Automated Regression Methods for Turbine-Penstock Modeling and Simulation

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Abstract

Utilization of turbine-generator system modeling can provide distinct advantages when considering capital improvement projects in hydropower facilities. Such modeling facilitates the design and validation of specific turbine control systems. However, because modeling can often prove complex and time intensive, such techniques are not often utilized as part of the turbine control system development process.

In order to simplify and shorten this modeling process an automated regression methodology can be utilized in conjunction with a series of simple performance tests to provide requisite system characteristics. Such a methodology combines performance test data with gradient-based, multi-variable optimization algorithms to determine a system model through the following steps:

1. Modeling the Turbine-Penstock System
2. Validating the Turbine Model using Empirical Data
3. Optimizing Turbine Control Parameters for a Modernized System
4. Validating the Optimized Turbine Control Parameters on the Modernized System

Utilizing this automated regression method yields results that can help to assess performance improvements for governor modernization proposals, and validate new parameters prior to implementing actual hardware improvements. This paper will outline the process and results of this approach as it applies to the Castaic Pumped Storage automation upgrade project currently underway with the Los Angeles Department of Water and Power.

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1. Modeling the Turbine-Penstock System

In order to properly apply the methodology contained herein, it is of paramount importance that the model of the turbine-penstock system accurately reflects the dynamics of the physical system under analysis. Achieving this level of accuracy necessitates the use of a system model that properly accounts for the nonlinear behavior of the turbine-penstock system. In past decades, such nonlinear models were not widely utilized because of the lack of numerical computing power required to solve them. However, with today's computational resources, these nonlinear systems can be solved iteratively. As a result, utilization of this type of advanced model can now provide insights into the dynamics of complex systems that was previously not possible. The model for Castaic Pumped Storage Powerhouse (Castaic PSP) system model was developed with this fact in mind.

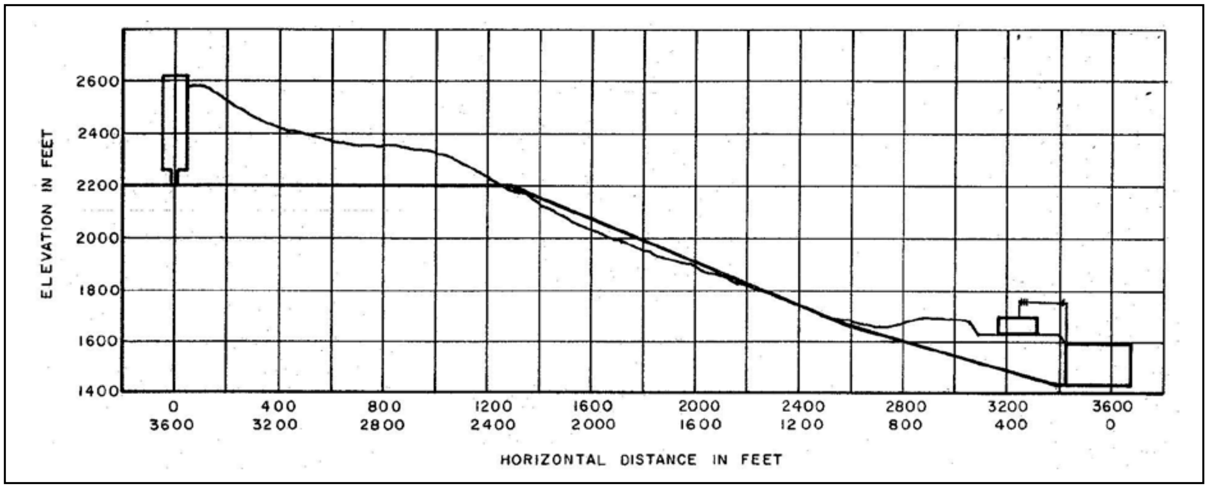

Figure 1: Elevation Diagram of Castaic PSP

As illustrated in Figure 1, the physical arrangement of a typical turbine-penstock unit at Castaic PSP consists of a supply tunnel, surge tank, penstock, and turbine. With knowledge of the key features of the plant, a properly suited model was then selected. Research into nonlinear models for turbine-penstock systems with elastic water columns provides numerous results. By making the assumption that the water column in the penstock is elastic and the water column in the tunnel upstream of the surge tank is inelastic, determination of the most appropriate model was possible. Figure 2 provides a graphical representation of this turbine-penstock system used in developing the Castaic PSP model. Table 1 provides the definitions of all terms used in the model.

