Identification of Dynamic Simulation Models for Variable Speed Pumped Storage Power Plants

C Moreira[1], N Fulgêncio[1], B Silva[1], C Nicolet[2] and A Béguin[2]

[1] INESC TEC – INESC Technology and Science, Porto, Portugal
[2] Power Vision Engineering, Ecublens. Switzerland

Abstract. This paper addresses the identification of reduced order models for variable speed pump-turbine plants, including the representation of the dynamic behaviour of the main components: hydraulic system, turbine governors, electromechanical equipment and power converters. A methodology for the identification of appropriated reduced order models both for turbine and pump operating modes is presented and discussed. The methodological approach consists of three main steps: 1) detailed pumped-storage power plant modelling in SIMSEN; 2) reduced order models identification and 3) specification of test conditions for performance evaluation.

1. Introduction

Pumped Storage Power (PSP) plants are expected to play a key role for handling the operation of electrical power systems with increasing shares of New Renewable Energy (NRE) sources (such as solar and wind) which are characterized by high variability and uncertainty [1]. Currently there exist 270 PSP stations worldwide (a combined capacity of 120 GW) and the vast majority of these plants employ a conventional setup based on reversible single-stage Francis pump-turbines [2]. An important drawback of these existing schemes is the prominent use of fixed-speed pump-turbines. Although the traditional fixed-speed design has worked well for many decades, there are inherent limitations which significantly reduce PSP plants ability to contribute to the balancing of the rapidly-varying output of NRE and ancillary services provision, especially when operating in pumping mode.

In response to these limitations, variable-speed machines have been a technological option that mostly rests on two main technological solutions: variable speed technology through the a Doubly-Fed Induction Machine (DFIM) or a synchronous generator connected to the grid through a Full Size Frequency Converter (FSFC). In order to study the PSP plants integration and operation in electric power systems, dynamic and transient stability studies are required. In fact, a wide range of models with different levels of complexity, capable of representing different operational conditions, have been developed and are widely accepted for the characterization of the dynamic response of hydro power plants, though only when equipped with fixed-speed units [3]. For the specific case of the variable-speed PSP technology, the associated dynamic models capable of representing the main dynamic response, both in turbine and pump operation modes, are not widely available and are not properly validated. A few references [4]–[6] can be found in the literature addressing some control issues of the power electronic interfaces in variable speed PSP, though without providing a global model that can be used in dynamic stability studies of large electric power (and operating as a generator or as a pump). Therefore, this paper aims at providing new contributions within the scope of variable speed PSP plant dynamic modelling, both for pump and turbine operating modes. The proposed models are extensively validated in coordination with detailed simulation results that were obtained from SIMSEN, a specific software package for hydro units simulation [7]. Additionally, the approach for model validation relies on the real hydraulic configuration of an existing 2x210 MW PSP plant.

This work was developed in the framework of the HYPERBOLE project – HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies – grant agreement number 608532, financed by European funds through the 7th RTD Framework Programme.

2. System Modelling

This section provides an overview regarding the modelling approaches for PSP plants that are used in SIMSEN as well as the reduced order model that was entailed to represent the variable speed PSP, which was assumed to use a DFIM.

2.1. Hydro-mechanical and DFIM modelling in SIMSEN

The SIMSEN simulation package is used here as a reference software in order to develop and perform detailed simulation of a PSP plant. Next sections introduce the hydro-mechanical and the DFIM electrical systems models implemented in SIMSEN. Both hydro-mechanical and electrical models are combined in a unique model – the hydro-electrical model of the hydro power plant, [6].

