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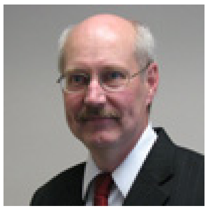
PSS®E Dynamic Simulation Models for Different Types of Advanced Pumped Storage Hydropower Units



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Introduction

In 2012, a project Team led by Argonne National Laboratory was awarded funding by the U.S. Department of Energy for a study: Detailed Analysis to Demonstrate the Value of Advanced Pumped Storage Hydropower in the U.S.

The Team members are:

- Argonne National Laboratory
- Siemens PTI
- Energy Exemplar, LLC.
- MWH Americas, Inc.
- National Renewable Energy Laboratory (NREL)

The project goal was to develop detailed models of advanced Pumped Storage Hydro (PSH) units to analyze their technical capabilities to provide various grid services, and to assess the value of these services under different market structures.

After reviewing the world experience in this field, two types of advanced PSH units were selected, namely:

1. Adjustable Speed PSH units employing a Doubly-Fed Induction Machine (DFIM)
2. Ternary PSH units

Both of these technologies are presently being applied in hydro plants around the globe.

Currently, no commercial software for power system stability study offers models for these technologies. These models are needed by ISOs, RTOs, transmission owners, developers and design consultants to evaluate the impacts of new advanced PSH projects on transient stability and to perform transmission interconnection studies, including:

- Transient stability
- Voltage control and reactive power control
- Primary fast frequency regulation – response to sudden generation/load imbalances
- Secondary slow frequency regulation (i.e., Automatic Generation Control or AGC)
- Compensation for changes in renewable generation

This article discusses the approach to modeling of advanced PSH units, provides a description of the newly developed models and presents the results of their testing. All models developed in the course of this project are written as user defined vendor neutral models. The intention is to make these models standard with the next PSS®E major release.

Modeling of Conventional PSH Plants

Conventional pumped storage hydro (CPSH) units have many similarities to conventional hydro plants. The major difference is that the flow is bidirectional. Usually, but not always, the same equipment is used for both generation and pumping; thus, the synchronous generator also operates as a motor, and the hydro turbine also operates as a pump. Both components are therefore reversible in their functionality. Some plants, particularly those with very high heads, may require separate turbines and pumps.

The system conditions being analyzed are appropriate for one mode or the other; for example, studies performed at peak load would model the units as generating while light load studies would model the units as pumping.

To represent the hydro units in pumping operation, the “governor” model for the motor must be different from the governor model used when generating. First, generally there is no speed regulation. The operator opens and closes the gates under manual control, and the gate position remains fixed. Second, the pump head is substituted in place of the static head. The pump head is a function of the water flow and can be described by a quadratic equation whose coefficients can be derived from pump characteristics provided in the specifications or determined by testing. If speed deviations during transient conditions are noticeable, the flow, head, and power of the pump should be adjusted.

Advanced PSH Technologies

1. Adjustable Speed PSH units employing a DFIM

The DFIM is shown schematically in Figure 1. It employs voltage source power converters utilizing fully controlled transistors. The rotor side converter can supply d and q components of rotor current that determine both active and reactive power at the unit’s terminals. The line side converter can not only transfer the active power from or to the rotor side converter, but can also control the reactive power injected or absorbed by the line side converter to or from the grid.

The approach to modeling DFIM power units was thoroughly investigated and tested for wind turbines with DFIM (type 3 wind machines). The modeling approach for the PSH units drew significantly from the knowledge gained from modeling these units.

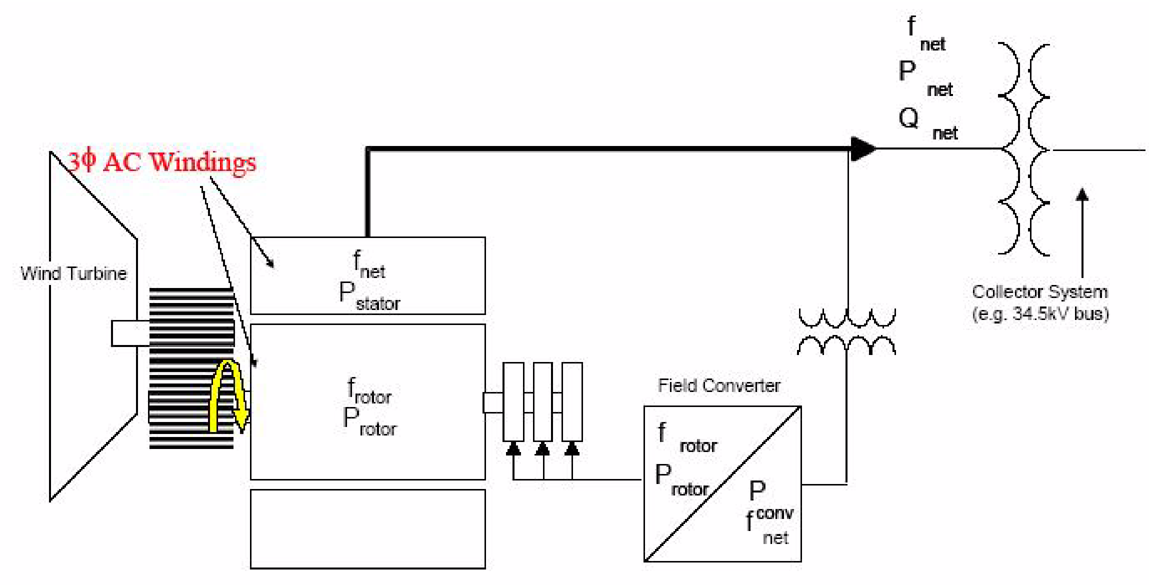


Figure 1 - Doubly Fed Induction Machine

The following two features of this technology make it attractive for developers and operators:

- Turbine and pump efficiency and operating range can be significantly improved by speed adjustment
- More flexible and fast controls due to a power converter. Probably, the most important in this regard is the fact that, due to an additional degree of freedom provided by a power converter, this unit, different from a conventional PSH unit, can participate in frequency regulation when pumping

2. Ternary PSH Units

A ternary pumped storage system is shown schematically in Figure 2. It consists of a separate turbine and pump on a single shaft with an electric machine that can operate as either a generator or motor without reversing the water flow direction.

