Pumped Storage Hydropower Plants Modeling in the Power Systems Research

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Abstract: Renewable energy sources (RES) will play an essential role in the future of the power systems because they can provide several benefits including reducing dependency on the fossil fuels market e.g. oil and gas and their price fluctuations, reducing emission of greenhouse gases, and climate change improvement. Among different RESs technologies, the highest share in the electricity production belongs to the hydropower systems which can be divided into the three main categories: run of river, storage, and pumped storage. In this paper, important techniques for modelling the pumped storage hydropower plants are presented and compared with simulation results in the MATLAB/Simulink program. According to the results, selecting proper modelling technique depends on the aim and outlook of the study. Finally, a powerful laboratory setup named power hardware in the loop (PHIL) system as a very useful laboratory equipment for power systems studies is introduced for verifying the simulation results and analyzing the real electrical quantities instead of pure simulation study.

Keywords: Pumped storage hydropower, Renewable energy sources, Power systems

1 Introduction

Global warming and climate change are very important topics in the current century. Increasing the population and developing process lead to higher energy consumption. Fossil fuels (oil, gas, coal) are main sources of energy production at the moment and they provide a large amount of CO_2 which is one of the famous greenhouse gasses. It seems that these gasses are responsible for global warming, air pollution, and climate change. Therefore, one possible way to control climate change and its effects is reducing emission of the greenhouse gasses. It means that clean and renewable energy sources have to be used instead of fossil fuels to provide energy in different areas. In the power systems, experts try to increase the share of RESs in the electricity production. Famous RESs in the power systems are hydropower, wind, and photovoltaic (PV) systems which have different benefits and challenges for the power systems. For instance, wind and PV systems can increase uncertainty in the power systems since they are dependent on weather conditions. However, hydropower, specially, pumped storage hydropower (PSH) plants are reliable RESs and they will play a vital role in the future power systems. Figure 1 presents the share of RESs in the electricity market in 2019 [1]. According to international energy agency (IEA), electricity production from hydropower will increase from 4333 TWh in 2019 to 5722 TWh in 2030 [2]. Hydropower has many advantages such as clean and renewable source of energy, flexibility, reliability, energy storage and backup source (green natural battery) to support uncertainty of wind and PV, and multi-functional applications (including water management, irrigation, water supply, flood control, recreation, and transportation).

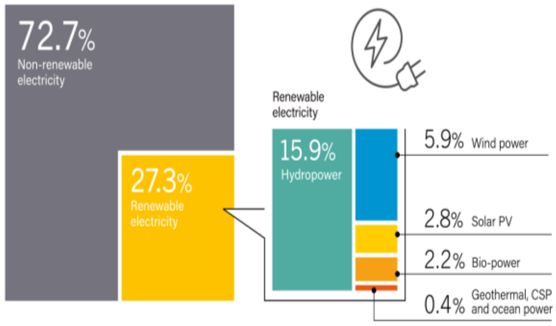

Figure 1: Estimated renewable energy share of global electricity production in 2019 [1].

Hydropower can be divided into three categories: run of river, storage, and pumped storage hydropower (PSH) systems. In the run of river and storage systems, water flow and also energy conversion (mechanical energy to electrical energy) are unidirectional, however, pumped storage units have bidirectional water flow in addition to bidirectional mechanical-electrical energy conversion. In other words, when PSH unit works in pumping mode, it receives electrical power and convert it to mechanical power to pump the water; and when it works in turbine mode, it provides electricity from water energy. One drawback of conventional PSHs is that they need several minutes to be ready to connect to the power systems, or changing the pump-turbine mode. However, with the new technology achievement as variable speed (adjustable speed) PSH, it is possible to reduce the preparation time of these units to one minute which enables us to use them for crucial tasks such as fast transient response and very fast power provision for the grid. Moreover, variable speed PSHs have higher efficiency for large head variation and also, they need less maintenance, have less cavitation and longer life span. The global PSH installed capacity in 2019 was 158 GW and it is predicted to be 240 GW by 2030 [3].