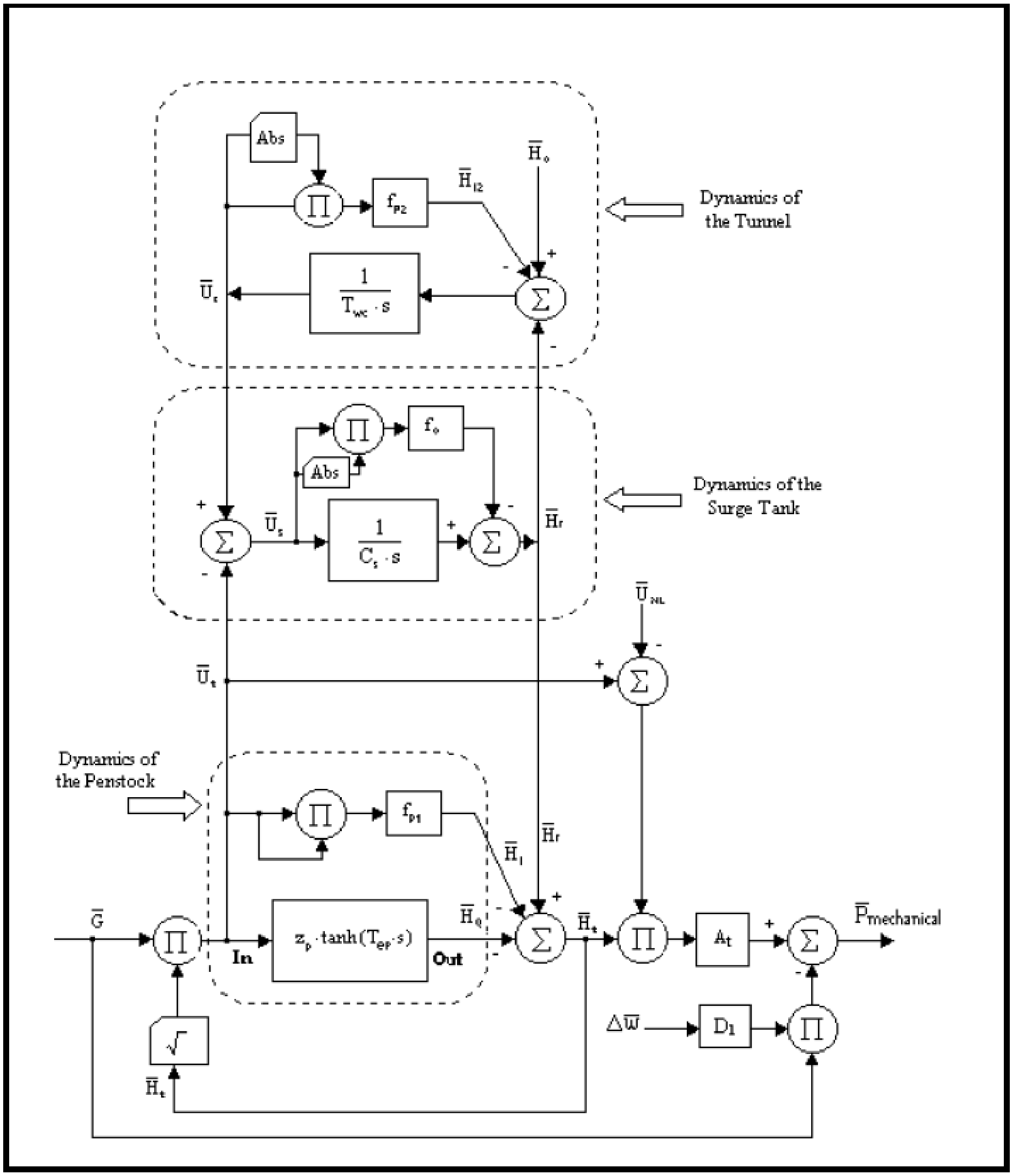

Figure 2: Nonlinear Math Model for Turbine-Penstock system with Surge Tank effects (Quiroga [1])

Constants

$I = Rotating\ Intertia$
$T_{Loss} = Turbine\ Power\ Losses$
$S_{NL} = Gate\ Position\ at\ Speed\ No\ Load$
$D_1 = Turbine\ Damping\ Coefficient$
$C_s = Surge\ Tank\ Storage\ Constant$
$f_0 = Head\ Loss\ Coefficient\ for\ Surge\ Chamber\ Orifice$
$T_{ep} = Elastic\ Time\ of\ Penstock$
$f_{p1} = Head\ Loss\ Coefficient\ for\ Penstock$
$f_{p2} = Head\ Loss\ Coefficient\ for\ Tunnel$
$z_p = Hydraulic\ Surge\ Impedance\ of\ Penstock\ Conduit$
$T_{wc} = Tunnel\ Water\ Starting\ Time$
$U_{NL} = Velocity\ of\ Water\ through\ Turbine\ at\ no\ Load$
$A_t = Turbine\ Gain$
$K_{spd} = Gate\ Offset\ for\ Damping\ on\ Torque$

Variables

$H_r = Head\ Level\ of\ Surge\ Tank$
$H_t = Head\ Level\ of\ Turbine$
$U_t = Water\ Flow\ through\ Turbine$
$U_c = Water\ Flow\ through\ Tunnel$
$U_s = Water\ Flow\ through\ Surge\ Tank$
$U_{tss} = Steady\ State\ Water\ Flow\ through\ Turbine$
$w = Angular\ Velocity$
$T_{mech} = Mechanical\ Torque$
$T_{load} = Steady\ State\ Load\ Torque$
$OnLine = Unit\ Paralleled\ to\ Grid\ (0\ or\ 1)$
$G_{Load} = Approximate\ Online\ Gate\ Position$

Inputs

$G = Gate\ Position$
$P_{Load} = Power\ Generated\ by\ Turbine$

Table 1: Definition of terms used in the Castaic PSP turbine-penstock model

The system of equations which express the model illustrated in Figure 2 are as follows:

$$U_c = U_s + U_t \quad (1)$$

$$H_r = 1 - f_{p2} U_c |U_c| - T_{wc} \frac{dU_c}{dt} \quad (2)$$

$$H_r = \frac{1}{C_s} \int U_s dt - f_0 U_s |U_s| \quad (3)$$

$$U_t = G\sqrt{H_t} \quad (4)$$

$$H_t = H_r - f_{p1} U_t^2 - z_p \tanh\left(T_{ep} \frac{dU_t}{dt}\right) \quad (5)$$

$$T_{mech} = A_t H_t (U_t - U_{NL}) - D_1 G(\omega) \quad (6)$$

Insofar as the aforementioned model details there is no expression defining the speed of the turbine. However, since the angular velocity is a primary characteristic of the dynamics of the turbine-generator system, and one of the variables which is readily measured during experiment for the purpose of model validation, it became necessary that AGC define speed in such a way so as to allow a state space model to be developed. Using heuristic analysis, a complementary system of equations was developed to link Equations 1-6 with the angular velocity of the turbine as follows:

$$G_{Load} = 0.4505 * (P_{Load})^2 + 0.3232 * (P_{Load}) + 0.1567 \quad (7)$$

$$U_{tss} = \frac{1}{f_{p1} + f_{p2} + \frac{1}{(G_{Load})^2}} \quad (8)$$

$$T_{Load} = A_t * \frac{U_{tss}^2}{(G_{Load})^2} * (U_{tss} - U_{NL}) - D_1 * G_{Load} * w - T_{Loss} \quad (9)$$

$$T_{mech} = \begin{cases} A_t \frac{U_t^2}{G^2} (U_t - U_{NL}) - D_1 G(\omega), \ OnLine = 0 \\ A_t \frac{U_t^2}{G^2} (U_t - U_{NL}) - D_1 G(\omega) - \ 0.1 * T_{Load}, \ OnLine = 1 \end{cases} \quad (10)$$

$$I = \begin{cases} 0.3389, \ OnLine = 0 \\ 2 * 10^{14}, \ OnLine = 1 \end{cases} \quad (11)$$

While offline the turbine-generator system is isolated, and must only supply enough mechanical power from flow through the turbine to account for the inertia of the unit itself. When online, however, speed is essentially constant because it is electrically coupled with the inertia of all other components on the grid. The above equations developed by AGC take this difference into account by using a split domain function for mechanical inertia dependent on online status.