2.1.1. Hydro-mechanical system: The SIMSEN model of the hydraulic system of a PSP plant includes the following elements: an upper reservoir with constant water level, two sub-horizontal square sections intake pipes, upstream gates, two vertical circular pressure shafts, two reversible Francis pump-turbines, linked to the rotating inertia of the turbine and of the generator rotor, downstream pipes, two downstream surge tanks, a downstream junction and tailrace tunnel, a lower reservoir with constant water level and the turbine governor. Regarding the SIMSEN hydraulic model, it is important to mention it takes into account: the water hammer phenomena in piping systems (pipe distributed head losses, water inertia and pipe elastic behaviour – fluid compressibility and wall deformation); the 4 quadrants transient behaviour of the pump-turbine including so-called S-shape unstable characteristics and the link with rotating inertias [6]; the surge tank mass oscillations phenomena between the lower surge tanks and the lower reservoirs 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 inertia linked through coupling shaft with given torsional stiffness.

2.1.2. DFIM electrical system: In the DFIM variable speed technology, a wounded rotor induction machine is fed by a back-to-back voltage source converter. Controlling the rotor current via the inverter control enables to achieve variable speed of the electrical machine with respect to the rated synchronous speed. The model developed in SIMSEN includes the representation of the induction machine with wound rotor, slip recovery cascade with rotor and grid side converters as well as the cascade transformer, and the unit step-up transformer, see [6].

2.2. Reduced order models for hydro-mechanical systems and DFIM

Regarding variable speed PSP plants modelling, turbine and pumping operation modes needs to be taken into account. Since these modes have distinct ways of control and operation, it was considered to develop different dynamic models for each case. Therefore, modelling the transitions from turbine to pump or vice-versa is out of the scope of this paper (however, it can be conveniently analysed using the full model in SIMSEN).

2.2.1. Turbine operation mode: IEEE standard models [3] for hydro turbines and its controls usually allow a direct separation between the turbine speed governor and the hydraulic system dynamics, which is the same approach that was also used in this work. The representation of the hydraulic system in the reduced modelling approach was based on the non-ideal turbine general expression given in [8], which relates gate opening and mechanical power variations around a given operating point. Due to the high dependence of the model parameters in relation to the machine characteristics and operational point, an approach relating the penstock coefficients to the ideal lossless model was used. This model constitutes the main approach that was used to represent the hydro dynamics for the turbine operation mode, once it is easy to handle in terms of simulation integration in power system studies.

2.2.2. Pump operation mode: Contrary to what happens in turbine mode, when the hydro unit is operating in the pump mode, there is no significant effect of the gate opening in the control of the system operation. Therefore, pump-turbines are typically operated with constant guide vane opening set for the best efficiency during pump operation. When variable speed machines are considered, the operation of the unit in pump mode is typically based on the control of the active power (which can be achieved by the control of the rotor side converters in DFIM-type units). Consequently, there is a direct effect on the unit speed and discharge, that must be taken into account in the model development. In order to model the different hydraulic components, a possible modelling approach is based on the use of an electrical analogy, where pressure is analogous to voltage and discharge is analogous to electric current [6]. This approach, applied to a simplified PSP system, is represented in Figure 1, being its mathematical formulation represented by the following equations: $H_0 = L_p \cdot \frac{\partial Q}{\partial t} + R_p \cdot Q + H_{pt}$ and $J \cdot \frac{\partial \omega}{\partial t} = T_{pt} + T_{el}$. In this sense, the hydraulic resistance R and the hydraulic inductance L correspond to energy losses and hydraulic inertia, respectively. The system comprises an upstream reservoir, a penstock and a pump-turbine linked to a rotating inertia then connected to a downstream reservoir. The upper reservoir is modelled with a constant pressure source through the reservoir gross head (H_0) and the penstock is modelled considering water inertia and head losses effects respectively modelled by hydraulic inductance L_p and hydraulic resistance R_p. The pump-turbine is modelled by a pressure source $H_{pt}(Q, \omega)$ (net head) driven by the associated 4-quadrant characteristic curve (knowing the pump-turbine discharge Q and rotating speed ω), while the guide vane opening is assumed to be constant. As the pump-turbine characteristic shows a typical S-shaped curve, it leads to numerical problems when interpolating between points of the curve (due to the multiple values problem). To overcome this numerical problem, the so-called Suter polar representation is used [6]. In this mathematical representation, the swing equation allows to derive the unit rotational speed, as far as the hydraulic torque T_{pt} is derived from the pump-turbine characteristics (as a function of the rotational speed and discharge), being T_{el} the electromagnetic torque from the DFIM and J the combined inertia of the system (hydraulic part and rotor of the DFIM).

