INL/CON-21-64078-Revision-0

Modeling a Bulb-Style Kaplan Unit Hydrogovernor and Turbine in Mathworks-Simulink and RTDS-RSCAD

April 2022

Changing the World's Energy Future

Abhishek Banerjee, S M Shafiul Alam, Thomas M Mosier, John Undrill

Idaho National Laboratory

INL/CON-21-64078-Revision-0

Modeling a Bulb-Style Kaplan Unit Hydrogovernor and Turbine in Mathworks-Simulink and RTDS-RSCAD

Abhishek Banerjee, S M Shafiul Alam, Thomas M Mosier, John Undrill

April 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Modeling a Bulb-Style Kaplan Unit Hydrogovernor and Turbine in Mathworks-Simulink and RTDS-RSCAD

Abhishek Banerjee
Power and Energy Systems
Idaho National Laboratory
Idaho Falls, USA
abhishek.banerjee@inl.gov

S M Shafiul Alam
Power and Energy Systems
Idaho National Laboratory
Idaho Falls, USA
SMShafiul.Alam@inl.gov

Thomas M. Mosier
Power and Energy Systems
Idaho National Laboratory
Idaho Falls, USA
thomas.mosier@inl.gov

John Undrill
Independent Researcher
Arizona State University
Tempe, USA
jundrill1@gmail.com

***Abstract*—Some run-of-river (ROR) hydropower plants use a horizontal bulb-style Kaplan turbine. This turbine and the corresponding governor are not represented well in standard high-fidelity power-system modeling platforms. This paper presents the characterization, development, and modeling of bulb-style Kaplan turbine and associated hydrogovernor equipment in two platforms: Simulink from the MathWorks, Inc., and RSCAD from RTDS Technologies, Inc. The developed models enable accurate assessment of the response of a bulb-style Kaplan hydropower unit to changes in electrical loading and water conditions. The resulting models enable accurate digital real-time simulation with hardware-in-the-loop testing of this class of turbine, which was not previously possible. This, in turn, improves the ability to innovate these technologies and hybridize them in a lab setting, accelerating the potential for innovation in this type of ROR hydropower plant.**

***Index Terms*—horizontal bulb-turbine, Kaplan turbine, H6E, run-of-river hydropower**

I. Introduction

Hydropower is a critical source of renewable energy in the U.S. and has significant potential to integrate other renewable-energy generation [1], [2]. Studying this potential, including options for hybridizing hydropower plants with energy storage, requires an accurate model of specific types of hydropower plants [3]–[5]. Bulb-style Kaplan hydropower units are important for low-head applications with moderate-to-high flows. Currently, they are primarily controlled to maximize efficiency, rather than to add stability. They are often connected to the distribution grid; therefore, they have the potential to enable new grid paradigms, such as distribution-system islanding, for the communities to which they are connected. Accurate turbine-generator models are necessary to study these new use cases, but these models do not currently exist in high-fidelity power-system modelling platforms.

An H6E model representating the Kaplan turbines is present in PowerWorld [6], TSAT, PSLF, and PSSE [7]. This original H6E model and its different versions are not yet available in high-fidelity power system modeling platforms like Simulink from the MathWorks, Inc., [8], and RSCAD from RTDS Technologies, Inc. [9]. This lack of compatible high-fidelity models inhibits the ability to study these units in digital real-time simulation (DRTS), with or without hardware-in-the-loop (HIL) testing. This high-fidelity model improves the capture of the dynamic behavior typical of a low-head bulb-style Kaplan turbine, especially in an islanded mode of operation. It is also essential for DRTS with HIL capability to assess the associated electromechanical instability (sustained or ceasing) properly so that an effective mitigation scheme (such as integrating an energy-storage system) can be analyzed offline, validated through field measurements, de-risked using DRTS with HIL in a controlled laboratory environment, and implemented in the field.