Before this model could be validated with empirical data, it was necessary to reorganize the system of equations into state space form. By utilizing this approach, state space equations were developed which allowed the model to be programmed into the discrete time form for numerical integration. Through some algebraic manipulation the necessary state space equations were computed as follows:

From Equation (2)

$$\frac{dU_c}{dt} = \frac{1 - f_{p2} U_c |U_c| - H_r}{T_{wc}} \tag{12}$$

From Equations (4) and (5)

$$\frac{dU_t}{dt} = \frac{1}{T_{ep}} \tanh^{-1}\left(\frac{H_r - f_{p1} U_t^2 - G^{-2} U_t^2}{z_p}\right) \tag{13}$$

From Equations (1) and (3)

$$\frac{dH_r}{dt} = \frac{1}{C_s}(U_c - U_t) - f_0 \left[\left(\frac{dU_c}{dt} - \frac{dU_t}{dt}\right)\left(\frac{(U_c - U_t)^2}{|U_c - U_t|} + |U_c - U_t|\right)\right] \tag{14}$$

From heuristic methods

$$\frac{d\omega}{dt} = \frac{(T_{mech} - T_{loss}) * \left(\min(U_t, SNL) + K_{spd}\omega^2\right)}{I} \tag{15}$$

Equation 15 is derived from Newton's First Law in the following form:

$$\begin{bmatrix} Net\ Water \\ Torque \end{bmatrix} = \begin{bmatrix} Rotational \\ Inertia \end{bmatrix} * \begin{bmatrix} Angular \\ Acceleration \end{bmatrix}$$

This relation is adjusted to reflect the fact that torque from water flow is scaled down at low speeds due to leakage and slip through the turbine blades using the following expression:

$$\min(U_t, SNL) + K_{spd}\omega^2$$

Such an expression was determined using heuristic methods. Due to time and cost constraints associated with the Castaic PSP project development, no structured evaluation of expression variations was done for this equation. A combination of first principles and black box modeling techniques qualifies the fourth equation as a "grey box" model. However, acceptable model consistency with performance test data collected on a typical unit at Castaic PSP provides sufficient evidence to accept this equation when developing a low cost system model for advanced governor tuning and validation.

2. Validating the Turbine Model using Empirical Data

In order to validate that an appropriate turbine-penstock model has been identified, its state space equivalent system was numerically optimized to emulate the actual turbine-penstock dynamics. With the optimization complete the model could then be compared to a typical unit at Castaic PSP to observe how accurately the model could capture the gate-speed relationship.

2.1 Performance Testing and Data Acquisition

In order to develop a profile of performance characteristics of a typical unit, AGC designed a series of simple performance tests, and in conjunction with plant operations, performed these tests with data acquisition equipment installed to provide gate position, unit speed, and power output. Appendix A outlines the performance test procedures used during this process. Shown below in Figures 3 and 4 are representative samples of the data collected during this process.

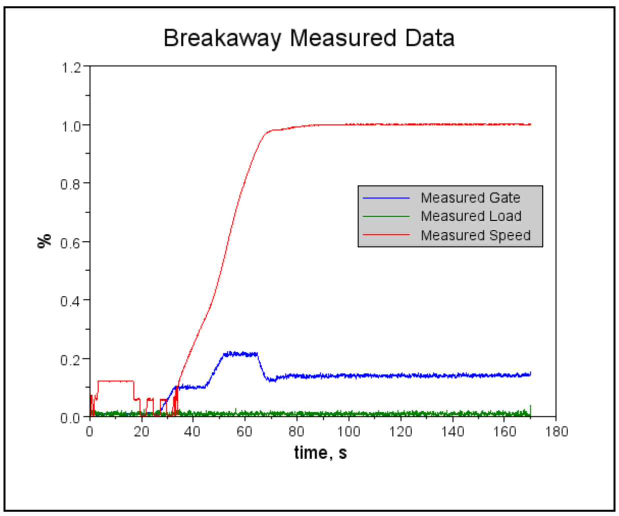

Figure 3: Measured Breakaway Sequence

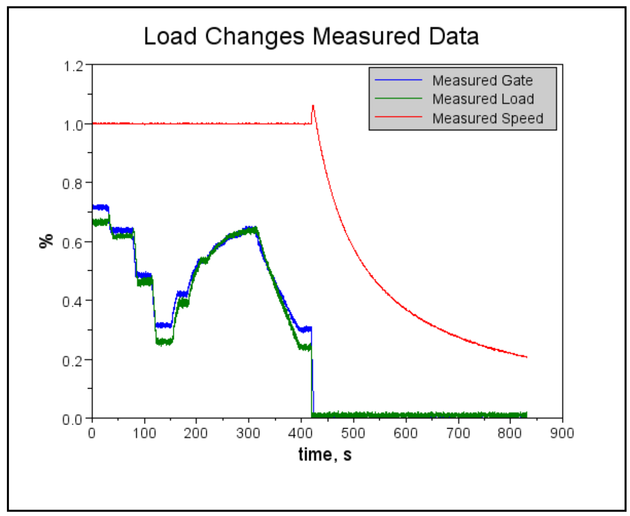

Figure 4: Measured Loading Sequence

2.2 Numerical Optimization of Model Parameters

After some basic post-processing of the data collected, a concatenation of data samples from various performance test trials was produced and used for model fitting. In order to fit the theoretical model to the empirical performance data, AGC employed a numerical gradient optimization routine in which a cost function was minimized. This cost function was defined as the variance of modeled speed to unit speed as sampled from the performance test data. In this cost function, penalties were also assessed on iterations that resulted in infeasible states or flows.

Using this methodology, the model parameters which resulted in the lowest cost function were calculated. In following such a process for the optimization of the system model, minimal time was spent defining these empirical constants, and acceptable accuracy of the model was achieved through automated iterative computing techniques.