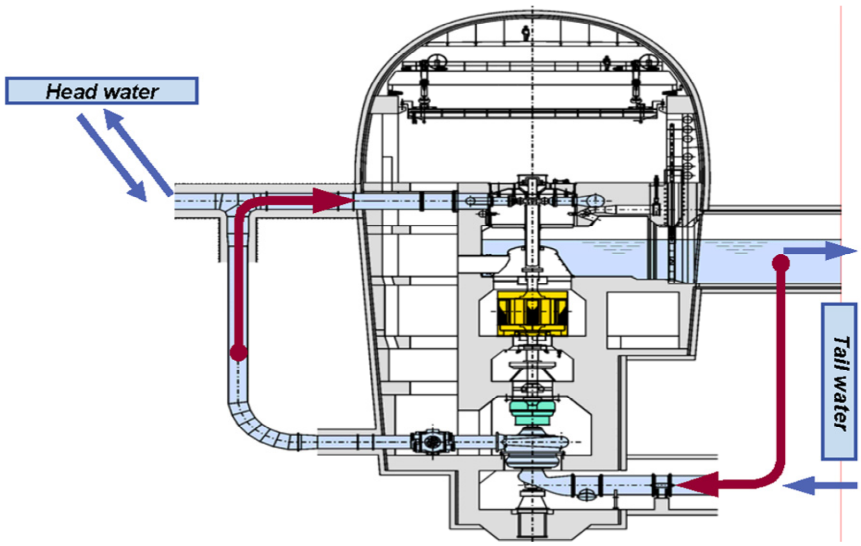


Figure 2 - A Ternary Power Unit
Source: Reference 1, Spitzer and Penninger (2008)

The ternary plant can simultaneously operate both the pump and turbine, referred to as a “hydraulic short circuit.” This is illustrated in Figure 3 where the 1000 MW plant is shown working as a pump, absorbing 500 MW net from the grid. The equivalent power flows are shown to illustrate effects of water flows.

This ability provides additional flexibility in the plant’s operation.

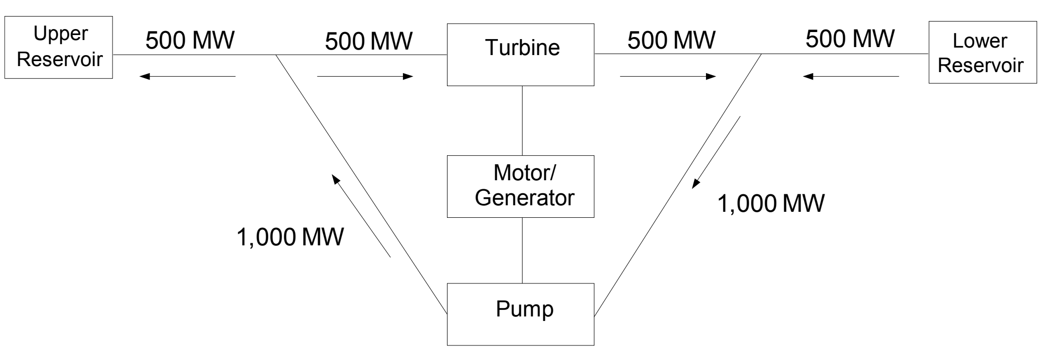


Figure 3 - A Ternary Power Hydro Unit Operating in the Hydraulic Short Circuit

Model for a PSH Unit Employing a DFIM

The model design drew heavily on the control structures described in a paper [2] written by engineers in Japan based on their experience with the 400 MW Adjustable Speed Pumped Storage Unit at the Ohkawachi Power Station.

Two controllable variables, gate position and speed, can be considered since for a DFIM, the speed of the machine is no longer locked to system.

Basic control approaches include:

1. **Fast Power Control** - The electrical power is controlled by the power converter and the rotating speed is controlled by the turbine governor adjusting the gate position
2. **Fast Speed Control** - The rotating speed is controlled by the power converter and the electrical power is controlled by the turbine governor adjusting the gate position
3. **A combination** of these

Investigations showed that Fast Power Control is a superior approach compared to Fast Speed Control and also superior to a unit with a synchronous machine.

Separate models for turbine and pump operation have been developed.

Modeling the Adjustable Speed PSH Turbine

The block diagram of the model for the adjustable speed PSH turbine employing a DFIM is shown in Figure 4.

