Operation ranges and dynamic capabilities of variable-speed pumped-storage hydropower

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Abstract. The development of renewable and intermittent power generation creates incentives for the development of both energy storage solutions and more flexible power generation assets. Pumped-storage hydropower (PSH) is the most established and mature energy storage technology, but recent developments in power electronics have created a renewed interest by providing PSH units with a variable-speed feature, thereby increasing their flexibility. This paper reviews technical considerations related to variable-speed PSH in link with the provision of primary frequency control, also referred to as frequency containment reserves (FCRs). Based on the detailed characteristics of a scale model pump-turbine, the variable-speed operation ranges in pump and turbine modes are precisely assessed and the implications for the provision of FCRs are highlighted. Modelling and control for power system studies are discussed, both for fixed- and variable-speed machines and simulation results are provided to illustrate the high dynamic capabilities of variable-speed PSH.

1. Introduction

Up to now, PSH has mainly consisted in large fixed-speed reversible pump-turbines driving or being driven by a grid-connected synchronous machine. The power in turbine mode is varied at the expense of efficiency by controlling the flow in the machine while the power is fixed in pump mode. The best efficiency point (BEP) corresponds to different speeds in pump and turbine modes, resulting in a loss in efficiency as the machine is operated at the synchronous speed.

In the last decades, developments in power electronics have enabled the supply of electrical machines with variable-frequency voltages, resulting in the possibility to vary the speed of PSH plants. Large machines, of more than 50 MW, use a doubly-fed induction machine (DFIM) with a power converter rated to only a few percent of the nominal power while smaller machines use a synchronous machine with a full size power converter [1, 2, 3].

This variable speed possibility can be used to always operate the hydraulic machine at its BEPs, as these are related to different speeds in pump and turbine modes, thereby increasing the revenues from price arbitrage on the energy markets. Sometimes the variable speed becomes a necessity in order for the pump mode to support high head variations and be able to operate between its stability and cavitation limits [1]. Besides, the increased head range improve the use of basins' capacity. Another option is to use of the variable speed to provide transmission system operators (TSOs) with ancillary services, in particular primary and secondary frequency control,

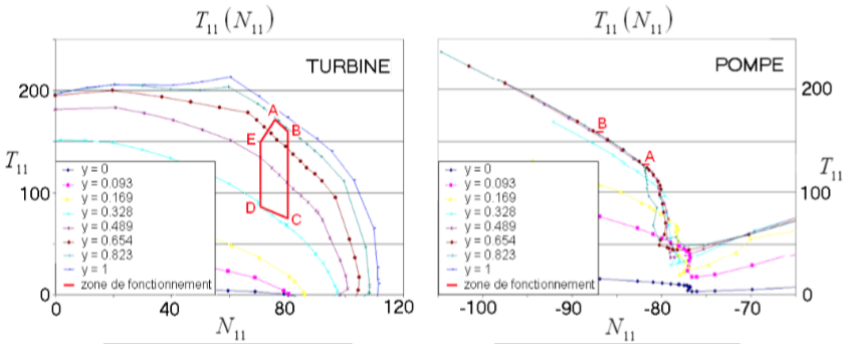


Figure 1: Characteristics and operation ranges of the studied pump-turbine, as found in [9].

both in pump and turbine modes. These services consist in adjusting power injections/offtakes in real-time, so as to keep the balance between electricity generation and consumption, which imposes high technical requirements on power plants, as these must have a range of power within which injections/offtakes can continuously and rapidly be varied.

Several authors have emphasized that a significant share of PSH revenues could be achieved through the provision of ancillary services [4, 5]. While these studies aim to give an overview of PSH, they fail to provide important technical details regarding the variable-speed operation of PSH to provide ancillary services. Economic calculus is often based on rather vague assumptions regarding the operation range of PSH [2], while it is also noticed that control aspects and dynamic capabilities are not well known. Besides, hydro turbine models and control schemes traditionally used in power system studies [6, 7, 8] have become inappropriate for variable-speed units.