2.3 Confirming Model Accuracy

With optimal parameters calculated, the system model was then compared to that of the unit measured at Castaic PSP. Through visual inspection of measured vs. modeled speed response to gate position, the model proved accurate in capturing the specific dynamics of the turbine-penstock system with surge tank effects. It should be noted, however, that inconsistencies between the model and test data were observed, as would be expected with any model. As illustrated in Figure 6, the modeled speed begins to deviate from its measured value below approximately 35% of rated unit speed. This was explained during the validation process by the presence of a continuously operating high pressure lift pump on the real unit which the established model did not have any mechanism for representing. The supposition was made during this validation process that a similar effect in the unit breakaway sequence (Figure 5) might explain the slight speed inconsistencies (for t > 40sec) taking into account the measured speed (for t < 40sec) represents a data acquisition anomaly, and not actual unit data.

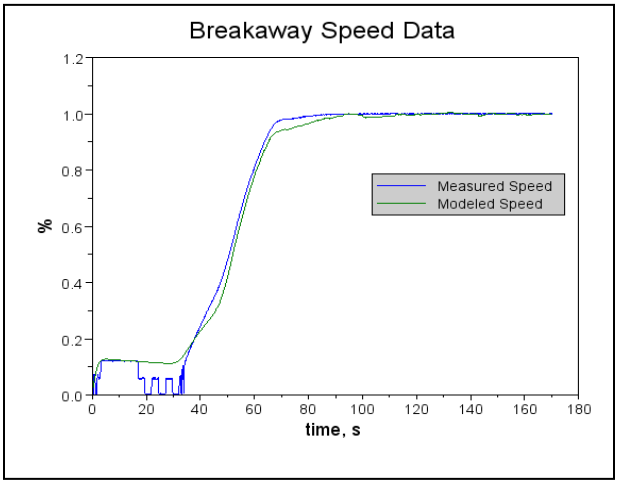

Figure 5: Modeled Breakaway Sequence

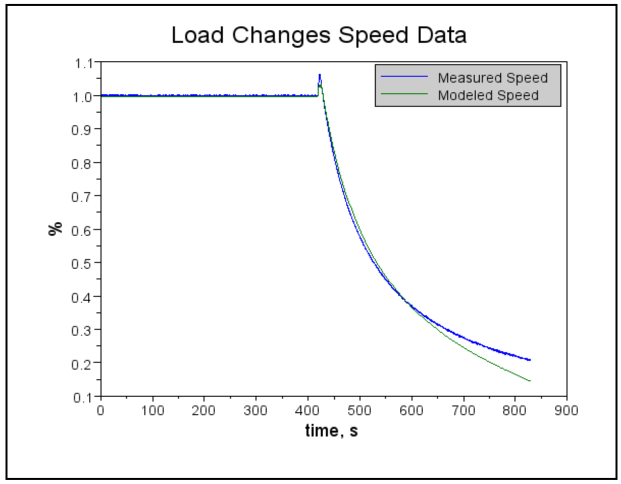

Figure 6: Modeled Load Reject Sequence

With these observations made, it was determined that considering the purposes of the model, and accounting for the time and cost constraints on testing, the model as established would accurately represent the typical dynamics of a unit at Castaic PSP. With the model validated, the key equations and parameters could be used to simulate operations at Castaic, and provide a virtual mechanism for tuning the governor control parameters before commissioning the unit.

3. Optimizing Turbine Control Parameters for a Modernized System

By utilizing the parameters of the theoretical model which most closely emulated the Castaic PSP turbine-penstock system, AGC was able to use the established model to manually iterate on a series of governor parameters in the same manner that would occur during field commissioning. In doing so, these parameters were established and used as the initial settings for the commissioning of the first new digital governor (Commissioned: August 2011).

3.1 Determining Optimal PID Parameters

In order to determine the PID gains best suited to provide responsive and stable control of the units at Castaic PSP, the established model was configured for use in a plant simulator in the AGC Digital Controls Office, and made to run in an offline state. In that way, the governor equipment to be installed at Castaic PSP could be connected to the plant simulator using the optimized model, and allowed to regulate speed as if it were controlling an actual isolated unit. With the simulator running, and the governor in its basic Speed Control Mode the system was configured to accept changes to the Speed Reference used in the Speed Governing equation:

$$\begin{bmatrix} Unit \\ Speed \end{bmatrix}(\%) = \begin{bmatrix} Speed \\ Reference \end{bmatrix}(\%) - \left\{ \begin{bmatrix} Gate \\ Setpoint \end{bmatrix}(\%) \times \begin{bmatrix} Droop \\ in\ Use \end{bmatrix} \right\} \qquad (16)$$

Through a series of iterations using the proprietary PID tuning method AGC utilizes during the standard governor commissioning process, an optimal set of gains was determined virtually and later used in the initial trials at Castaic PSP (see the Section 4.1 for validation remarks).

3.2 Determining Optimal Megawatt Feed-Forward Parameters

Similar to the determination of optimal PID gains, an optimal set of MW feed-forward parameters for the plant model was determined through a similar simulation process as would occur if one were performing such tests on an actual unit. With the simulator running, and the governor in its Load Control Mode the system was configured to accept changes to the Megawatt Setpoint used in the Load Control equation:

$$\begin{bmatrix} Unit \\ Speed \end{bmatrix}(\%) = 100 + \left\{ 100 \times \left(\frac{\begin{bmatrix} MW \\ Error \end{bmatrix}}{\begin{bmatrix} MW \\ Max \end{bmatrix}} \right) \times \begin{bmatrix} Droop \\ in\ Use \end{bmatrix} \right\} \qquad (17)$$

Over a series of iterations using the load control tuning method AGC utilizes during the standard governor commissioning process, an optimal set of parameters was determined virtually and later used in the initial trials at Castaic PSP. (see the Section 4.2 for validation remarks).

4. Validating the Optimized Turbine Control Parameters on the Modernized System

In order to verify the efficacy of the turbine control parameters established through the methods discussed in Section 3, initial tuning trials were performed during the commissioning of the first modernized turbine control system at Castaic PSP using these parameters. After these initial values were tested, further trials were done following the standard AGC tuning method in order to finalize and perfect the parameters of the controller on the real system. By comparing the PID and feed-forward parameters determined through model testing with those determined in situ, AGC was able to assess the accuracy of the model developed.