This paper presents a high-fidelity model of a bulb-style Kaplan turbine in Simulink (enabling DRTS in OPAL-RT [10]) and RSCAD (enabling DRTS in RTDS [9]). These models include automatic initialization through Matlab and Python scripting, respectively. The automation of initialization enables faster and less-error-prone setup of steady-state loading conditions before any dynamic stability test. It also helps in models that simulate multiple units. Automatic initialization brings the additional advantage of creating a desired set of initial conditions that can be embedded through RSCAD's runtime automation. In particular, these models were essential in preparing a DRTS with utracapacitor storage system HIL test, conducted in preparation for a recent field demonstration of islanded distribution-grid black start with Idaho Falls Power [11].

The remainder of this paper is organized as follows: Sec. II defines the different components of the integrated model; Sec. III describes the design conceptualization and framework, including initialization routine and software tests; Sec. IV presents the simulation results; Sec. V provides concluding remarks and future research directions; and Sec. VI denotes the parameters used in the design.

This manuscript has been authored by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517 with the U.S. Department of Energy. The work was supported through the U.S. Department of Energy Water Power Technology Office HydroWIRES Initiative.

II. Components of the Integrated Model

The hydrogovernor and the bulb-style Kaplan turbine comprise the integrated model.

A. Hydrogovernor Model

The hydrogovernor model operates under two modes of operation: the speed-control and load-control modes. Essentially, the major difference between these is that the speed-control mode takes the measurement of the rotor speed of the generator and compares it with the power reference signal whereas the load-control mode incorporates an additional electrical-power output from the generator and considers it in the PID control design. Fig. 1 depicts a transfer-function block diagram of hydrogovernor models for the speed-control and fig. 2 for the load-control mode.

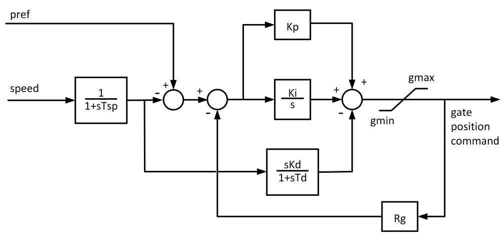

Fig. 1. Governor transfer function diagram: speed control mode [7]

As can be observed in fig. 1, a low-pass filter with time constant (T_{sp}) has been introduced to the speed measurement to attenuate the higher frequencies of the speed-measurement signal. Similarly, in fig. 2, the electrical-power input signal is subject to a low-pass filter with time constant (T_{pe}). The parameter R_g represents the $\%$ droop gain in speed-droop characteristics. The PID controller is used to generate the gate position command. It should be noted here that, whereas the proportional (K_p) and integral gain (K_i) work on the error signal generated by the comparators, the derivative gain (K_d) is a feed-forward signal from the speed transducer. At the planning stage, the PID gains for the hydrogovernor model are primarily set using the Ziegler-Nichols method [12], within the governor-stability margins [13]. The settings, however may go through additional adjustment when applied to the digital hydrogovernor system in the actual hydropower unit.

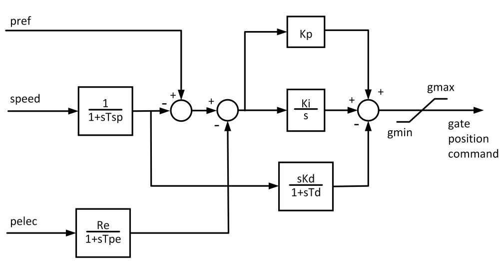

Fig. 2. Governor transfer function diagram: load control mode [7]

B. Kaplan Turbine Model

The Kaplan turbine model is representative of the horizontal bulb-style turbine unit used in the black-start field demonstration [11]. The turbine model depicts a rather complex series of controls and parameters that capture the behaviour of the Kaplan turbine. The input to the turbine is the gate position command (ggv) is generated by the governor output, and this output is the mechanical power input to the generator. Fig. 3 depicts the turbine model and its various components. The ggv from the governor is used as the input to a blade-vs-gate characterizer. The blade position is determined by a 1-dimensional interpolation function, based on the gate-position command and the number of interpolation points. This characterizer, represented as ① in the turbine model, can be seen in fig. 3.