In the hydropower systems, turbine has a significant role. Generally, turbine is a mechanical equipment which provides rotational movements from kinetic or potential energy of the water. Table 1 shows turbine types and their subcategories and applications based on the available head [4]. Among these turbines, Francis and Pelton turbines are more common in PSH applications. Another important equipment of the PSH unit is the electrical machine which can work as a motor and generator in the pumping and turbine modes of PSH unit, respectively. The most common electrical machine in the conventional storage and PSH units is electrically excited synchronous machine (EESM) which has several benefits such as controlling the output terminal voltage and reactive power exchange, in addition, this type is suitable for variable speed PSH units, as well. Besides, doubly fed induction machines (DFIM) are well-known electrical machines in variable speed applications such as wind and variable speed hydropower plants. In recent years, hydropower industry pays more attention to variable speed PSH units since they can be promising technology for the future power grid based on high share of RESs. According to the International Hydropower Association (IHA): "*No country has come close to achieving 100 % renewables without hydropower in the energy mix*" [5]. To conduct research on the PSH, it is necessary to consider a reliable and exact model to gain more realistic results from simulation and calculations. In the power systems field, there are standard models for dynamic studies of electrical equipment such as electrical machines, transformers, transmission lines. Then it is important to implement a proper model for hydraulic parts regarding the purpose of the investigation to achieve an accurate outcome. Consequently, two main models for penstock and waterway are presented and their differences are compared afterward.

Table 1: Classification of hydropower turbines [4].

Head classification	Impulse	Reaction	Gravity
High (>50 m)	• *Pelton* • *Turgo*	• *Francis*	
Medium (10-50 m)	• *Crossflow* • *Turgo* • *Multi-jet Pelton*	• *Francis*	
Low (<10 m)	• *Crossflow* • *Undershot Waterwheel*	• *Alden* • *Propeller* • *Kaplan* • *Francis* • *Bulb* • *Straflo* • *Free-flow*	• *Overshot Waterwheel* • *Pitchback Waterwheel* • *Breastshot Waterwheel* • *Archimedes Screw*

The rest of this paper presents modeling approaches for dynamic of penstock and waterway. Then simulation results and discussion regarding modelling techniques are presented. Finally, conclusion and future steps to improve and compare the simulation results with real quantities are explained.

1.1 Modeling Approach for dynamic of Penstock and Waterway

PSH unit has various hydraulic parts including upper reservoir, lower reservoir, penstock, waterway (tunnel), surge tank, and pump-turbine. Penstock and waterway are important parts which they have dynamic behavior due to water elasticity and this dynamic behavior depends on the physical properties of them such as length of them. If PSH units have common waterway/penstock, this hydraulic interconnection leads to more dynamic interaction between units which is also visible in the electrical network. There are two famous methods for modeling the penstock and waterway: one is by considering the elastic behavior of water and another is non-elastic (rigid) model for the penstock and waterway. Following equations from ref. [6] demonstrate elastic water column dynamics in the separated penstock and waterway of the fig. 2:

$$H_c = H_{s1} - Z_{ht} Q_c \tanh(sT_{et}) \tag{1}$$

$$H_d = H_{s2} + H_c \operatorname{sech}(sT_{ep}) - Z_{hp} Q_d \tanh(sT_{ep}) \tag{2}$$

$$Q_c = Q_d \cosh(sT_{ep}) + \frac{1}{Z_{hp}} H_d \sinh(sT_{ep}) \tag{3}$$

$$Q_d = \frac{1}{Z_{hp}\tanh(sT_{ep})}(H_s - H_d) - \frac{Z_{ht}\tanh(sT_{et})}{Z_{hp}\tanh(sT_{ep})} Q_c \tag{4}$$

H_c : Dynamic head at the junction of Tunnel and penstock(s)

Q_c : Dynamic flow at the junction of Tunnel and penstock(s)

H_d : Dynamic head established by Pump-Turbine unit(s)

Q_d : Dynamic flow established by Pump-Turbine unit(s)

H_s : Total available static head (H_{s1} + H_{s2})

H_{s1} : Static head between upper reservoir water surface and tunnel-penstock junction

H_{s2} : Static head between tunnel-penstock(s) junction and lower reservoir water surface