This paper aims to clarify the technical capabilities of variable-speed PSH, and to put in light state of the art control schemes and transient modelling for power system studies.

2. Operation range of variable-speed PSH

The detailed characteristics of a Francis pump-turbine are given in [9]. These characteristics are obtained from laboratory measurements on a scale model by varying the head H, for different wicket gate positions y, while the rotational speed N is kept constant and measurements of discharge Q and torque T are made, which gives measurement vectors (y,N,H,Q,T). The measurements are then provided as charts giving the relations between unit speed N_{11}, unit flow Q_{11} and unit torque T_{11}. The operation ranges are also provided [9], and indicated on the T_{11}-N_{11} charts, as shown in Figure 1. In turbine mode, the limitation of the operation range is mainly due to several flow phenomena taking place in the hydraulic machine [10]. The A-B and C-D limits are defined by the manufacturer in order to avoid discharge ring swirl cavitation. Indeed, at high and low discharge, a swirling flow appears at the runner outlet, with eventually cavitation at its center, in which case it is referred to as vortex rope. The whirl dynamics compromises the machine's operation stability, since it is the main source of pressure fluctuations in the hydraulic installation. The B-C and D-E limits are set to respectively avoid leading edge pressure- and suction-side cavitation as it can lead to a severe erosion of the blades. Finally, the A-E limit is set by the rating of the electrical generator. In pump mode, the operation range is limited by lower and upper N_{11} bounds, i.e. higher and lower head values, to respectively prevent suction- and pressure-side cavitation on the runner blade [3, 10]. In addition, the operation range is limited by another upper N_{11} bound, corresponding to the pump's stability limit [3].

The power P_m associated to each measurement can be derived from the unit numbers using the following relation:

$$P_m = \frac{2\,\pi\,N\,T}{60} = \frac{\pi}{30}\,H^{3/2}\,D_{ref}^2\,N_{11}\,T_{11} \tag{1}$$

with D_{ref} the pump-turbine's reference diameter. Given N_{11}, Q_{11} and T_{11} numbers, e.g. those associated with the BEP or the operation limits, one has just to set two variables among D_{ref}, N, Q, H, T and P_m in order to define a pump-turbine, i.e. to derive its diameter and operation ranges in terms of head, flow and power. Given a nominal rotational speed of 675 RPM, and a maximum mechanical power of 2 MW in pump mode, one can derive the corresponding head and reference diameter, 93.04 and 1.2413 m respectively. It can be shown that at given head, the variable-speed feature provides the pump mode with a non-zero power range, while the turbine mode does not see its power range affected. The variable speed enables both modes to operate at lower heads. Besides, the extent of the power range varies with head, both in pump and turbine modes, and can precisely be quantified using 1 and the ranges of Figure 1, i.e. substituting in 1 the extreme values that can be taken by N_{11} and T_{11}. Using this methodology, it is found that given a head, the allowed power range is 24 and 53 % of the maximum allowed power at that head, respectively for the pump and the turbine modes. The maximum allowed power depends on the available head. The lower the available head, the lower the maximum allowed power. The fact that the power range varies with head is crucial for the provision of FCRs. Indeed, as the level of water varies with time, so does the available power range and the amount of FCRs that can be provided. Whether in pump or turbine mode, the amount of FCRs that can be provided by a pump-turbine should be computed based on the minimum operation head. Besides, variable-speed PSH must be operating rather far from the zero output to be able to provide FCRs, which implies frequent switches from pump to turbine, and vice versa. Energy market implications significantly impact the revenues of variable-speed PSH providing FCRs.