4.1 Validating the Optimal PID Parameters

During initial trials with the PID gains derived from simulation, it was immediately apparent that the unit was stable. After the unit accelerated through its breakaway sequence and began PID operations near synchronous speed, it was clear that even for significant speed fluctuations the governor provided a damping effect which restored the system to a steady state value. This converged system was not critically damped, however. Instead, when observing the trending data recorded during these trials (see Figure 7) it is apparent that this system was slightly underdamped. Consequently, using these values for the PID gains provided a clear starting point from which to precisely tune the PID response for the real system at Castaic PSP.

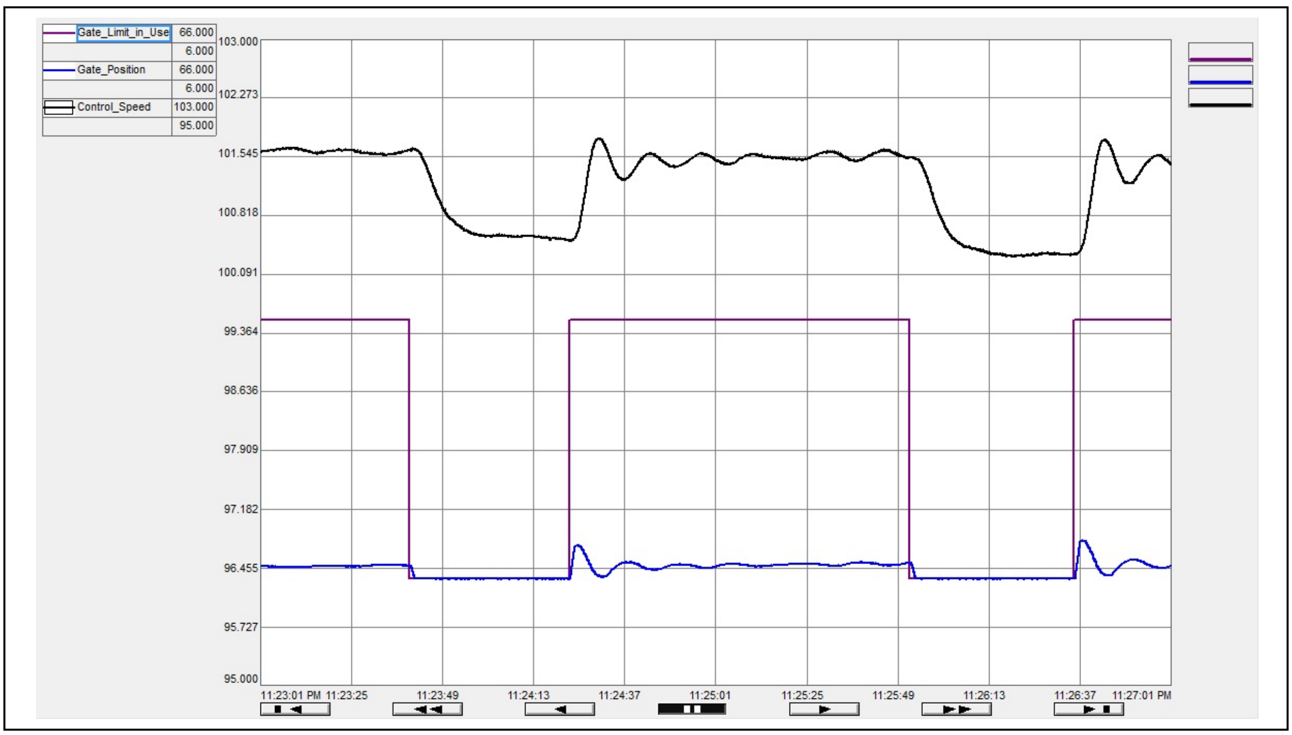

Figure 7: PID Response with gains derived from Simulation

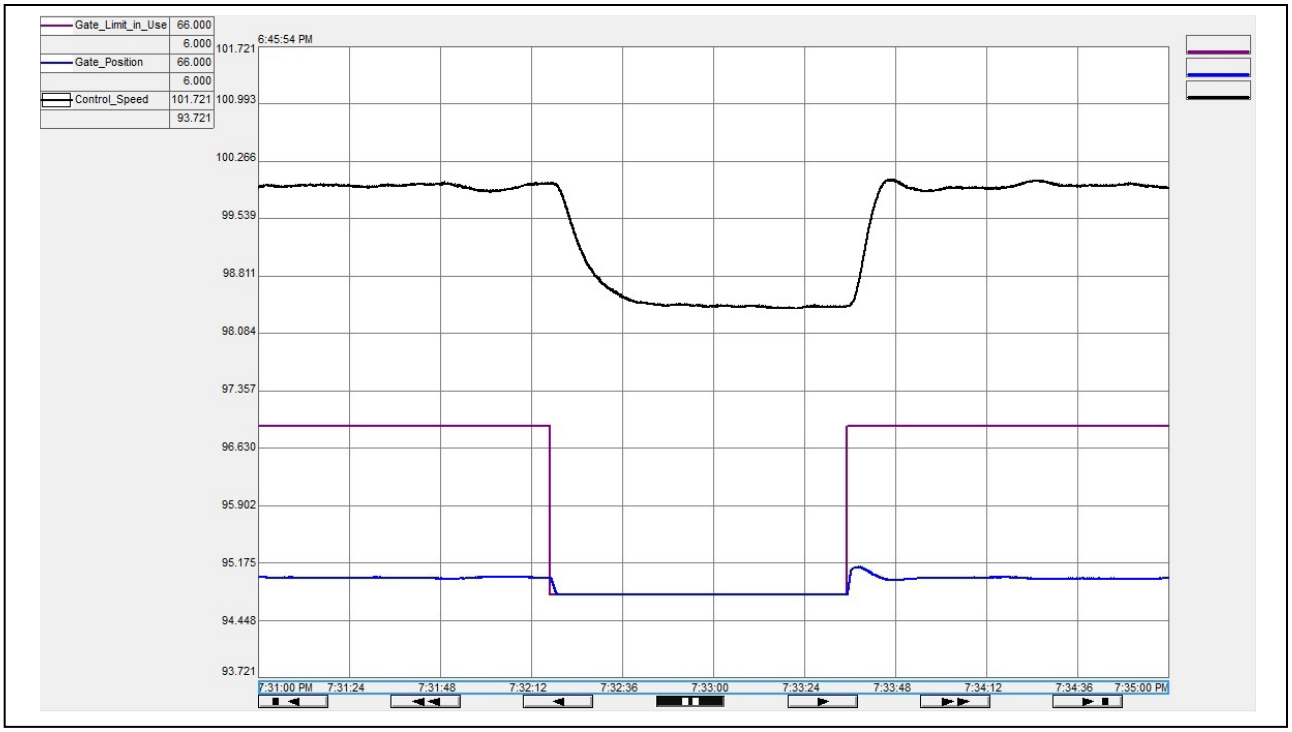

Figure 8: PID Response with gains derived from Commissioning

In fact, only minor adjustments to the initial PID gains were required thus validating the simulated model as one capable of providing an acceptable level of accuracy for such predictive tuning purposes. Figure 8 illustrates the final PID response and shows the critically damped system attained through real trials.

4.2 Validating the Optimal Megawatt Feed-Forward Parameters

The efficacy of the simulation at capturing the power response of a typical unit at Castaic PSP also proved to be acceptable. During initial trials, with the unit placed into load control, the Megawatt feed-forward parameters determined through simulation proved to be capable of overriding the integrator component of the PID logic accurately. As illustrated in Figure 9 this initial response was, however, also slightly underdamped. As a result the gates responded more than needed causing an overshoot in the power output as compared to the power setpoint. This was generally, however, not out of an acceptable range, and allowed for relatively quick tuning of Load Control to achieve stable operation (see Figure 10). Because of this advance knowledge, undue fluctuations of power could be avoided during this initial phase of testing.