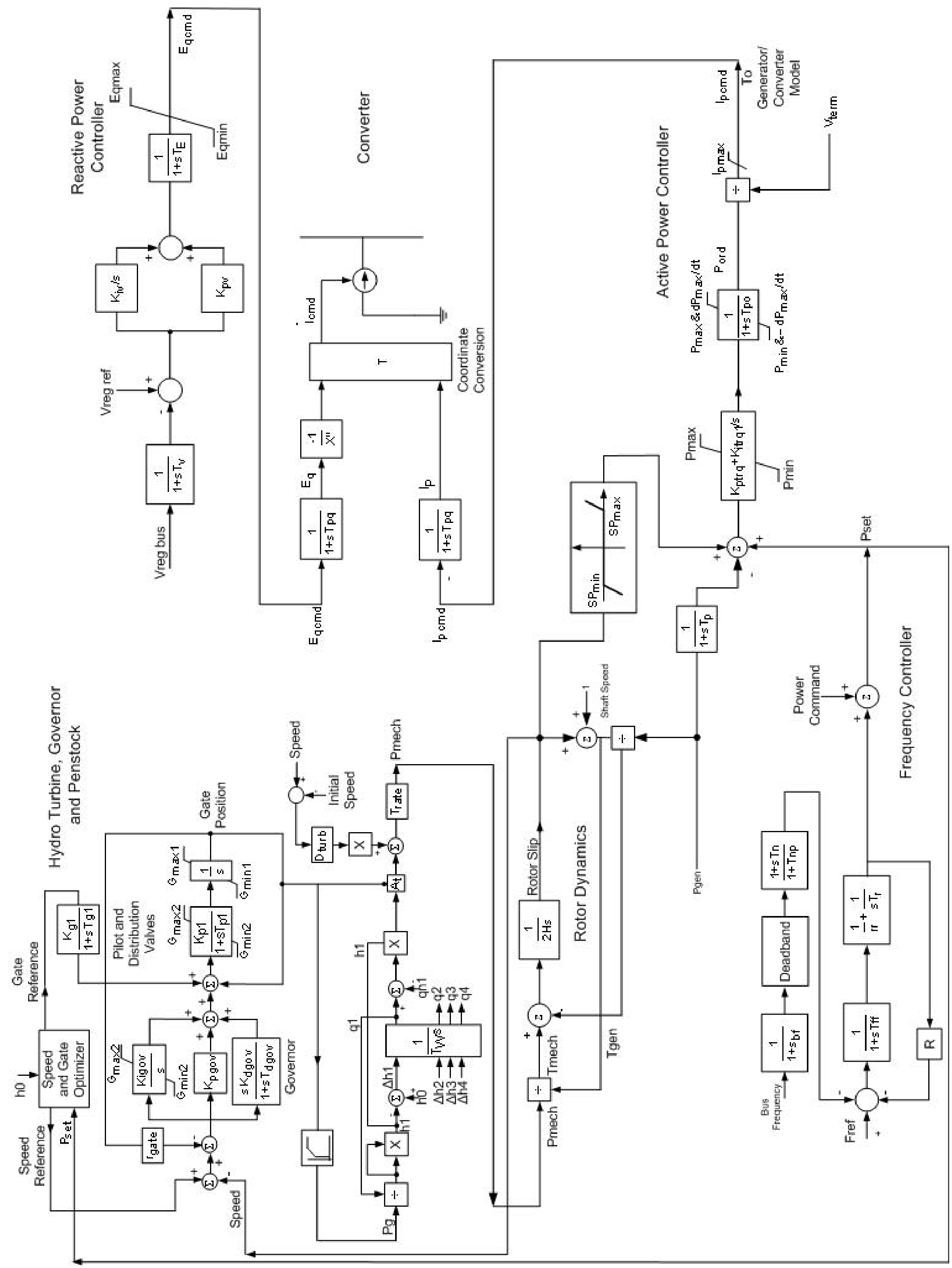
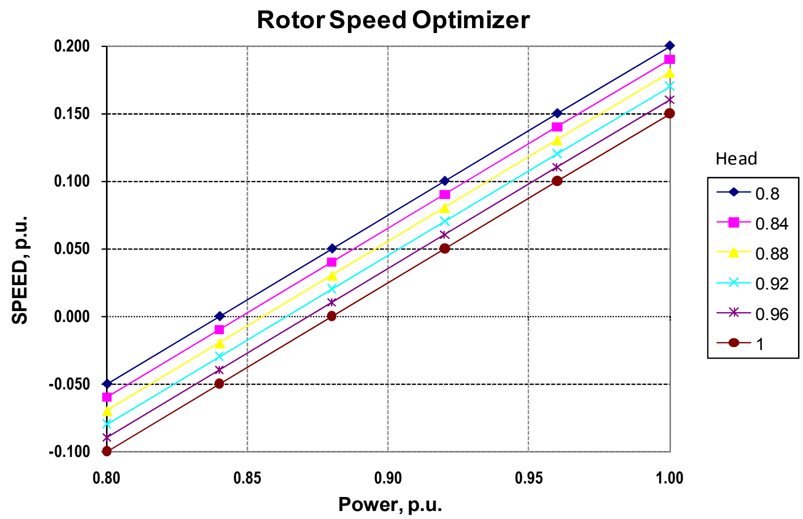


Figure 4 - Block Diagram of the AS PSH Turbine Model

The controls associated with the hydro turbine, governor and penstock dynamics are shown on the upper left side of Figure 4 and are similar to the controls for a conventional turbine. The principal difference is that the two main controlled variables, namely the rotor speed and the gate position, have their references provided by the speed-gate optimizer. Examples of optimal characteristics obtained as a result of calculations or tests of existing projects available in publications [2-4] were analyzed. Usually, optimal speed and gate position are provided as functions of power and static head as shown in Figure 5.



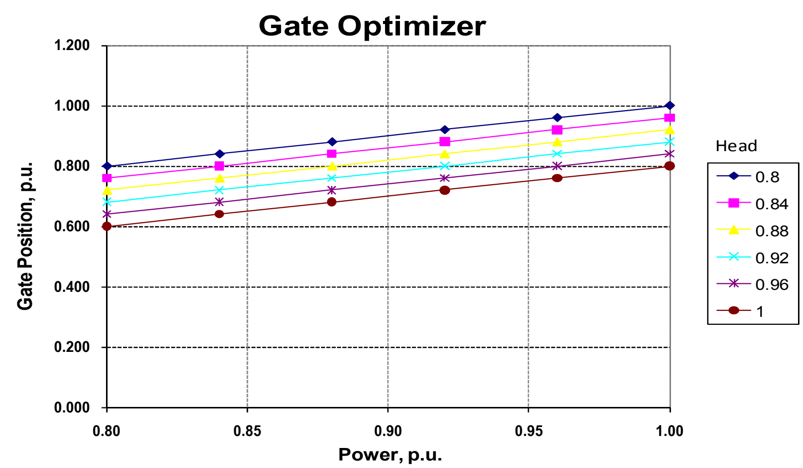


Figure 5 - Example of Speed and Gate Optimizer Characteristics Based on Analysis of Existing Projects

The model of the power converter shown on the upper right side of the block diagram of Figure 4 is similar to one used in the type 3 wind turbine model. It includes active and reactive power controllers.