3. Transient modelling of PSH for power system studies

3.1. Hydraulic model

Various models can be used to study transients in hydropower plants. Although most of them are dedicated to hydraulic turbines, those models can be adapted/generalized to pumps and pump-turbines. They most often consist in the combination of a model for the water column, in the penstock, with the characteristics of the turbomachinery, which can be with or without guide vanes. The water column is generally considered either elastic or inelastic and is modelled, in the former case, through a first-order dynamic model. The characteristics of the hydraulic turbine is static, i.e. non-dynamic, meaning that it does not consist in differential equations. The characteristics can be represented through two classes of models. First, several models, linear or non-linear, have been developed for small to medium deviations around an operating point [6, 7, 8]. Those models target hydraulic machines operated at fixed or nearly fixed speed, i.e. those connected to the grid through a synchronous machine with no power electronics converter. In the second class of models, the turbine is considered through its detailed characteristics [9, 11, 12], i.e. interpolation curves joining various operation points, as in Figure 1. Those models are suited for the study of large variations in operating conditions, as variations in rotational speed. Modelling the water column and coupling it to the characteristics of the turbomachinery, as is done in [9, 11] but not in [12], enables to account for water hammer phenomena resulting from variations in guide vane position and/or rotational speed.

3.2. Control scheme

Reference [6] describes a governor for fixed-speed hydraulic machines, enabling the control of power thanks to the wicket-gate position Y. It implements a droop characteristics whose stability is ensured by a low transient droop. This scheme should be different for variable-speed machines. In pump mode, power should be controlled, thanks to the variable speed, while in turbine mode, power can be controlled through rotational speed and/or wicket gate position. In [13], power in turbine mode is controlled through Y while the variable speed enables to completely dampen power oscillations normally resulting from changes in Y. In [9], two control

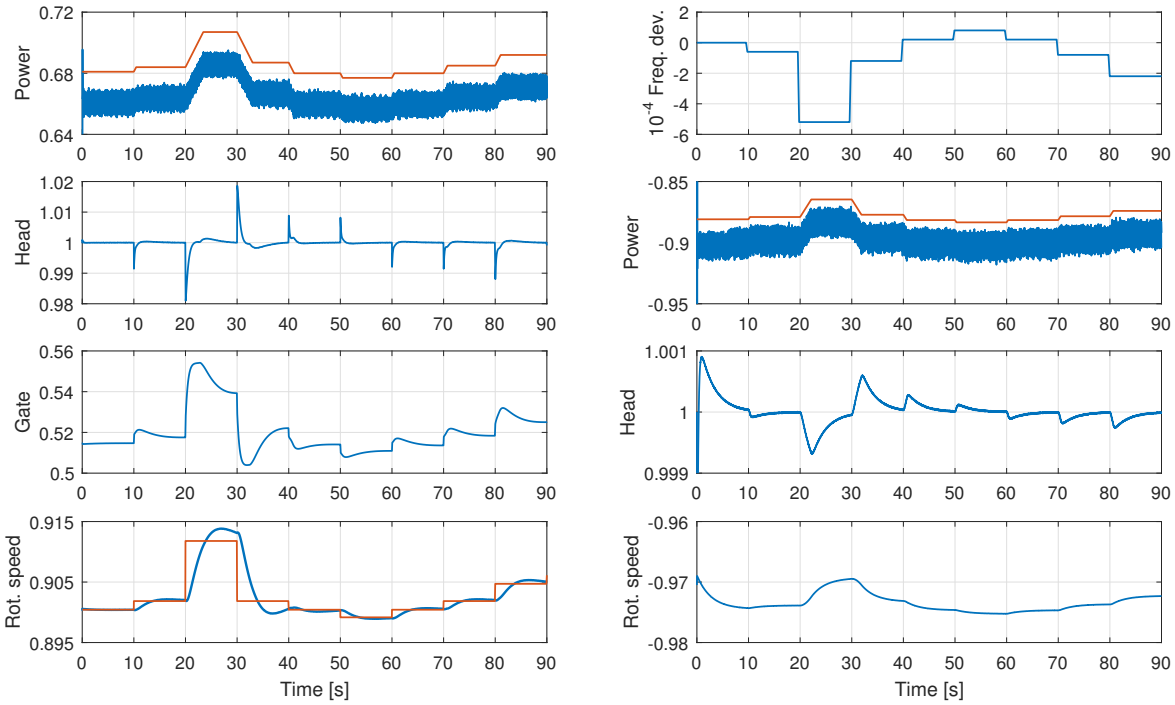


Figure 2: Transient operation of variable-speed PSH in turbine (left) and pump (right) modes for the provision of FCRs. All values are given in per unit. Red curves are reference signals.