T_{et} , Z_{ht} : Elastic time and hydraulic impedance of the tunnel or waterway

T_{ep} , Z_{hp} : Elastic time and hydraulic impedance of the penstock

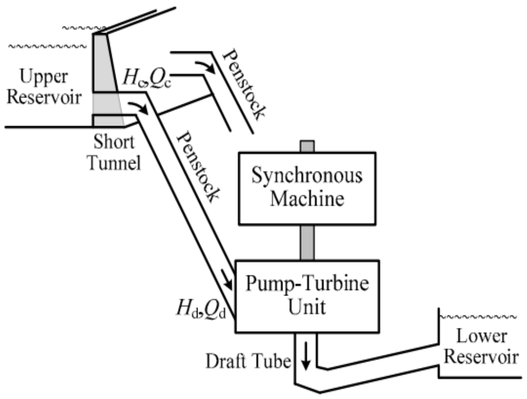

Figure 2: PSH unit with separate penstock and waterway, from ref. [6].

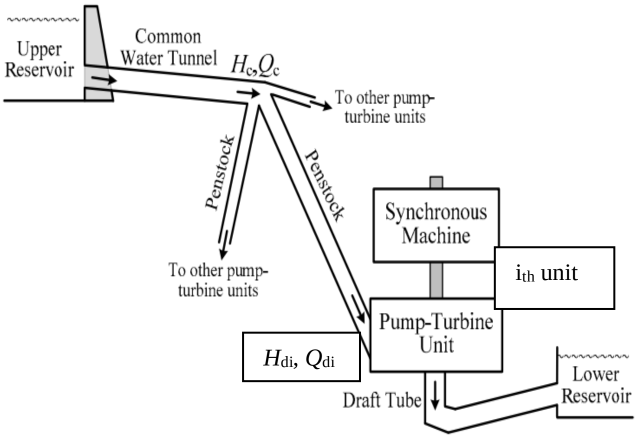

Figure 3: PSH units with common water tunnel, modified from ref. [6].

For PSH units with common waterway, the water flow (discharge) in the common waterway (tunnel) is the sum of water discharge in all penstocks connected to it. For example, if N units have common water tunnel such as fig. 3, dynamic flow in the i_{th} penstock and dynamic flow in the common water tunnel can be calculated by [6]:

$$Q_{\mathrm{di}} = \frac{1}{Z_{\mathrm{hp}}\tanh(sT_{\mathrm{ep}})}(H_{\mathrm{s}} - H_{\mathrm{di}}) - \frac{Z_{\mathrm{ht}}\tanh(sT_{\mathrm{et}})}{Z_{\mathrm{hp}}\tanh(sT_{\mathrm{ep}})}\,Q_c \tag{5}$$

$$Q_{\mathrm{c}} = \sum_{i=1}^{N} Q_{\mathrm{di}}\cosh\left(sT_{\mathrm{ep}}\right) + \frac{1}{Z_{\mathrm{hp}}}H_{\mathrm{di}}\sinh\left(sT_{\mathrm{ep}}\right) \tag{6}$$

Q_{di} : Dynamic flow established by the i_{th} Pump-Turbine unit

H_{di} : Dynamic head established by the i_{th} Pump-Turbine unit

As mentioned earlier, another method for modeling the waterway and penstock is non-elastic or rigid water dynamic consideration. This method neglects the traveling water wave effect in the waterway and penstock and simplifies the dynamic equations for head and flow. Rigid model of a separate waterway-penstock unit can be presented as [6]:

$$Q_{\mathrm{c}} = Q_{\mathrm{d}} \tag{7}$$

$$Q_{\mathrm{d}} = \frac{1}{(Z_{\mathrm{hp}}T_{\mathrm{ep}} + Z_{\mathrm{ht}}T_{\mathrm{et}})s}(H_{\mathrm{s}} - H_{\mathrm{d}}) \tag{8}$$

To compare the effect of different dynamic models for waterway and penstock, the electrical network in fig. 4 is simulated in MATLAB/Simulink software. The waterway, penstock, turbine, excitation and governor models and data are obtained from ref. [6]. Other parameters of the simulated system are presented in table 2.