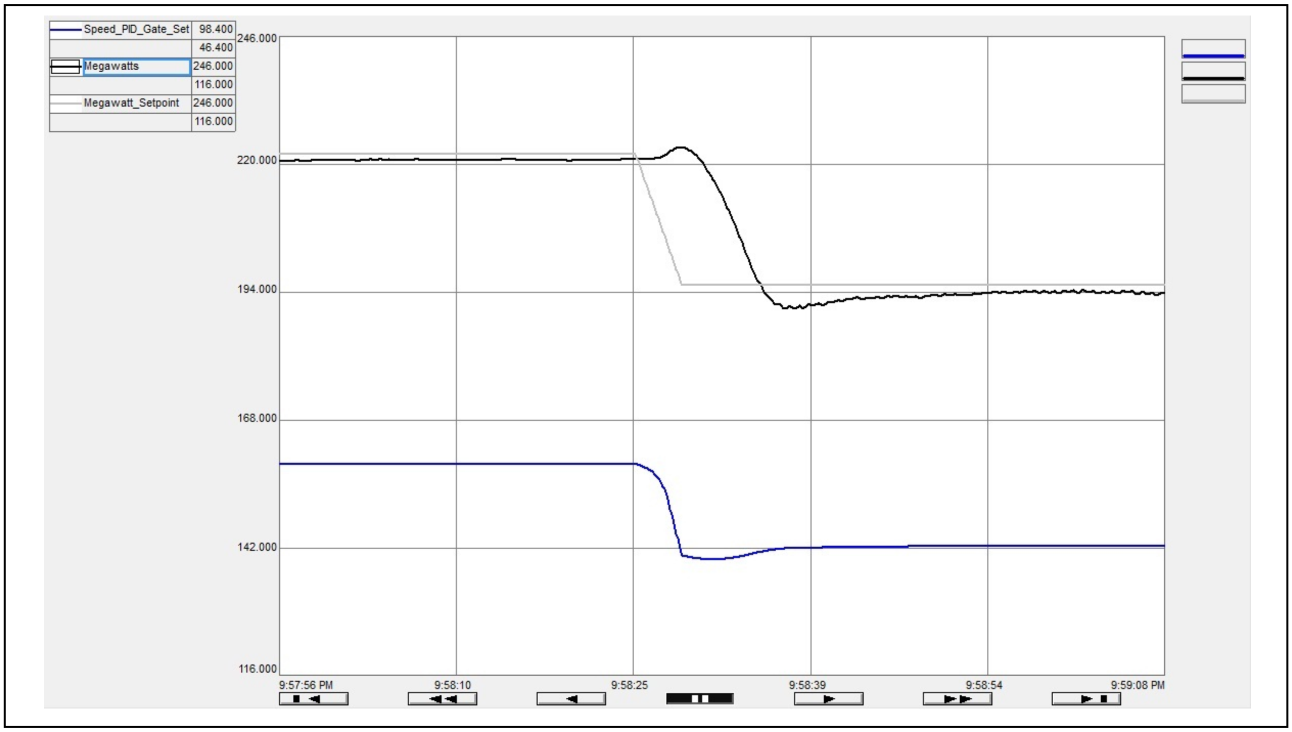

Figure 9: MW Feed-Forward Response with gains derived from Simulation

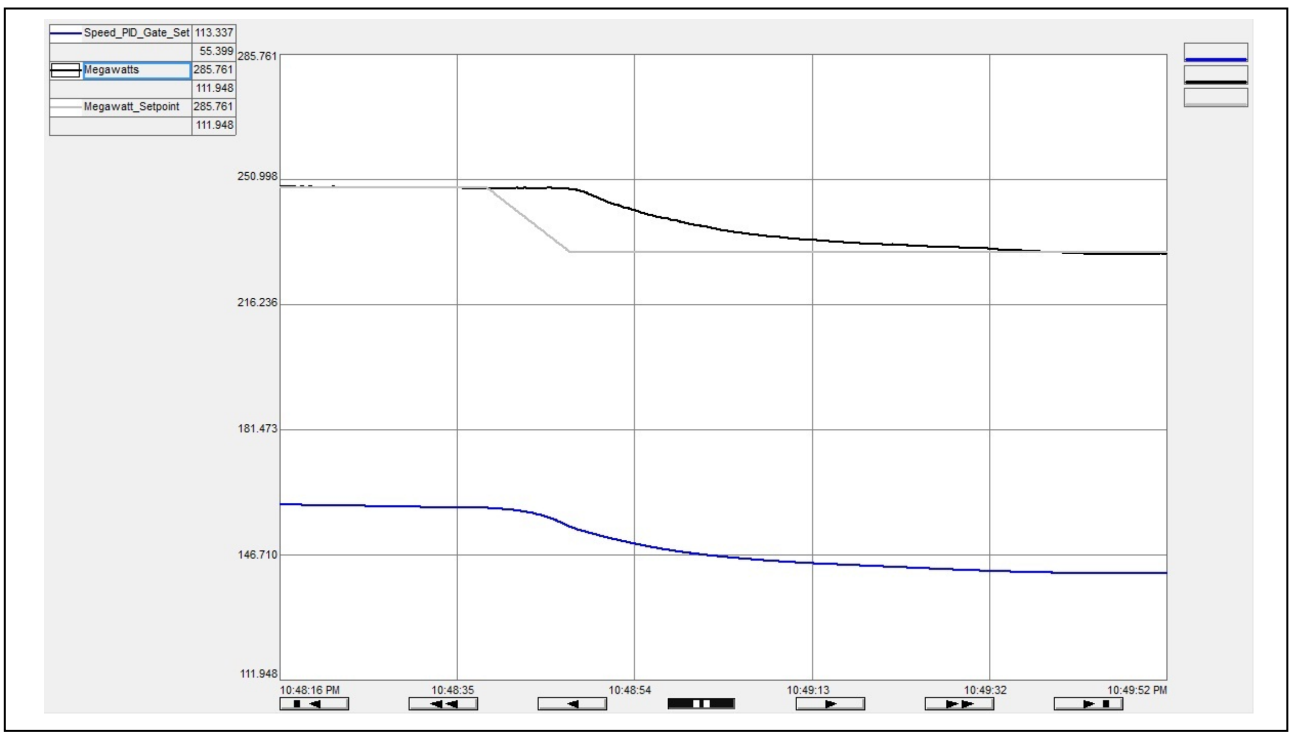

Figure 10: MW Feed-Forward Response with gains derived from Commissioning

In this regard, the model proved capable of capturing the power response of the system. However, it is worth noting that in practice the error-based Megawatt feed-forward scheme utilized during simulation and initial testing proved to lack the level of precision and repeatability across the power curve and for varying setpoint ramp rates that LADWP required for these critical infrastructure assets. Additionally, because each turbine-penstock system was fed from a common distribution header, there existed a high likelihood of hydrodynamic interaction between units. For these reasons, the predictive scheme utilizing the error on megawatt setpoint was later abandoned, and a fully deterministic approach to load control was implemented. After confirming model integrity using the original scheme, however, it is posited here that similar validity would be observed if the model was ran through additional iterations using the deterministic approach now implemented at Castaic PSP.

5. Conclusions

Through the process described in the preceding sections, AGC was able to develop a nonlinear turbine-penstock model and optimize its defining parameters to accurately represent a typical unit at Castaic Pumped Storage Powerhouse. Using this model AGC was then able to iteratively tune the virtual system before commissioning and thus be positioned to quickly tune the real system with the advanced knowledge of its dynamics. Although the model itself did not fully capture all system effects (e.g. high pressure lift pumps, hydrodynamic interactions between units, etc.) the level of accuracy attained in this virtual tuning was sufficient to afford AGC insight into the nature of the system and how best to control it.

5.1 Quality of Results vs. Optimization Time

When considering the quality of the results of the model with respect to the time it takes to achieve them, there are some interesting points to note. For one, due to the fact that the optimization algorithm is automated, achieving an accurate model of a given powerhouse can be determined relatively quickly. For instance, in the case of the Castaic PSP model, a converged solution to the parameter optimization routine was achieved in less than 48 hours of computing time on an average personal computer. Because this turbine-penstock model included the effects of a surge tank and elastic water column in the penstock, it required a 13-dimensional optimization routine which would generally be larger than the type required for more standard hydraulic plant arrangements. Even so, once the model has been developed, creating a plant-specific model only requires executing the optimization routine with a constituent sample of plant performance data.