This unit works on 1-dimensional interpolation function based on the ten predefined values for the gate positions. Fig. 4 shows the corresponding blade-vs-gate, and power-vs-gate curves. These piece-wise linear curves are set from the index test [14], performed over IFP's hydropower unit in grid connected mode of operation. A gate-servomotor design has been implemented into which the gate servo pilot time constant (t_g) and gate servo pilot gain (k_g) have been introduced. It should be noted that the gate servo-motor induces a delay in the the gate-velocity command (g_v), as can be seen from the fig. 5. It can be observed in fig. 3 that the gate servo stroke has an integrator and two limiters, the minimum and maximum gate-velocity limit (velm) and gate-position limit (gmin/gmax).

III. Initial H6E Design and Software Platforms

The improved H6E model has been developed on the MATLAB/Simulink [8] and RTDS/RSCAD [9] platforms. Previous field-testing data were collected, and the initial model of the hydrogovernor and turbine were captured in Matlab code by defining m-codes for the various elements of the integrated system.

A. Initialization Routine

One of the most important aspects of the proper functioning of the governor and the turbine is based on their initial states. Each internal state needs to be initialized properly. The initialization routine is developed into a Matlab code where the turbine power output is considered as the first measurement used to back-calculate the other initial states of the turbine. Once the gate position command (ggv) is estimated, the turbine initialization is complete, and then the governor is initialized next. As shown in fig. 3, turbine power (P_{turb}) is determined by the load connected to the machine. Once, (P_{turb}) is known, the flow-area versus gate table is determined by calculating the flow values (*qgv*) in (1), estimated using (1). The resulting *qgv* estimate yields ten distinct values, which are later used as points in the characterizer ②, as shown in fig. 3.

$$qgv(i) = ggv(i) \times ab \times bgv(i), i \in [1, 10]$$
$$ab = bgvmin + \{bb \times (1 - bgvmin)\} \tag{1}$$

Once *qgv* has been calculated, the initial flow (*q*)—i.e the input to the characterizer ②—is calculated using the 1-D interpolation function as shown in (2). Note that *pmt* used

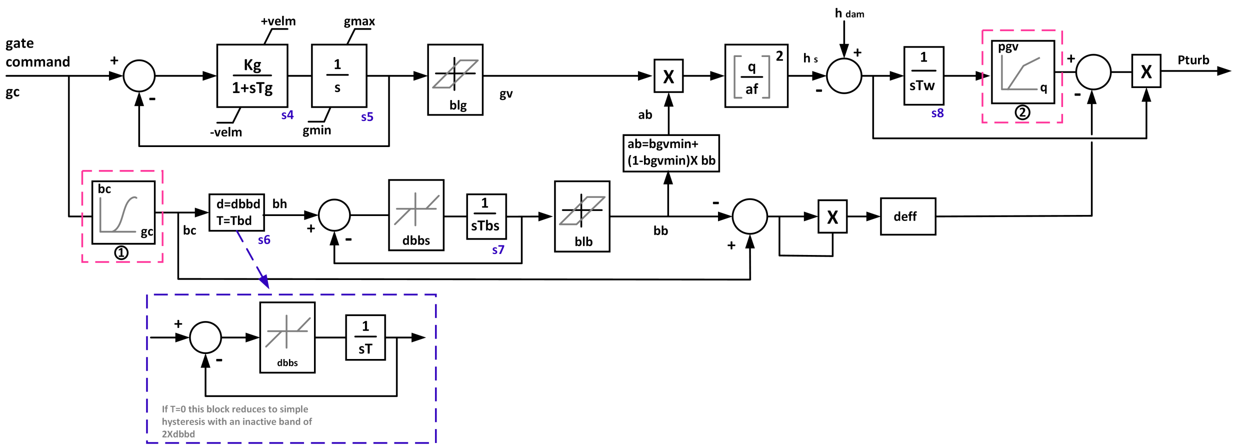

Fig. 3. Bulb-style Kaplan turbine transfer-function model (adopted from [7])