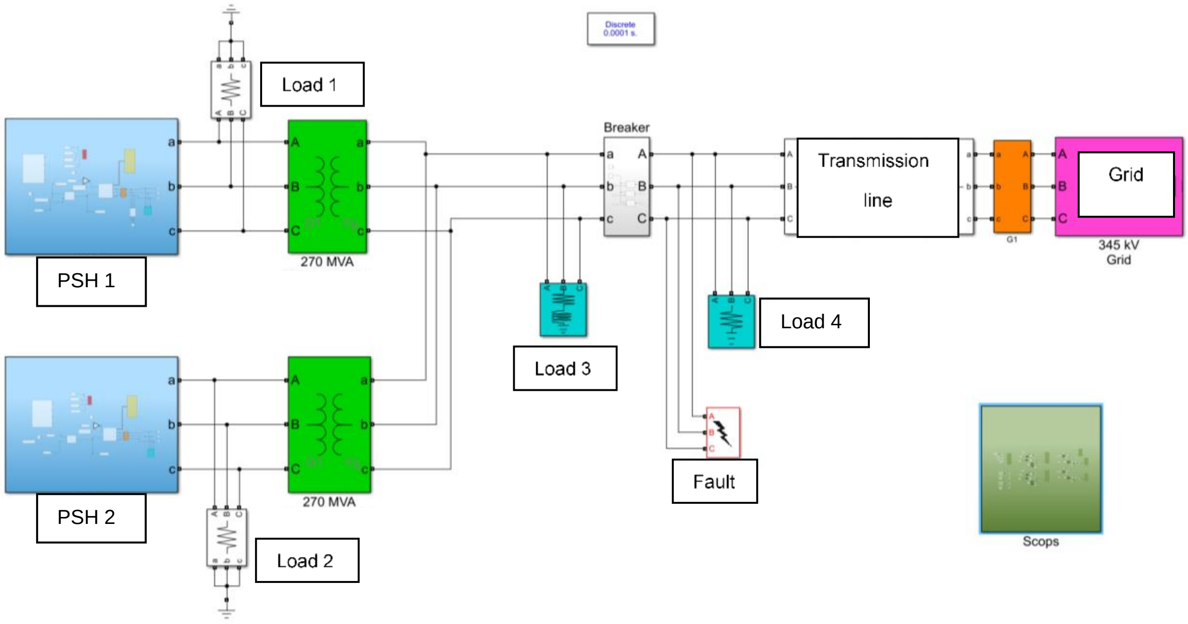

Figure 4: Simulated systems in the MATLAB/Simulink software.

1.2 Simulation Results and Discussion

The simulated systems of fig. 4 is considered for comparing elastic and rigid models of waterway and penstock, while all events and parameters are the same. In the simulated systems, there are two PSH units with common waterway and similar properties connected to the ideal grid through two step-up transformers and a transmission line. Several events are simulated for both modeling approaches to compare them. At t = 80 second (s), there is an unsymmetrical fault (line to line to ground-LLG) on the grid side terminals of the circuit breaker and it is cleared after 0.2 second. Next event is three phases to ground fault (LLLG) at t = 110 s for 0.2 second. Then the setpoint of power for the PSH unit 1 (PSH1) decreases by 0.8 pu at t = 120 s and then increases 0.8 pu at t = 150 s. Finally, at t = 200 s, another LLLG fault happens and causes tripping the circuit breaker and due to islanding situation, the power setpoints for both units reduce by 0.83 pu to match the local loads (Load 1, Load 2, and Load 3). Figure 5 and fig. 6 present the per-unit values for turbine heads, water flows, mechanical output power of turbines, and rotational speed of turbine-generator sets for bot units and for elastic modeling and rigid modeling, respectively.

According to the simulation result, changing the setpoint of power for one unit affects the water flow, turbine head, and turbine's output power of another unit because of the hydraulic coupling in the common water way. Since units are connected to strong (ideal) network, LLG and LLLG faults at t = 80 s and t = 110 s cause some fluctuations in turbine-generator speed (frequency). The more important behavior is related to the LLLG fault at t = 200 s and islanding situation afterward. Based on the fig. 5 and fig. 6, changes in the turbine heads and turbine-generator speeds are significant. As depicted in fig. 6, in the rigid model, the fluctuations and dynamic behavior of turbine head, water flow, and turbine output power is not visible after the first high peak. However, in elastic modeling (fig. 5), it is possible to observe the dynamic behavior of turbine head, water flow, and turbine output power in all time.