The command for the active power controller is in terms of an active current command that is made as a combination of 3 inputs:

- Pgen, the current value of active power
- Pset, an output of the frequency controller shown in the bottom left part of Figure 4
- Rotor speed limiter. The purpose of this limiter is to prevent the rotor speed from increasing above SPmax or reducing below SPmin, using a deadband function

The hydro governor module allows the hydraulic coupling effect of up to four units sharing a common penstock to be taken into consideration. It uses a non-linear model assuming a non-elastic water column and is suitable for short to medium length penstocks. The major portion of the penstock is designed to handle the full flow of all the units and the penstock is bifurcated near the powerhouse into sections supplying flow to the individual units. A change in the flow through one unit results in a change in the dynamic head at the bifurcation point.

A system of four units is modeled by a 4 by 4 matrix of water time constants as a multiplier to the vector of units' water flow q to get the unit dynamic head h.

$$\begin{bmatrix} Tw_{11} & Tw_{12} & Tw_{13} & Tw_{14} \\ Tw_{21} & Tw_{22} & Tw_{23} & Tw_{24} \\ Tw_{31} & Tw_{32} & Tw_{33} & Tw_{34} \\ Tw_{41} & Tw_{42} & Tw_{43} & Tw_{44} \end{bmatrix} \cdot \begin{bmatrix} \frac{dq_1}{dt} \\ \frac{dq_2}{dt} \\ \frac{dq_3}{dt} \\ \frac{dq_4}{dt} \end{bmatrix} = \begin{bmatrix} \Delta h_1 \\ \Delta h_2 \\ \Delta h_3 \\ \Delta h_4 \end{bmatrix}$$

The algorithm of the model is designed in such a way as to automatically handle the situation when one or more of four units sharing the same penstock is initially off-line. However, the model does not allow tripping of one of the units sharing the same penstock in the course of the simulation (the simulation program does not call the governor model for an off-line unit, and hence the flow to that unit would not be calculated for each time step). Trip of the unit would not cause the water flow to go instantaneously to zero. Isolation of a unit from the system (for example, simulating trip of its main breaker) can be simulated as shown in Figure 6, as the unit would remain on-line (albeit not connected to the system), and the closing of the gate and reduction in flow to stop the unit's over-speed would be calculated.

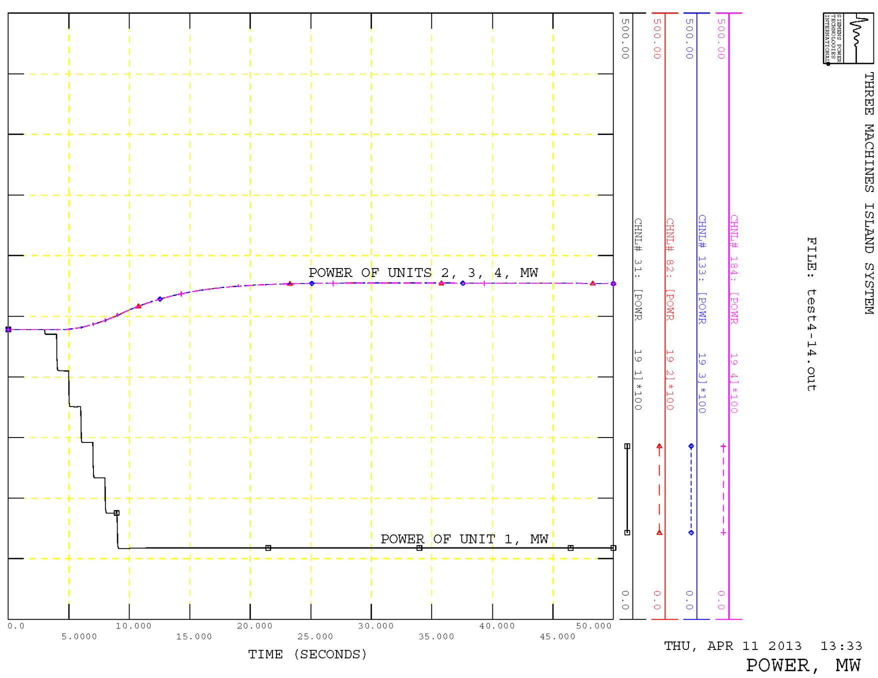


Figure 6 - Response of the Power of Units 2, 3, and 4 to a Step Reduction in the Power of Unit 1 with Four Units Sharing a Common Penstock

Modeling an Adjustable Speed PSH Pump

The block diagram of the model for adjustable speed PSH pump employing a DFIM is shown in Figure 7.

As in the generating mode, the converter module is responsible for controlling active power and voltage. However, the AS PSH unit has two significant advantages over a conventional PSH unit. Whereas a conventional PSH unit does not participate in frequency control when pumping, the AS DFIM unit is able to participate in frequency control in both generating and pumping modes. The AS PSH unit also has the ability to improve the efficiency of pumping by optimizing the rotor speed and gate position.

The power command is combined with the command from the frequency controller to create the power set point. It is used as an input for the speed optimizer whose output is the speed reference. The speed error processed through the “slow” speed controller makes up an additional input to the “fast” power controller. Hence, finally, frequency will be controlled and the rotor speed will be adjusted.

The pump module represents the hydro pump, gate, and penstock dynamics. The total power command is also used by the gate optimizer to determine the desired gate position. The speed and gate optimizers select the proper coordination of speed and gate position to maximize efficiency. The optimal power/gate/speed relationships (Figure 8) are represented through a simplified functional characteristic that should be built based on the information provided by the manufacturer.

For the pump model, the static head in the turbine model must be replaced by the pump head, which is a function of the water flow. An example of this function obtained from an existing plant is shown in Figure 9 for a unit rotating at rated speed. A quadratic approximation was suggested for this pump head versus flow function. However, if speed deviations during transient conditions are noticeable, the pump head should be adjusted accordingly. The model allows adjustment of the pump head, per affinity law, proportionally to the square of speed.

$$hp = (A_o + A_1 \times q + A_2 \times q^2) \times (1+dw)^2 \qquad (1)$$

where dw is the initial rotor speed deviation.