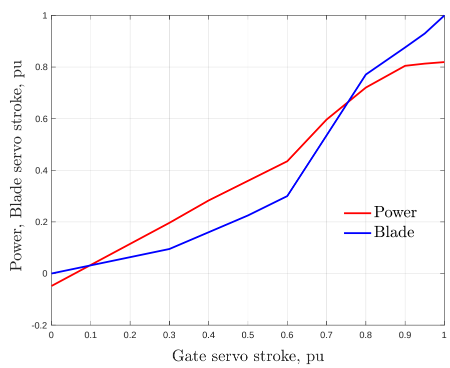

Fig. 4. Blade position and power versus gate position

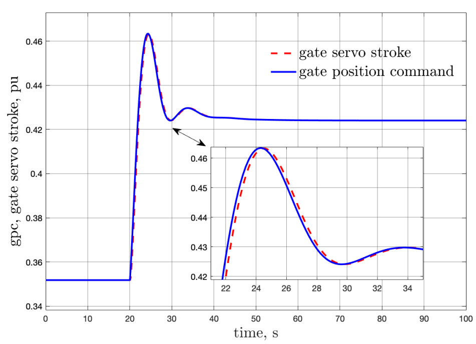

Fig. 5. Gate servo-motor position vs. gate-position command

in (2) refers to the initial mechanical output to the output of the characterizer ②.

$$q = qgv(i) + \left[\{pmt - pgv(i)\} \times \frac{\{qgv(i+1) - qgv(i)\}}{\{pgv(i+1) - pgv(i)\}}\right],$$
$$i \in length(n)$$
$$n = total\ number\ of\ points \tag{2}$$

After the flow has been calculated, a quadratic-based approach is used to determine the initial estimate of the gate opening (g). The coefficients (a,e,d) of the quadratic are first calculated and leveraged to determine the estimate of the gate opening based on (3). Equations (1) - (3) breaks down an iterative process to determine initial steady-state blade and gate position by searching through the piece-wise linear blade-vs-curve. For each linear piece of the curve, (d, e) presents the starting point and a represents the slope.

$$\begin{aligned} aqc &= A \times a \\ bqc &= B + (A \times e) - (A \times a \times d) + (A \times bbias) \\ cqc &= q/sqrt(hdam) \\ g &= -bqc + \frac{\sqrt{bqc^2 + (4 \times aqc \times cqc)}}{2 \times aqc} \end{aligned} \tag{3}$$

where, B = bgvmin and A = 1-B

Following this step, we refine the gate estimate in the case in which the gate and blade lie on different segments over five iterations; finally, we are able to assign internal states to the turbine. As depicted in fig. 3, the internal states for the turbine are detailed as $[s8, s7, s6, s5, s4]$. Subsequently, based on the initial gate-opening estimate, the governor's internal states are calculated. Further details on the initialization of the turbine and the governor can be found in the GitHub repository [15] where we have detailed our models, uploaded with their initialization routines and presented in multiple simulation platforms.

B. Simulink Models

The H6E model has been translated from the Matlab code to the Simulink model based on a state-flow and block-diagram approach. In this process, the main building blocks have been preserved, and their development has been incorporated in the Simulink platform. The Simulink model was designed for two modes of the operation—i.e., the grid-connected and the isolated modes.

- **Grid-Connected Mode**. The main aim was to match the Simulink model as closely as possible to actual filed-test results obtained under grid-connected conditions at IFP. The grid-connected scenario was emulated in the Matlab code, where the grid was emulated using swing equation dynamics. In order to preserve the model design, a similar approach was considered for the Simulink environment. Fig. **??** shows the interconnected system in the grid-connected mode of operation, as designed in Simulink. The swing-equation-based grid model has been depicted in fig. 6, where the electrical-damping coefficient (d_{elec}) and the electrical-synchronizing coefficient (k_e) were considered. More information on the values used can be found in Sec. VI, and details of the design can be found in the INL GitHub repository [15].

- **Isolated Mode**. This mode is representative of the actual black-start field demonstration [11]. In this mode of operation, the imperative is to bring critical loads by approx $0.5MW$ in isolated condition. The goal is to support critical infrastructure while re-energizing during a black-start procedure in the event of a blackout. In this scenario, the governor and turbine are directly connected to the load, and the mechanical-power output from the turbine is directly governed by the local load on the system. The isolated mode of operation is composed of two models: the swing-equation-based model and the actual synchronous-generator dynamic-model-based islanded mode.