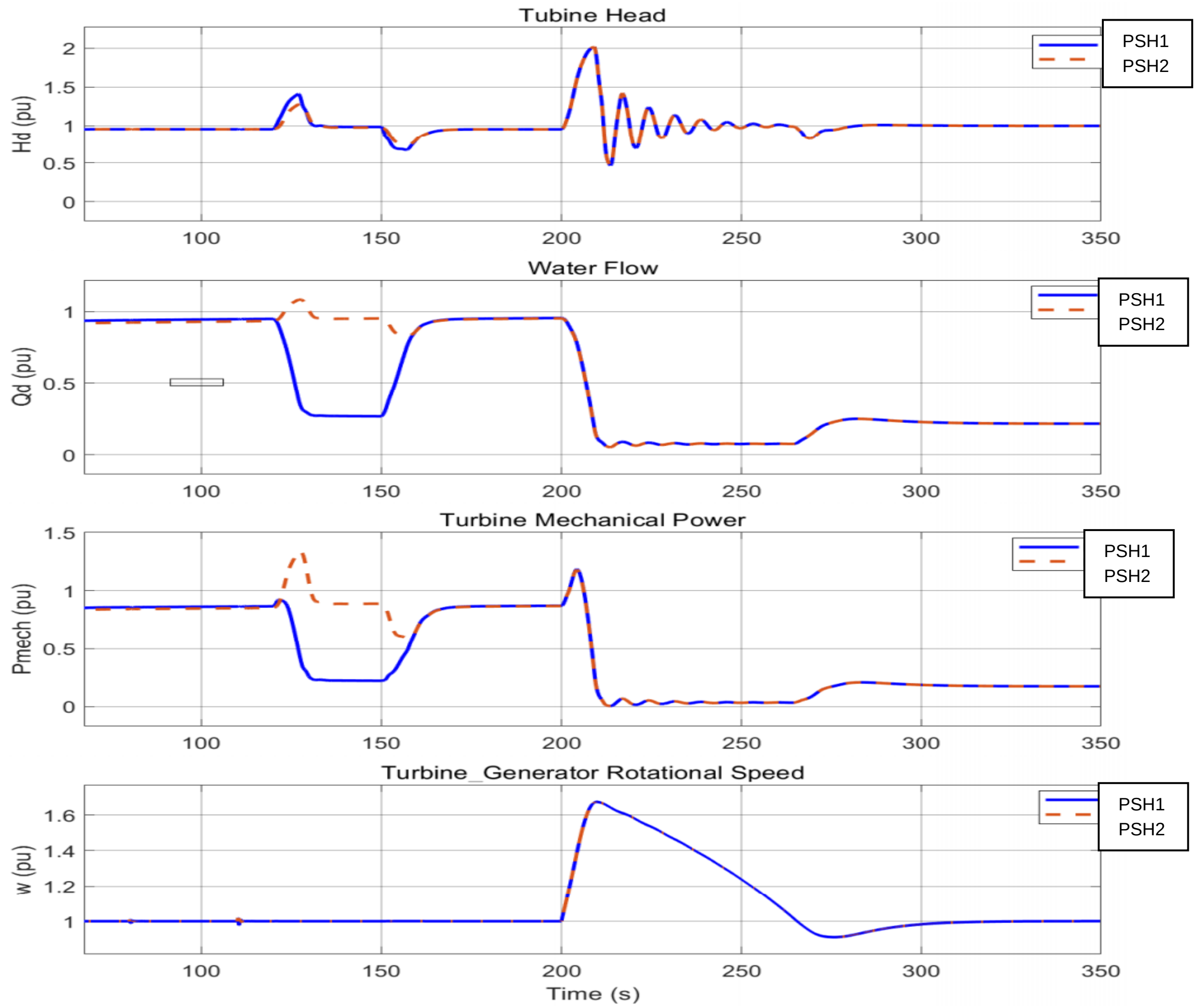

Figure 5: Simulation results for the elastic model of penstocks and common waterway

As a conclusion, rigid model is suitable for transient and short time (few seconds) dynamic studies and it reduces computational burden and calculation time. On the other hand, elastic model is proper for accurate and long term dynamic studies, however, it has more complex calculation and needs more calculation time

1.3 Conclusion and Future Steps

According to the simulation result, it is recommended to use rigid model for short term or transient studies, however, for long term dynamic studied, elastic model is recommended, though, it increases the complexity of the model and computational burden. To improve the accuracy of the model, it is useful to add the hill chart of the pump-turbine which is also important in the variable speed PSH studies. One of the significant aims as a future work is modeling and simulation variable speed PSH considering the hill chart of pump-turbine and combined control algorithm as depicted in fig. 7.