Mechanical power is calculated as the product of flow and head divided by efficiency.

The sign convention being used for the pump model is that mechanical power Pmech < 0, water flow q < 0, and head hp > 0.

From the block diagram in Figure 7:

$$P_{mech}/T_{rate} = hp \times q/Eff \qquad (2)$$

The mechanical power of the pump is known from the initial steady state mode of operation. During the model initialization, the initial water flow q must be found based on the initial mechanical power Pmech. After substituting the pump head from (2) into (1), a cubic equation is obtained, as follows:

$$P_{mech}/T_{rate} = (A_o \times q + A_1 \times q^2 + A_2 \times q^3) \times (1+dw)^2/Eff \qquad (3)$$

Curves in Figure 10 represent solutions of this equation for several combinations of the rotor speed deviation dw and efficiency Eff. From these curves, we know the values of Pmech/Trate at which the model can be successfully initialized. The initialization of the model is very sensitive to the nonlinear nature of these characteristics.

This model allows the hydraulic coupling effect for up to four pump units sharing a common penstock to be taken into consideration.

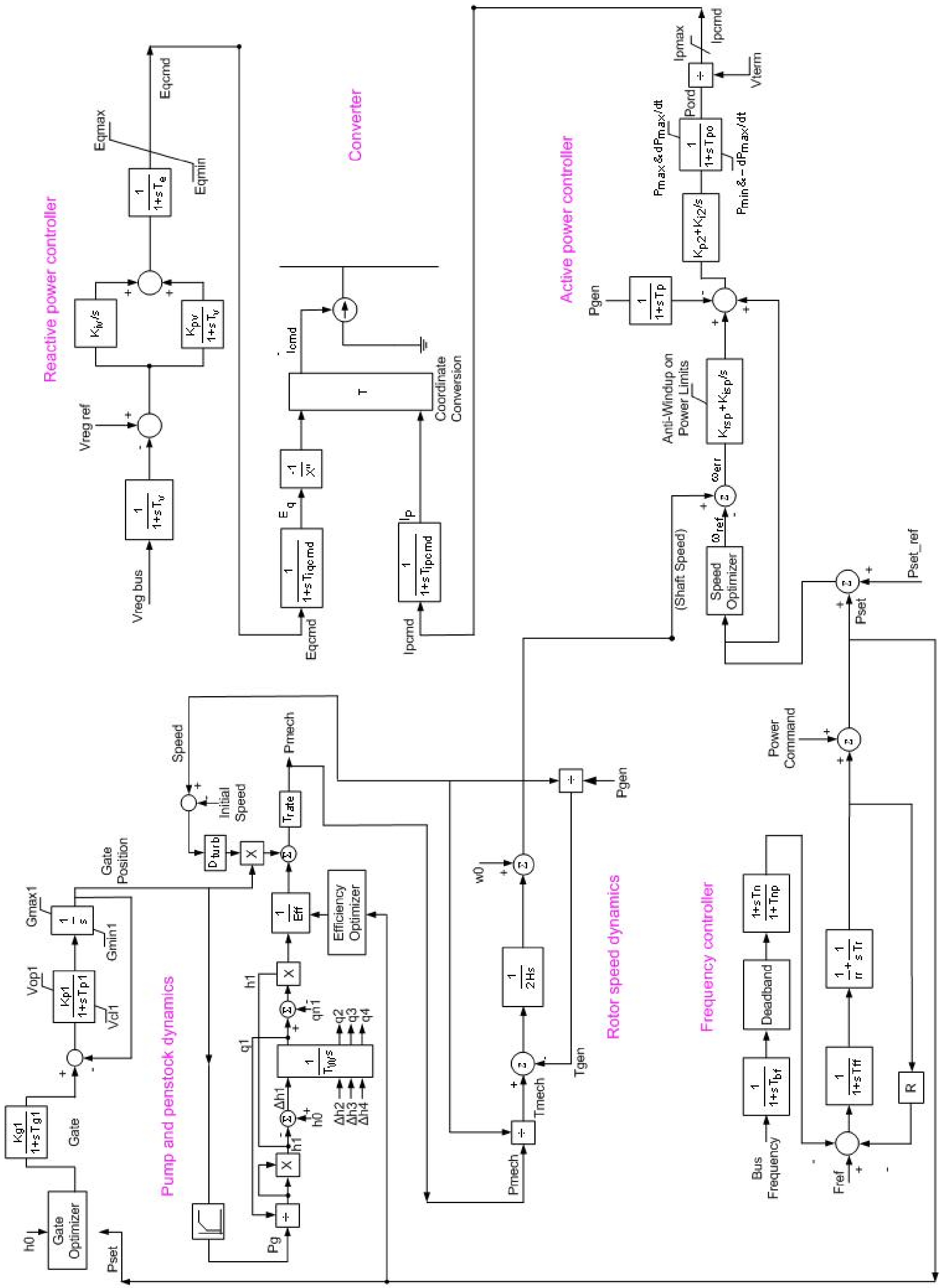


Figure 7 - Block Diagram of the AS PSH Pump Model

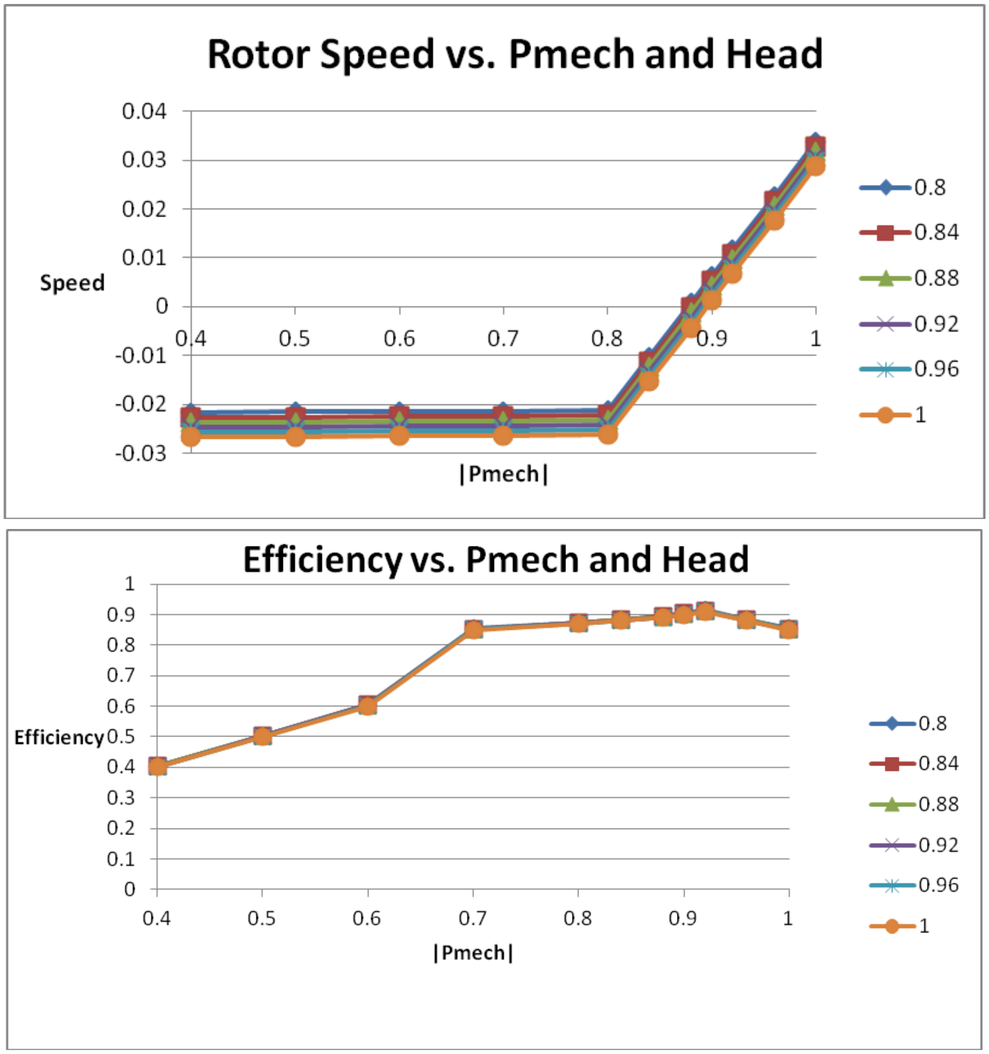


Figure 8 - Example of Speed and Gate Optimizer Characteristics for AS PSH Pump Based on Analysis of Existing Projects

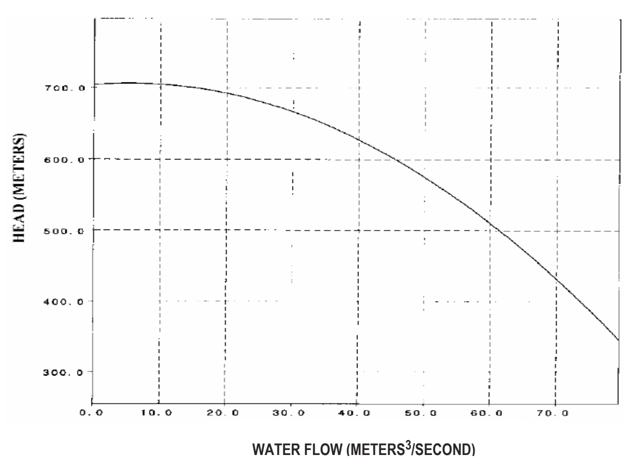