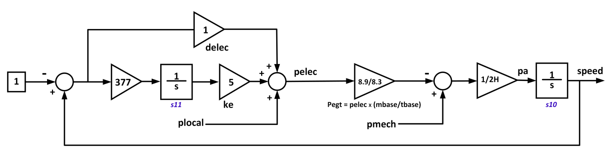

Fig. 6. Grid modeled as swing equation

C. RTDS/RSCAD Model

An RSCAD model of the H6E hydrogovernor and Kaplan turbine was developed, tested, and validated in the RTDS Lab. This model of the H6E would be available on the RTDS (EMT), and the energy storage and other components were actual hardware equipment's connected to the RTDS Novacor [9]. Fig. 7 represents the RSCAD model of the hydrogovernor and fig. 8 represents the turbine model.

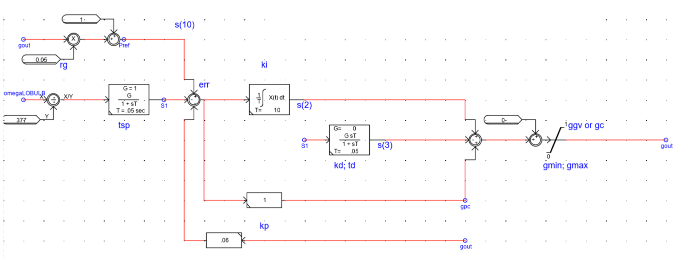

Fig. 7. Hydrogovernor model snapshot from [15]

The initialization of the integrated model in RSCAD is very important in running HIL tests. There is no inbuilt method to perform this in the RSCAD environment. In order to facilitate HIL testing, a Python-based scripting tool [15] has been developed that interacts with the RSCAD (.dft) file and changes the parameters of the RSCAD model blocks as

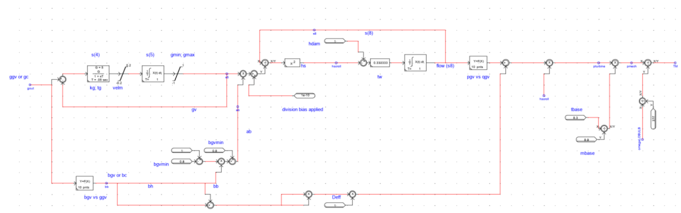
Fig. 8. Bulb-style Kaplan turbine model snapshot from [15]

required for the initialization. This novel Python-based scripting tool with RSCAD computes internal states using Python code; subsequently, using i/o capabilities, it is able to edit the changes in the RSCAD model based on unique identifier tags for the required components in the hydrogovernor and turbine model.

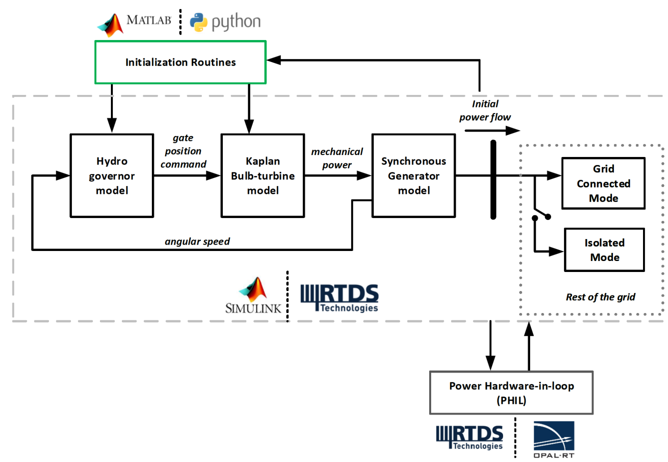

Fig. 9. Python/Matlab-based initialization routines for software/hardware-in-loop platforms

The integration of the initialization in both platforms can be seen in fig. 9, where both hardware- and software-based platforms are equipped with initialization capabilities using Python- and Matlab-based scripting, respectively.