2.2.3. DFIM model: A phasor modelling approach is used to represent the DFIM. The electric machine is represented by a transient model based on a voltage source being a transient reactance [9], being the mechanical part represented by a single-mass model (rigid shaft). Regarding the converters operation and control in the DFIM, a phasor model was also used, in line with the approach that is followed in SIMSEN.

3. Control Strategies for Variable Speed PSP

The control strategies used in variable speed PSP units are the same both for SIMSEN detailed modelling and the reduced order models. Regarding the turbine operation mode (see Figure 2), when a power set-point change is requested to the PSP plant, (for example, resulting from the action of the frequency controller) it can be directly used at the machine power converters to control the active power output. The power set-point can be also used at the "speed optimizer" to define the most efficient speed reference at which the machine should operate. In order to have better compatibility conditions between detailed simulation to be performed in SIMSEN and reduced order models it was adopted the same type of turbine governors in both cases. In the specific case of the variable speed unit, as a result of the improved performance it usually demonstrates, a PID-type governor with a feed-forward power-to-gate control action was adopted [6]. Its main block diagram is presented in Figure 3. The main parameters of the PID-type governor are: the unit permanent droop (R_p, (p.u. MW)/(p.u. rad.s^{-1}), the tachometer time constant (τ_ω), the proportional, integral and derivative constants (K_p, T_i and T_d, respectively) and the filter time constant T_{filter}. The output of the PID governor is limited in amplitude (gate position limits between 0 and 1.p.u.), but also in the gate opening/close speed limit rate (U_o, U_c). The main function of the turbine governor is to control the guide vane opening in response to turbine speed or power variations. By controlling the opening or closing of the guide vanes it performs a primary speed/load control. The normal approach to this type of governing systems consists in modelling the action of a servomotor, by eliminating the speed error feedback from the machine using a permanent and a transient droop feedback and/or a PID or a PI controller. Regarding the pump operation mode, and as already referred, gate opening control has only slightly influences on the efficiency of the PSP plant. Therefore, the control strategy of the unit consists on the active power control through the VSC converters, being the speed defined through the characteristic curves of the unit. A general overview about the corresponding block diagram is presented in Figure 4.

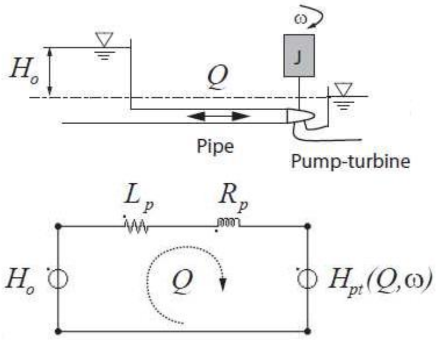


Figure 1. Reduced hydraulic model description used to represent pumping mode operation.

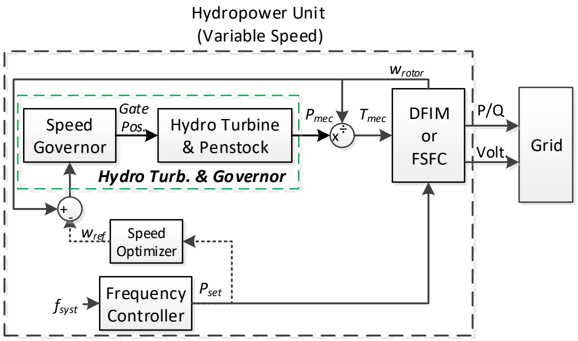


Figure 2. Functional block diagram for of a variable speed hydro unit – turbine operation mode