Figure 9 - Pump Head Characteristic

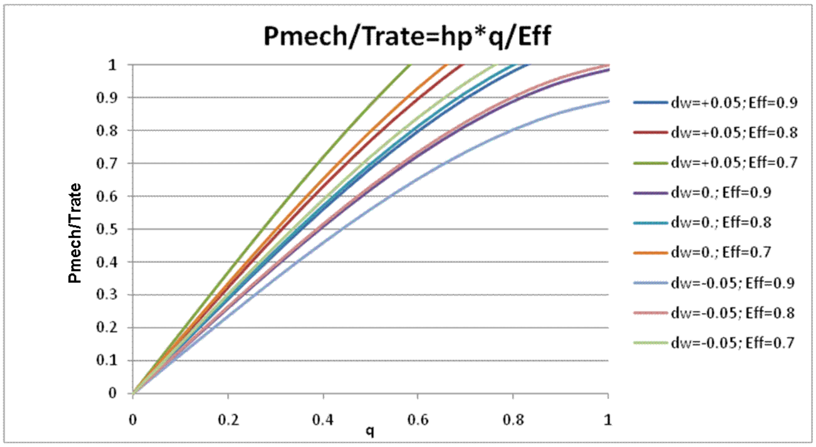


Figure 10 - Solution for the Pump Model Initialization

Modeling a Ternary Unit

The model for the ternary unit incorporates all three potential modes of operation; turbine operation only, pump operation only, or both turbine and pump operation, i.e., hydraulic short-circuit.

A block diagram of the model for the ternary unit is shown in Figure 11.

In the generating mode, with only the turbine in operation, the model of the ternary unit is similar to that of a conventional hydro unit. Conventional models are used for the salient pole machine and the excitation system. The turbine model is shown in the left part of the diagram. The machine will participate in the usual governor speed control, in a manner similar to the other generators on the system.

In pumping mode, with only the pump in operation, the model of the ternary unit is again similar to that of a conventional hydro pump unit. Conventional models are used for the salient pole machine and the excitation system. The pump model is shown in the right part of the diagram. The unit will not participate in governor speed control.

The third mode is the hydraulic short-circuit operation when both the turbine and the pump are working together. In this mode, the unit can participate in governor speed control. Again, conventional models are used for the salient pole machine and the excitation system.