strategies are proposed in turbine mode, which consist in (i) controlling power thanks to the wicket gate position, while speed control enables to optimize the efficiency and (ii) controlling power through the electromagnetic torque while varying the wicket gate position to optimize the efficiency through the rotational speed. It is shown that the second strategy, which goes one step further than [13] through efficiency optimisation, implies much faster dynamic response. This strategy is definitely the best suited for the provision of ancillary services. Whether it is in [9] or in [13], no information is given on the methodology followed for tuning the speed controller.

In order to design the control in speed for the turbine mode, transfer functions linking the guide vanes position to the rotational speed have to be established. An approximate transfer function is therefore needed for the turbine characteristics. Besides, this transfer function should be linear in order to be able to use linear control theory to design the speed controller.

3.3. Simulation results

A PSH case has been set up in *MATLAB/Simulink* in order to illustrate the dynamic capabilities brought by the variable speed. The hydraulic model consists of a rigid water column coupled to the pump-turbine characteristics of Figure 1. On the electrical side, a permanent magnet synchronous machine (PMSM) is fed by two-level voltage source inverters (VSIs) in back-to-back configuration with a DC link. The power converter is connected to an infinite medium-voltage bus through a short distribution line. The goal of the simulation is to observe the dynamics of the whole system while the PSH unit is providing FCRs with a control scheme developed as explained in the previous subsection. Simulation results are given in Figure 2. Based on requirements imposed by the Belgian TSO, an active power reference is derived from the 2013

frequency deviation measurements at ten-second time steps. FCRs are provided for an amount equal to 20 and 12.5 % of the pump rated power, respectively in turbine and pump modes. For both modes, the results show that power injections can effectively be varied to follow a power reference for the provision of FCRs. Mismatches between power injection and reference are around two percentage points and are explained by losses in the electrical machine, the VSIs and the distribution line. In turbine mode, speed control through guide vanes position is effective. Variations in guide vanes position induce water hammer effects. The latter are reduced in pump mode, where guide vanes are kept fixed and power is controlled through the VSIs.

4. Conclusion

Compared to their fixed-speed counterparts, variable-speed hydraulic machines are able to operate over wider head ranges. For a given head, the variable speed allows power variation in pumping, while a unique power is possible at fixed speed, but leaves the power range unchanged in turbine mode. Variable-speed PSH is thus able to provide FCRs both in pump and turbine modes. The operation ranges are limited to prevent undesired flow phenomena. Given a head, the studied pump-turbine's allowed power range spreads 24 % and 53 % of and from the maximum allowed power at the given head. In absolute values, these ranges vary with head, which impacts the amount of FCRs that can be provided. Besides, the continuous provision of FCRs requires PSH units to constantly be operating far from the zero output, which implies frequent switches from pump to turbine and vice versa. The energy market consequences should be taken into account when assessing the revenues of variable-speed PSH providing FCRs.

Modelling and control for power systems studies have been discussed, both for fixed- and variable-speed machines. A variable-speed PSH model has been set up based on the detailed characteristics of a Francis pump-turbine, a rigid water column, the dynamic model of a PMSM, a short impedance line and two two-level back-to-back VSIs. In pump as in turbine mode, power control has been achieved through the VSIs. The guide vanes position has been kept fixed in pump mode while its adjustment enabled speed control in turbine mode. Simulation results have shown the high dynamic performances of variable-speed PSH, in line with FCR requirements.

5. Acknowledgments

The paper was made in the frame of SmartWater, a project supported by the Walloon Region.

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