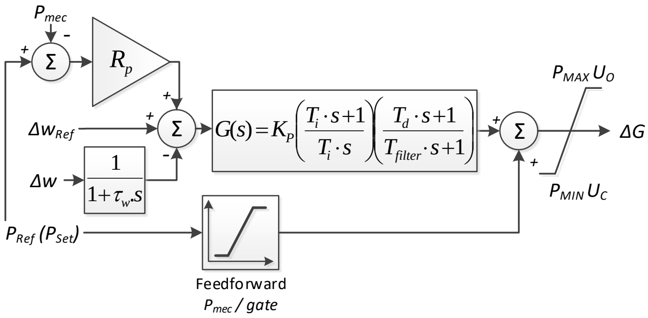


Figure 3. PID-type speed governor for variable speed PSP plant.

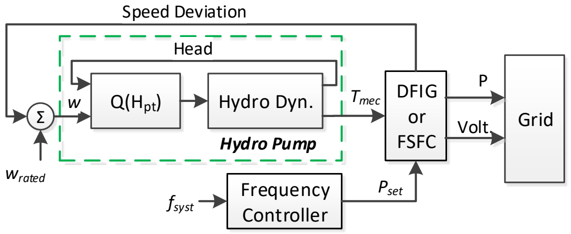


Figure 4. Functional block diagram for a variable speed hydro unit – pumping mode.

4. Test case and simulation results

To perform the derivation and validation of reduced-order models of PSP units, a detailed model was implemented in the dedicated simulation platform of SIMSEN. The highly detailed approach that was followed, considering the necessary hydraulic phenomena and its associated behaviour, was then compared with the developed models implemented exploiting the software MATLAB/Simulink®. Electric models and their parameters, the hydraulic governors and control strategies for voltage source convertors in variable speed units were kept equal between both approaches. The PSP plant considered for the test case is based on an existing 2x210MW power plant equipped with reversible Francis pump-turbines. The key characteristics of the hydroelectric scheme are summarized in Table 1 referring to the original fixed speed configuration with synchronous generators.

Table 1. Test case PSP plant original hydroelectric scheme characteristics.

Number of units	2	50 Hz	Frequency
Total installed capacity	421 MW	400 kV	Voltage at the connection point
Total discharge in pumping mode	350 m3/s	420 MVA	Total rated apparent power
Total discharge in turbine mode	266 m3/s	15 kV	Generator’s stator line voltage
Maximum gross head	148 mWC	15	Generator’s poles pair
Penstock length	260 m	200 rpm	Generator’s rotational speed

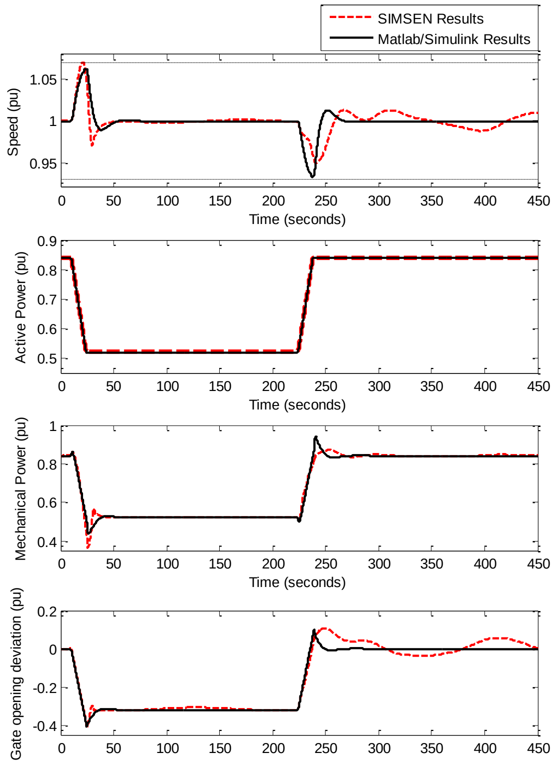
The simulations were based on a single pump-turbine unit, the other being at rest. The validation procedure consisted then in studying the operation in turbine and pump operation modes, comparing the response of both detailed and reduced order models. The representativeness of the reduced order models was validated based on the pre and post disturbance values, as well as response times and associated magnitude.