The block diagram of the model is supplemented with a block diagram that illustrates calculation of the rotor speed deviation with the governor model's output mechanical power Pmech as an input (this portion of the figure is actually part of the generator model). The total mechanical power is the summation of the power produced by the turbine (positive quantity) and absorbed by the pump (negative quantity).

The total power for the hydraulic short-circuit mode of operation is always negative, i.e., the pumping power is always greater than the turbine power. At initialization of the dynamic model, the net electric power Pgen will be split between the turbine and the pump, based on the distribution coefficient Kd:

$$\begin{aligned} \text{Pgen\_pump} &= \text{Kd} \times \text{Pgen} \\ \text{Pgen\_turbine} &= (1 - \text{Kd}) \times \text{Pgen} \end{aligned}$$

Note that since the net power must be negative (the magnitude of the pump power is greater than the magnitude of the turbine power), Pgen_pump must be < 0, and Pgen_turbine must be > 0, it is necessary that Kd be > 1. The user should be careful to ensure that the distribution coefficient Kd results in powers for both the pump and turbine that are within their respective capabilities.

This model allows the hydraulic coupling effect for up to two ternary units sharing a common penstock to be taken into consideration.

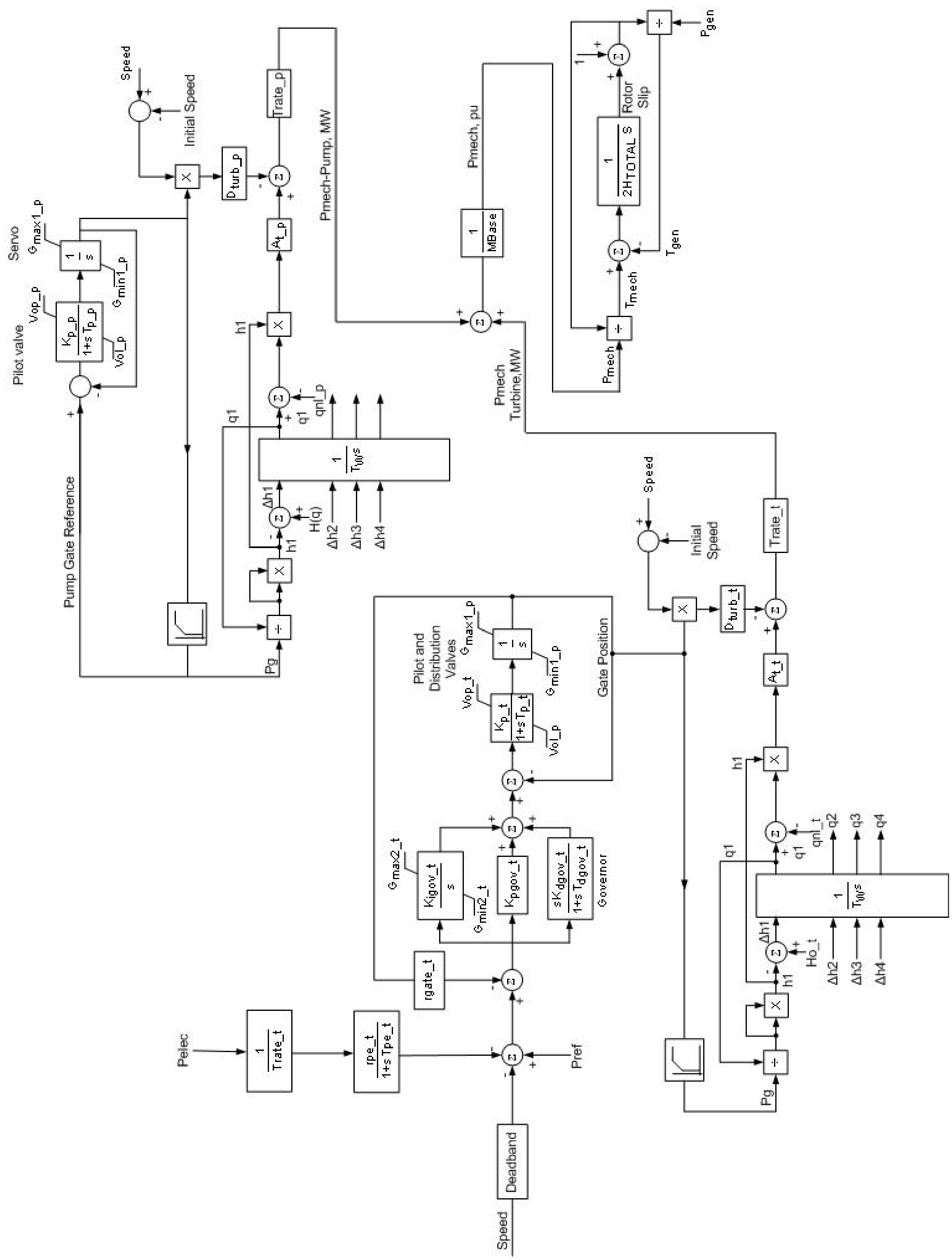


Figure 11 - The Model of a Ternary Unit

Testing the AS PSH Models

A small sample test system was used to make sure that models showed adequate performance responding to different disturbances such as under-frequency and over-frequency events caused by loss of generation or load, and three-phase and single-line-to-ground faults in the vicinity of the plant under study. This test system allowed for variation in the level of penetration of the advanced technology. The following types of pumped storage hydro units were tested:

- Conventional turbines, to have a basis for comparison
- Conventional pumps, to have a basis for comparison
- AS PSH turbine
- Up to four AS PSH turbines sharing a common penstock
- AS PSH pump
- Up to four AS PSH pumps sharing a common penstock
- Ternary unit in the pump mode of operation
- Ternary unit in the turbine mode of operation
- Ternary unit in the hydraulic short-circuit mode of operation

Simulations were performed to test transient stability response and voltage control/reactive power control capabilities, and to demonstrate fast frequency regulation for events involving loss of generation or other events that result in an imbalance between system load and generation. These tests ensured that the newly developed models can be used to simulate the PSH unit's response to different disturbances and to demonstrate the potential for fast frequency control of the AS PSH units.