Another step is to observe the electrical behavior of the simulated system in real world which is possible by using power hardware in the loop (PHIL) laboratory set up depicted in fig. 8.

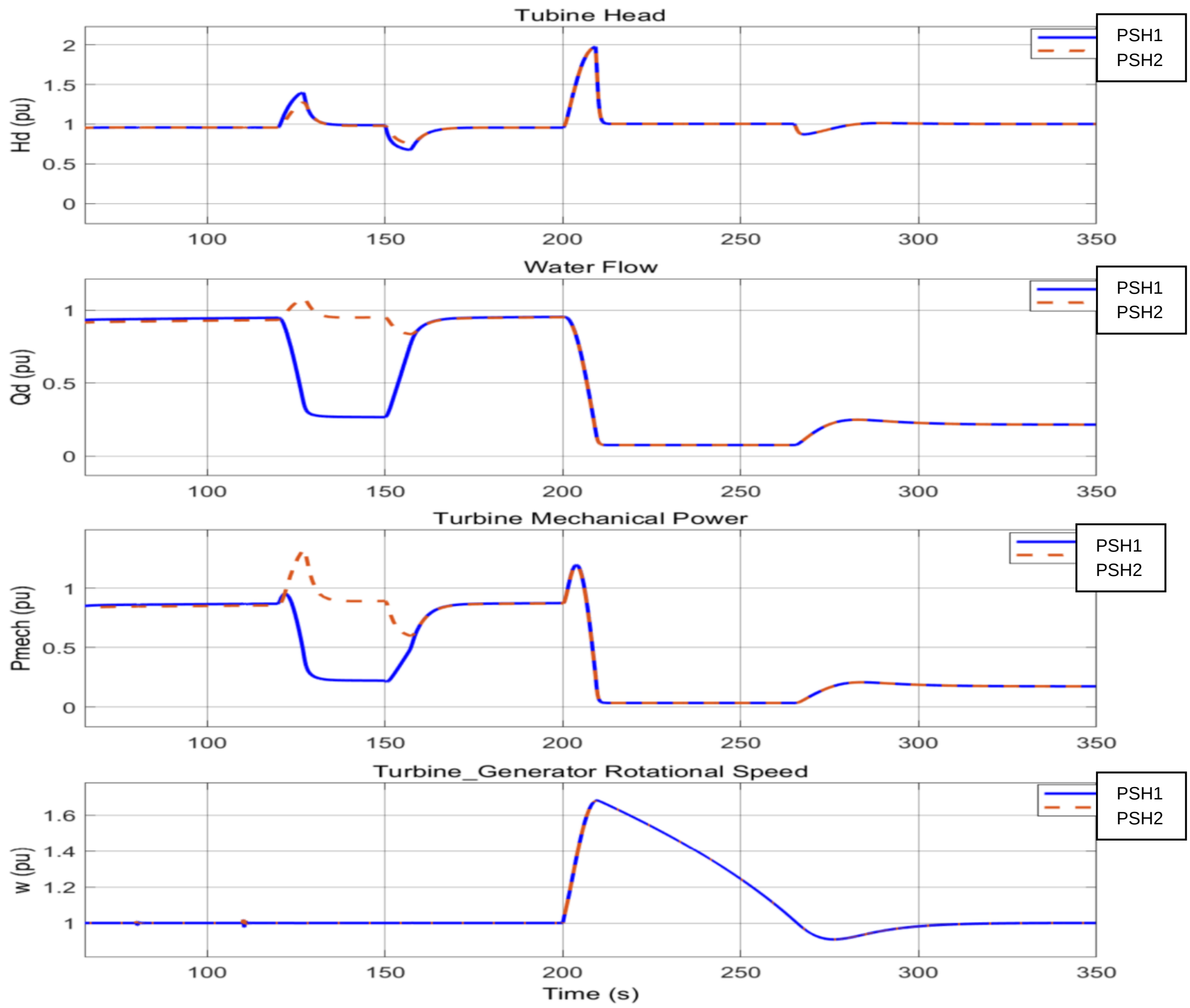

Figure 6: Simulation results for the rigid model of penstocks and common waterway