4.1. Turbine operation mode

To perform the reduced-order models validation, the following test condition was specified, in the turbine operation mode: *unit operating at the nominal power conditions* ($P_{elec} = 210\ MW$)*, followed* *to a step load reference reduction to* $P_{elec} = 130\ MW$ *and back to* $P_{elec} = 210\ MW$ *after a suitable time for unit stabilization.*

A critical issue of the DFIM operation is related with the unit speed deviation resulting from the load change. To preserve rotor converters' control capabilities, the unit needs to keep its speed within a given band. Therefore, a ±7% speed deviation range around the nominal value was considered, which was achieved by the introduction of ramp rates that limited the active power to the grid. To comply with this requirement, it was necessary to identify appropriated ramp rates to the prescribed load step (controlled through the active power control loop implemented in the rotor-side converters). For the specified test conditions, the ramp time was set to 14 s.

As it is depicted in Figure 5, a very good agreement between reduced-order and detailed models is achieved, being possible to state that a good degree of representativeness was obtained. As expected, some oscillations can be observed in the speed and gate opening in the detailed solution, which results from the detailed modelling of a downstream surge tank, not reproduced in the reduced order model.



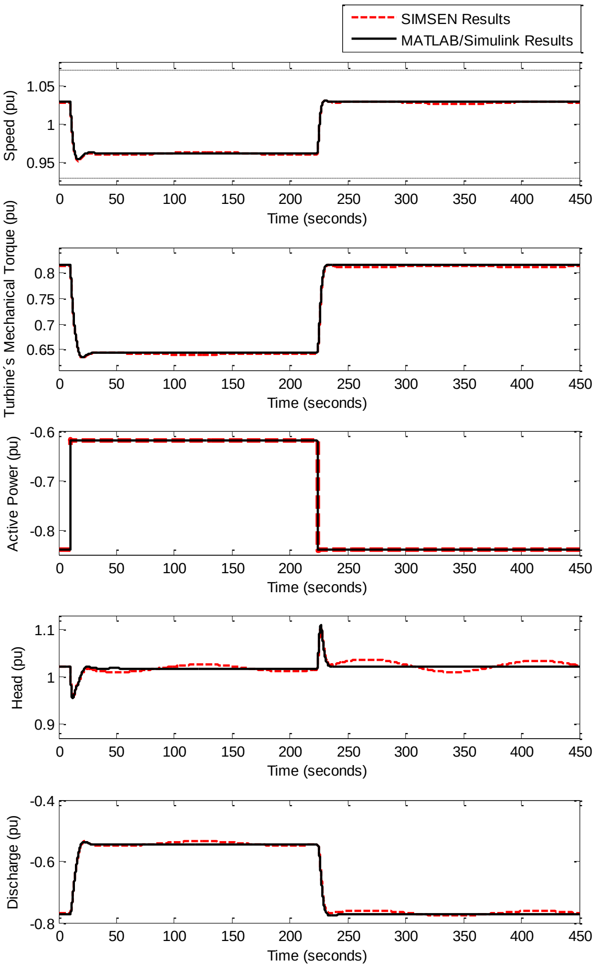


Figure 5. Turbine operation mode: comparison between the SIMSEN and the Matlab/Simulink® simulation results for a PSP plant with a DFIM.

Figure 6. Pump mode: comparison between the SIMSEN and the Matlab/Simulink® simulation results for a PSP plant with a DFIM.

