for power set point decrease are due to this limited accelerating torque.

5. Conclusions

This paper presents simulation results of a hydro-electrical model of a 2x210MW variable speed pumped-storage power plant, considering in two different variable speed technologies: DFIM and FSFC. The simulated load cases are changes of the active power set point of the generating unit. The shortest ramping time of the set point changes are tight to resulting transient responses on speed and penstock pressures respect the hydro-mechanical constraints. It could be highlighted that using FSFC can globally improve the response time of the power plant compared to DFIM, in particular for power decrease. It was also highlighted that despite the converters fast response time, the speed range, the turbine torque characteristic as well as the penstock pressure limitation restricts the improvement of response time offered by variable speed technologies. For the considered case study, the maximum power set point change that can be performed quasi instantaneously is 0.1 pu. For larger step magnitude, a response time of about 10s is a was obtained for a set point change of magnitude ±0.4pu, which is still an improvement compared to a fixed speed technology. However, it should be mentioned that higher active power steps have been found for other case studies, with about 0.2 pu achieved within less than 0.2s. see [4], [5]. Therefore, it is important to mention that the maximum active power step that can be achieved with variable speed technology strongly depends on the hydro-mechanical characteristics of the pumped storage power plant, and thus has to be carefully evaluated on a case by case basis at early stage of a project using detailed simulation model.

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