IV. Simulation Results

Simulations are conducted on both grid-connected and grid-isolated modes of operation. The Simulink model was tested against the Matlab code in both cases to replicate the data recorded in field testing. The grid-connected mode was tested by introducing a 1% speed-load reference step-up at $t = 51s$, followed by a 1% step-down in the speed-load reference at $t = 352s$. Other model parameters such as the governor PID settings, blade-vs-gate curve, and net electrical loading are set exactly as in the actual ROR hydropower unit. Fig. 10 shows the change in the governor and turbine parameters during this event. The black trace depicts results from field test, and the Simulink and Matlab models show comparable results. The accuracy of this model response was sufficient for field demonstration [11] preparation, but further improvement would be possible through adjusting other parameters like the power-vs-gate curve or the nominal head (h_{dam}) [16].

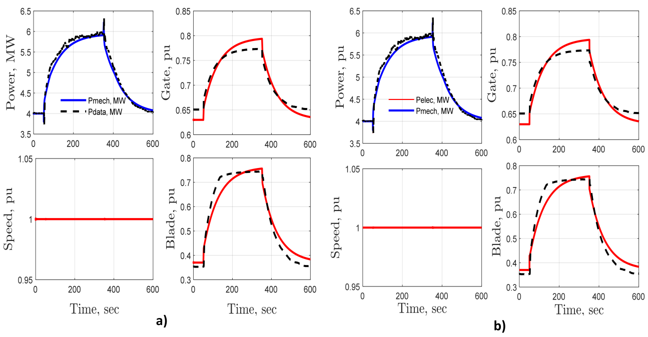

Fig. 10. Governor and turbine parameters at 1% step in speed at 60% output in a) Simulink model and b) Matlab code

The RSCAD model for both the hydrogovernor and turbine was simulated in the islanded mode of operation to check the performance of the design. The performance can be seen in fig. 11b), where the mechanical-power output (P_{mech}), the gate position, and the blade position are plotted. It can be also be observed from fig. 11 that the Simulink and RSCAD models for the isolated mode of operation agree very closely with each other. It should be noted the isolated mode is being tested here in both platforms, where the baseload is at 3MW and a load step of 375KW is applied locally on the isolated system. The governor here has PID gains of $k_p = 1$, $k_i = 0.1$, $k_d = 0$ and a droop setting ($r_g = 6\%$) in both the Simulink and RSCAD models, as shown in fig. 11. .

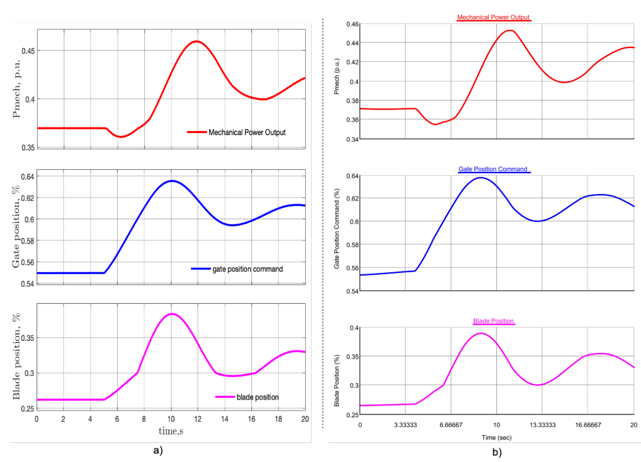

Fig. 11. Isolated mode-of-operation testing for governor and turbine during a load step of 375 KW in a) Simulink and b) RSCAD

V. Conclusion

This paper demonstrates the new high-fidelity Simulink and RSCAD models of ROR hydrogovernor and bulb-style Kaplan turbine hardware. The models have been designed and tuned to match the governor-turbine response for a real-world hydropower unit. The Simulink and RSCAD models enable real-time testing with HIL implementation using OPAL-RT and RTDS digital real-time simulators, respectively. An automatic initialization for dynamic simulation has also been integrated into the models. RSCAD initialization involves a novel Python-based interface for automatic modification of initial conditions in the model. The parameters of these models can be tuned to match other hydropower plants in the same class. The models are made publicly available via GitHub for public use and will be beneficial for researchers/utilities aiming to integrate these hydropower units with other complementary technologies or to use these units in new ways.