4.2. Pump operation mode

The ability of proving power variations while operating in the pump mode is a distinctive feature of variable speed PSP plants. In line with the previous test case, the following test condition was considered: *unit operating at the nominal power conditions* ($P_{elec} = -210\ MW$)*, followed by a step load reference reduction to* $P_{elec} = -155\ MW$ *and back to* $P_{elec} = 210\ MW$ *after a suitable time for unit stabilization.*

The simulation results are presented in Figure 6 and feature a very good agreement in terms of rotational speed and active power, even if the head and discharge fluctuations related to the downstream surge tank are not reproduced. It should be mentioned that due to short penstock length, the inertia effect of the penstock is dominant as compared to penstock elasticity effects, especially when the hydro unit controllability is concerned, while for long penstocks, the elasticity effect and the related water hammer phenomenon has to be considered, [3] and [4]. Nevertheless, from the power system stability perspectives, good simulation results can be obtained with reduced simulation model of the hydraulic system for pumping mode provided that the model includes penstock inertia and realistic pump characteristics.

5. Conclusions

Following the integration of new PSP technologies in electric power systems (along with the integration of NRE), specific studies are required to evaluate system stability with respect to different grid disturbances and considering different operational scenarios. Though dynamic simulation models of different sources have been defined for many decades, defining a well-established base for most of the available generation technologies, the specific case of the new PSP technology is not widely available. Particularly when considering new variable speed technologies, the associated dynamic models are generally not capable of representing the main dynamic response either in turbine and pump operation modes. In this sense, the work presented in this paper provides important contributions regarding the identification and validation of variable speed PSP plants dynamic models, both for pump and turbine operating modes. The proposed models are validated in several operating conditions, considering different load changes and relying on existing PSP data. Such approach provides a solid background on the extensive validation of the proposed models with respect to its future use in electric power system studies involving large disturbances requiring significant changes in the units' power output. The process described provides the necessary confidence for model exploitation in system studies where these type of units are expected to have a key role in important grid services, such as the participation in the frequency containing reserve or synthetic inertia to the system.

Acknowledgments

The authors would like to thank Mr. Johann Hell from ANDRITZ Hydro GmbH, Partner of the Hyperbole EU project, for his contribution in the definition of the DFIM solutions considered in this paper.

References

[1] M. A. Hozouri, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, “On the Use of Pumped Storage for Wind Energy Maximization in Transmission-Constrained Power Systems,” *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 1017–1025, Mar. 2015.

[2] J. P. Deane, B. P. Ó Gallachóir, and E. J. McKeogh, “Techno-economic review of existing and new pumped hydro energy storage plant,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 4, pp. 1293–1302, 2010.

[3] E. De Jaeger, N. Janssens, B. Malfliet, and F. Van De Meulebroeke, “Hydro turbine model for system dynamic studies,” *IEEE Trans. Power Syst.*, vol. 9, no. 4, pp. 1709–1715, 1994.

[4] C. Nicolet, B. Greiveldinger, J. J. Herou, B. Kawkabani, P. Allenbach, J.-J. J. Simond, and F. F. Avellan, “High-order modeling of hydraulic power plant in islanded power network,” *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1870–1880, Nov. 2007.

[5] A. C. Padoan, B. Kawkabani, A. Schwery, C. Ramirez, C. Nicolet, J. J. Simond, and F. Avellan, “Dynamical behavior comparison between variable speed and synchronous machines with PSS,” *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1555–1565, 2010.

[6] Y. Pannatier, B. Kawkabani, C. Nicolet, J. J. Simond, A. Schwery, and P. Allenbach, “Investigation of control strategies for variable-speed pump-turbine units by using a simplified model of the converters,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3039–3049, 2010.

[7] SIMSEN, “Simulation software for the analysis of electrical power networks, adjustable speed drives and hydraulic systems.” [Online]. Available: http://www.powervisioneng.ch/Simsen_hydro/MainFeatures/SIMSEN_leaflet_14_detailed.pdf.

[8] P. Kundur, N. J. Balu, and M. G. Lauby, “Power system stability and control.” p. 1176, 1994.

[9] R. G. de Almeida and J. A. P. Lopes, “Participation of doubly fed induction wind generators in system frequency regulation,” *Power Syst. IEEE Trans.*, vol. 22, no. 3, pp. 944–950, 2007.