PHIL lab is a powerful tool to use as a scaling prototype for a wide range of research in the power systems. One example is to simulate dynamic behavior of different RESs and provide real electrical quantities e.g. voltages, currents, and frequency for further studies. With the help of PHIL lab, researchers are able to investigate performance and behavior of various equipment (power converters, electrical machines, RESs, control strategies) in the safe lab. The PHIL lab of the institute of electrical power systems at TU Graz includes two power amplifiers as electrical systems simulators, dSpace – SCALEXIO real-time system, back to back converter, loads, transformer, and measurement devices [7]. By using PHIL lab and elastic model of the waterway-penstock, we will be able investigate the behavior of variable speed PSH units considering different control strategies and events in the power systems.

Table 2: Properties of the simulated system

Load 1 = Load 2 = 20 MW; Load 3 = (40 MW + 20 Mvar lagging); Load 4 = 100 MW
Transformers: 270 MVA, 18/380 kV, YNd1, x =0.12 pu, r = 0.004 pu, 50 Hz
Synchronous Machines: 250MVA, 18 kV, 50 Hz, xd = 1 pu, xd' = 0.35 pu, xd" = 0.25 pu, xq = 0.7 pu, xq" = 0.23 pu, xl = 0.12 pu, rs = 0.002 pu, H = 3.5 s, pole-pairs = 6, Td' = 3 s, Td" = 0.08 s, Tq" = 0.08 s
Transmission Line: R = 0.5 Ohm, L = 0.025 H
Penstocks and Waterway: Z_{hp} = 2 pu, Z_{ht} = 1.5 pu, T_{ep} = 0.5 s, T_{et} = 2 s

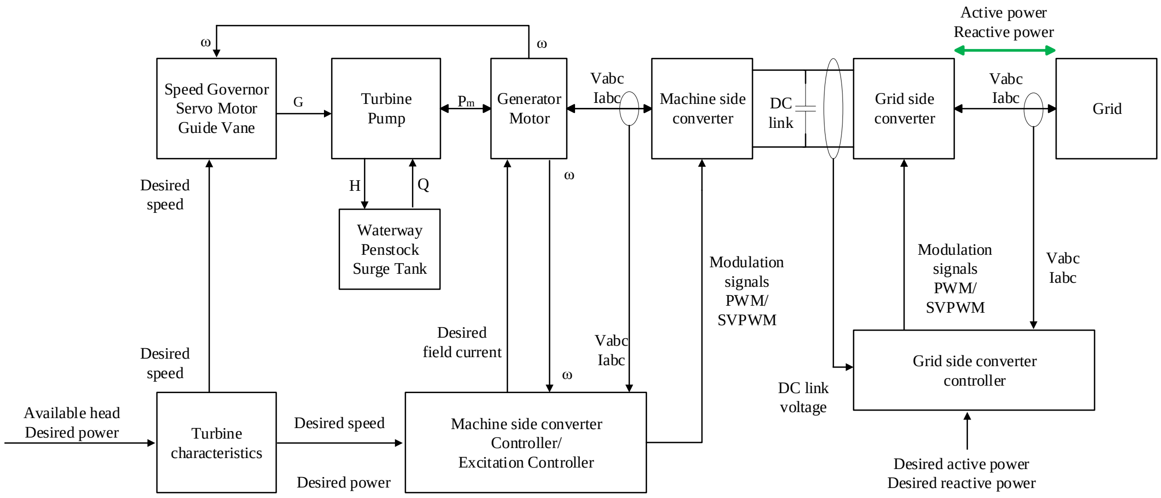

Figure 7: General concept for modeling and simulating a variable speed PSH.

Figure 8: PHIL lab equipment at the institute of electrical power systems, TU Graz [7].

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