A second series of tests was performed to demonstrate the potential benefits of the faster frequency control capability of the AS PSH technology.

The use of the models as part of a large U.S. system was demonstrated through tests performed using the Western Interconnection (WI) power system that has about 190 GW of generation capacity. Power system data for modeling of the WI were obtained from the Western Electricity Coordinating Council (WECC). Six existing pumped storage hydro plants, totaling about 3,200 MW of installed capacity, were simulated using the newly developed models as well as their original conventional PSH models. The response of these units (and of the system with these units) was simulated for a wide variety of typical disturbances, including the response to changes in the amount of power generated by renewable energy sources. These tests ensured that the newly developed models could be used for practical analyses of real systems.

Thus, the tests demonstrated that the new models performed well and can be used for the typical dynamic simulation analyses required by planning and interconnection studies. The tests also demonstrated the new capabilities available in these models (e.g., the use of an adjustable speed pumped storage plant to provide regulation services in pump mode). The tests showed the improved capabilities of the equipment such as a faster response to system events.

The Sacramento Municipal Utility District (SMUD), as a typical balancing authority and project team member, was suggested by the Advanced Technology Modeling Task Force for testing the models of the advanced pump storage hydro technology newly developed in the course of the DOE project and for demonstration of the potential benefits of this technology.

Based on the 2017 summer peak load Western Interconnection (WI) case, an equivalent was created comprising the full model of SMUD connected to a single machine equivalent of the WI system, with all 230 kV tie lines to the WI retained. All machines of the SMUD system were retained including the hydro units of the Upper American River hydro plants.

The dynamic simulation model of the Automatic Generator Control (AGC) was updated to add the capability to control not only conventional generating units whose prime movers are simulated by standard PSS®E turbine-governor models but also the newly developed models of the advanced pump storage hydro units.

Taking into consideration the size of the Western Interconnection, the frequency deviation occurring as a result of a large load or generating unit turning on or off is relatively small. Hence from the two components of the AGC area control error (ACE), namely frequency and intertie power flow, the latter component can be considered as the major criterion of AGC performance quality.

A list of disturbances used to demonstrate AGC performance included:

- Drop of generating units of different sizes in SMUD
- Ramping down the generation in SMUD
- Ramping up the generation in SMUD

The two latter disturbances can be construed as a change in renewable power, e.g., a drop or an increase in wind or solar generation power.

The following scenarios in terms of SMUD hydro units have been considered:

- All conventional hydro turbines (present condition)
- All conventional hydro turbines plus two conventional pumps
- All conventional hydro turbines plus two adjustable speed (AS) pumps
- All conventional hydro turbines plus two ternary pumps in hydraulic short circuit mode of operation

The proposed Iowa Hill pumped storage hydro plant was also added to the SMUD system. Its three AS PSH units were tested as pumps for two WI system conditions, namely the 2017 summer peak load case and 2022 light load case. Wind power ramping up from zero to 400 MW was used as a disturbance.

For all these scenarios and disturbances the newly developed models of AS PSH units and ternary units showed the expected performance and allowed demonstration of the expected advantages of the advanced PSH technology, specifically the capability of AS pumps and ternary pumps to participate in secondary frequency control (AGC).

Conclusion

The new models of adjustable speed pumped storage hydro units and ternary units fill a major need in the transmission system interconnection activity with regard to system dynamic performance studies for new hydro power plants. These models will be very useful in studies investigating how these technologies can be implemented to help address concerns related to the increasing integration of wind and solar photovoltaic renewable resources.

For Further Reading

The models described above were documented in much greater detail in the series of reports shown below:

1. Review of Existing Hydroelectric Turbine-Governor Simulation Models, Vladimir Koritarov, Leah Guzowski, James Feltes, Yuriy Kazachkov, Baldwin Lam, Carlos Grande-Moran, Gary Thomann, Larry Eng, Bruno Trouille and Peter Donalek, Argonne National Laboratory Report ANL/DIS-13/05, August 2013.
2. Modeling Adjustable Speed Pumped Storage Hydro Units Employing Doubly-Fed Induction Machines, Vladimir Koritarov, Leah Guzowski, James Feltes, Yuriy Kazachkov, Bo Gong, Bruno Trouille and Peter Donalek, Argonne National Laboratory Report ANL/DIS-13/06, August 2013.
3. Modeling Ternary Pumped Storage Units, Vladimir Koritarov, Leah Guzowski, James Feltes, Yuriy Kazachkov, Bo Gong, Bruno Trouille, Peter Donalek, and Vahan Gevorgian, Argonne National Laboratory Report ANL/DIS-13/07, August 2013.
4. Testing Dynamic Simulation Models for Different Types of Advanced Pumped Storage Hydro Units, Vladimir Koritarov, James Feltes, Yuriy Kazachkov, Bo Gong, Peter Donalek, and Vahan Gevorgian, Argonne National Laboratory Report ANL/DIS-13/08, August 2013.

5. Simulation of the Secondary Frequency Control Capability of the Advanced PSH Technology and Its Application to the SMUD System, Vladimir Koritarov, James Feltes and Yuriy Kazachkov, Argonne National Laboratory Report ANL/DIS-13/10, November 2013.

These reports have been published by Argonne National Laboratory and are publicly available on the ANL website www.dis.anl.gov/psh.

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3. Kopf, E., Brausewetter, S., Giese, M., and Moser, F., “Optimized Control Strategies for Variable Speed Machines,” 22nd IAHR Symposium on Hydraulic Machinery and Systems, June 29–July 2, Stockholm, 2004.
4. Nagura, O., and Yoshida, M., “Transient Behavior Analysis of Adjustable Speed Pumped Storage System,” Hydro Vision International 2011, Session 414; Sacramento, CA, July 20, 2011.