5.2 Applications

The purpose of developing this model, and following the procedure outlined on the preceding pages, was to assign control parameters for operation of the new digital governor system at Castaic PSP. For that purpose it performed well in capturing the speed profile of the turbine as a function of variable flow rates through the turbine-penstock system. Through that success it reasons to posit that a procedure as outlined could be used as a cost-effective method for providing advanced knowledge of the system dynamics of any given hydro power plant. Instead of basing initial tuning decisions on calculation of theoretical time constants (water starting time, and machine starting time) and using these constants as inputs to generalized equations to attain PID gains, the engineer can directly experiment on the virtual power plant making such initial tuning efforts more accurate.

In addition to affording the user an opportunity to tune a virtual representation of a turbine-generator in advance of its actual commissioning, this type of nonlinear modeling technique can provide other tangible benefits. For instance, after a model has been properly selected, and the system optimized to real performance data, the plant has acquired a model that can be used as part of a more inclusive plant-wide model. This can help with load response mapping and simulation of system disturbances both with energy control centers and other grid management organizations. Additionally, such models can be directly incorporated into plant simulator equipment, as was done in Section 3, in order to afford plant personnel an accurate representation of the governor and plant response for training or troubleshooting purposes.

5.3 Summary

Although challenges arise when trying to mathematically solve a system of differential equations, which serves as a turbine-penstock model, solutions are available to numerically solve such systems. By correctly identifying the system model which most accurately represents the system under analysis, then resolving that system into state space form, a numerical optimization routine can be employed to fit the model most accurately with existing plant performance data. In this way, an accurate turbine-penstock simulator can be quickly developed and tailored for many different power plant scenarios. As with any model, such a simulator would undoubtedly have its areas of agreement and disagreement with that of the real equipment. However, for general purposes, such a setup can serve to predict system behavior thus reducing commissioning time, or emulate system behavior and serve as a general simulator for test equipment. Incorporating an automated optimization routine as discussed in this paper, therefore, can serve to produce highly accurate non-linear models of such hydrodynamic systems even as the mathematics defining them evolves into even more complex non-linear representations.