VI. Appendix

☐ Controller parameters in Fig. 1, 2, 3:
$K_p = 1, K_i = 0.1, K_d = 0, T_{sp} = 0.05, T_{pe} = 0.5, T_d = 0.05,$
$R_g = 0.06, velm = 0.2, g_{max} = 1, g_{min} = 0, d_{turb} = 0.5,$
$p_{gc} = 0.0, h_{dam} = 1.0, deff = 1.0, buf = 0.1, buv = 0.03,$
$tw = 3, tbd = 0, tbs = 0, dbbd = 0.0, dbbs = 0.0, blg = 0,$
$blb = 0.0, bvlm = 1.01, bgvmin = 0.8$

☐ Parameters used in equations (1), (2), (3):
$ggv = [0,\ 30,\ 40,\ 50,\ 60,\ 70,\ 80,\ 90,\ 95,\ 100]\,/100;$
$pgv = [-.4, 1.63, 2.35, 2.98, 3.61, 4.95, 5.98, 6.68, 6.75, 6.8]/8.3;$
$bgv = [0,\ 9.50,\ 16.0,\ 22.5,\ 30.0,\ 53.5,\ 77.1,\ 87.6,\ 93.0,\ 100]\,/100;$

References

[1] "International Hydropower Association."
[2] "Office of ENERGY EFFICIENCY and RENEWABLE ENERGY," accessed: 2021-08-15. [Online]. Available: https://www.energy.gov/eere/water/new-vision-united-states-hydropower
[3] B. Stoll, J. Andrade, S. Cohen, G. Brinkman, and C. Brancucci Martinez-Anido, "Hydropower modeling challenges," 4 2017.
[4] N. Voisin, D. Bain, J. Macknick, and R. S. O'Neil, "Improving hydropower representation in power system models - report summary of pnnl-nrel technical workshop held march 6-7, 2019 in salt lake city, ut," 11 2020.
[5] A. Banerjee, S. M. S. Alam, and T. M. Mosier, "Impact of hybrid energy storage system (hess) topologies on performance: Exploration for hydropower hybrids," in 54^{th} *Hawaii International Conference on System Sciences*, 1 2021, pp. 3102 – 3110.
[6] "Powerworld corporation," accessed: 2021-08-14. [Online]. Available: https://www.powerworld.com/
[7] P. Zadkhast, "Powertech h6e benchmarking results," Western Electric Coordinating Council, November 2019, accessed: 2021-08-14.
[8] MATLAB, *9.8.0.1323502 (R2020a)*. Natick, Massachusetts: The MathWorks Inc., 2020.
[9] RTDS, *Technologies (version 5.013)*. Winnipeg, MB R3T 2E1, Canada: Real-Time Digital Simulators, 2021.
[10] "OPAL-RT Technologies, Inc." accessed: 2021-08-14. [Online]. Available: https://www.opal-rt.com/
[11] S. M. S. Alam, A. Banerjee, C. Loughmiller, B. Bennett, N. S. Smith, T. M. Mosier, V. Gevorgian, B. Jenkins, and M. Roberts, "Idaho Falls Power Black Start Field Demonstration - Preliminary Outcomes Report," April 2021.
[12] J. G. Ziegler and N. B. Nichols, "Optimum Settings for Automatic Controllers," *Journal of Dynamic Systems, Measurement, and Control*, vol. 115, no. 2B, pp. 220–222, 06 1993.
[13] S. Hagihara, H. Yokota, K. Goda, and K. Isobe, "Stability of a hydraulic turbine generating unit controlled by p.i.d. governor," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 6, pp. 2294–2298, 1979.
[14] L. H. Sheldon, "Optimizing kaplan turbine efficiency with minimal cost, effort, and time," April 2019, accessed: 2021-10-05. [Online]. Available: https://www.powermag.com/optimizing-kaplan-turbine-efficiency-with-minimal-cost-effort-and-time/
[15] "GitHub - INL Hydropower Unit Models," https://github.com/IdahoLabResearch/Hydropower_Unit_Models, accessed: 2021-10-04.
[16] R. Bhattarai, "Gaps in modeling hydro power plant in steady state and dynamic analysis," Model Validation Subcommittee Workshop, Western Electric Coordinating Council, April 2021, accessed: 2021-10-05.