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   Cornell University

Bibliography

1. Oscar Daniel Quiroga. "Modeling and Non-Linear Control of Voltage Frequency of Hydroelectric Power Plants." Universidad Politecnica de Catuluna, Doctorial Thesis, Ch. 3, July 2000.
2. C. K. Sanathanan ."Accurate Low Order Model for Hydraulic Turbine-Penstock." IEEE Trans On Energy Conversion, Vol. EC-2, No. 2, pp. 196-200 June 1987.
3. C. K. Sanathanan. "A Frequency Domain Method for Tuning Hydro Governors." IEEE Transactions on Energy Conversion, Vol. 3, No. 1, pp. 14-17, March 1988.
4. Y.C. Choo and K. M. Muttaqi. "Modeling of Hydraulic Turbine for Dynamic Studies and Performance Analysis." University of Tasmania.
5. Larry Clifton. "Bart Lake Governor Study." Clifton Labs, Ltd. May 21, 2008.
6. R. Oldenburger and J. Donelson. "Dynamic Response of a Hydroelectric Plant." October, 1962.
7. Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies. "Hydraulic Turbine and Turbine Control Models for System Dynamic Studies." Transactions on Power Systems, Vol. 7, No. 1, pp. 167-179, February 1992.
8. Bruno Strah, Ognjen Kuljaca, and Zoran Vukic. "Speed and Active Power Control of Hydro Turbine Unit." IEEE Transactions on Energy Conversion, Vol. 20, No. 2, pp. 424-434, June 2005.
9. D.B. Arnautovic and D.M. Skataric. "Suboptimal Design of Hydroturbine Governors." IEEE Transactions on Energy Conversion, Vol. 6, No. 3, pp. 438-444, September 1991.
10. Nand Kishor, S.P. Singh, A.S. Raghuvanshi. "Dynamic simulations of hydro turbine and its state estimation based LQ control." Energy Conversion and Management 47 (2006) 3119-3137.
11. E. De Jaeger, N. Janssens, B. Malfliet, and F. Van De Meulebroeke. "Hydro Turbine Model for System Dynamic Studies." IEEE Transactions on Power Systems, Vol. 9, No. 4, pp. 1709-1715, November 1994.
12. Nand Kishor, R.P. Saini, S.P Singh. "Simulation of reduced order hydro turbine to study its hydraulic transient characteristics." Indian Institute of Technology.
13. Larry Clifton and James Golder. "Sitka Governing Study Phase 1 System Model Revision 01." Clifton Labs, Ltd. March 31, 2009.

Appendix A – Performance Test Procedure (April 2011)

a. Offline Tests

i. Breakaway and Initial Acceleration
   1. Begin with the unit in a complete shutdown state.
   2. Issue a start command and allow the unit to accelerate to near synchronous speed without connecting the system to the grid.

ii. Gates at Coincidence
   1. Begin with the unit at or near synchronous speed.
   2. Lower the gate limit until the gate position remains fixed against the gate limit. This will effectively eliminate the speed control functionality of the governor and provide data describing the intrinsic speed stability of the unit.
   3. After 2 minutes, raise the gate limit until the gate position is no longer at coincidence with the limit.

iii. Gate Limit Suppression
   1. Begin with the unit at or near synchronous speed.
   2. Lower the gate limit significantly enough to reduce the speed of the unit.
   3. After the speed decreases by approximately 1%, quickly raise the gate limit allowing the governor to return the system to synchronous speed.

iv. Gate Position Control
   1. Begin with the unit at or near synchronous speed. Disable the governor PID if active by placing the unit into its maintenance/test mode.
      a. Record the gate position at which synchronous speed is reached.
   2. Slowly ramp the gate position higher to achieve 105% speed.
      a. Record the gate position at which 105% speed is reached.
      b. Calculate the amount of added gate needed above Speed-No-Load gate position to achieve 105% speed. Call this amount X.
   3. Return the unit to synchronous speed. Ensure the gate limit remains higher than the gate position required for 105% speed.
   4. Quickly change the gate setpoint to [SNL+X]
   5. After 30 seconds, quickly change the gate setpoint to [SNL-X]
   6. After 30 seconds, quickly change the gate setpoint to [SNL+X]
   7. After 20 seconds, quickly change the gate setpoint to [SNL-X]
   8. After 20 seconds, quickly change the gate setpoint to [SNL+X]
   9. After 10 seconds, quickly change the gate setpoint to [SNL-X]
   10. After 10 seconds, quickly change the gate setpoint to [SNL+X]
   11. After 05 seconds, quickly change the gate setpoint to [SNL-X]
   12. After 05 seconds, quickly change the gate setpoint to [SNL+X]
   13. Return the unit to synchronous speed.

b. Online Tests (Generating)

i. Gates at Coincidence
   1. Begin with the unit generating at approximately 25% of rated output.
   2. Lower the gate limit until the gate position remains fixed against the gate limit. This will effectively eliminate the speed control functionality of the governor and provide data describing the intrinsic power stability of the unit.
   3. After 2 minutes, raise the gate limit until the gate position is no longer at coincidence with the limit.

ii. Full Range Loading
   1. Begin with the unit generating at its minimum possible output.
   2. Slowly ramp the gate position up until the unit is generating at its maximum possible output after 10 minutes.

iii. Load changes
   1. Begin with the unit generating at its maximum possible output.
   2. After 20 seconds, ramp the gate position down by 10% at 2%/sec.
   3. After 20 seconds, ramp the gate position down by 20% at 2%/sec.
   4. After 20 seconds, ramp the gate position down by 30% at 2%/sec.
   5. After 20 seconds, ramp the gate position up by 10% at 2%/sec.
   6. After 20 seconds, ramp the gate position up by 20% at 2%/sec.
   7. After 20 seconds, ramp the gate position up by 30% at 2%/sec.

iv. Load Rejection
   1. Begin with the unit generating at approximately 50% of rated output.
   2. Issue an emergency trip causing a load rejection.
   3. Allow the unit the coast down as normal without prematurely engaging the brakes.