Improved accuracy optimal tuning method for hydropower units’ governor controller

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Abstract. This paper aims to improve the model of the hydro-turbine system under the effect of water-hammer for frequency-domain studies. It brings out a novel way to overcome the accuracy limitation linked to the simple first and second-order approximations of the gate-turbine transfer function. The proposed study is based on the detailed model of the hydraulic system considering the effects of water compressibility and pipe elasticity. The improved system is controlled using particle-swarm optimization algorithm, which is shown to be very efficient in controlling the overshoot and stability of the system connected to a single machine single load test system. Step response and load disturbance are simulated. Results from our example prove that covering accurately a frequency range from 0 to over 30Hz is easily made when using this method for frequency-domain simulations of hydropower plant load-frequency control.

1. Introduction
Dynamic characteristics of the hydro-turbine and governor system considerably influence the performance of any power system subjected to load or fault disturbances. In the case of turbine load acceptance or rejection under governor control, emergency shutdown or unwanted runaway, opening-closure of the safety shutoff valve, a pressure wave is induced in hydraulic systems, along with rotational speed variations in hydraulic turbomachinery (turbines, pump-turbines, storage pumps)[1]. Due to noise and vibration consequently occurring in the pipes and penstock, water-hammer phenomena may lead to a collapse and affect the power system[2].

Numerous model structures and approximations for the different types of governors and the hydraulic effects in the penstock have been developed in research articles to support accurate studies of dynamic response[3]. On the one hand, fully detailed non-linear hydro-turbine models exist for studies under the effect of water hammer concerning large variation in frequency and power output such as islanding, load rejection, and system restoration[3]. Still, these non-linear models need not be turned into rational transfer functions and hence are not readily valid for frequency-domain studies[4]. On the other hand, the validity of first-order transfer functions approximated models, used to represent the dynamics of hydraulic turbines near the frequencies of electromechanical oscillations has been questioned and second-order models have also been proposed[5].

Several methods are used for tuning the PID parameters. They range from standard techniques, such as the root locus or Ziegler-Nichols methods, to heuristic techniques using multi-objective non-
derivative optimization techniques, such as Bacterial Foraging Algorithm, Genetic Algorithm, Simulated Annealing, Tabu-Search Algorithm, Ant-Lion Algorithm and Particle Swarm Optimization (PSO)[6,7]. Trending publications are also applying gain scheduling, robust optimal control theory, adaptive control, and neural networks to the specific controller design problem for hydro-turbines. The PSO-PID controller is proven to possess the ability to reject plant anomalies in its search for optimal solutions.

In this paper, an improved accuracy hydro-turbine modelling method is proposed. At first, the hydro-turbine model with the water-hammer effect for hydro-generator unit frequency-domain studies is discussed and implemented. Secondly, the optimization model is presented along with the chosen PSO tuning algorithm. In Section 4, graphical results, showing the dynamic response of the improved and controlled system subjected to disturbances, prove the applicability. Finally, conclusions are drawn in Section 5.

2. Plant Model

2.1. Basic Knowledge

The study of the HPP is generally carried out using a linearized block diagram[1] shown in Figure 2 for a single machine single load test system. The model of the hydropower plant is later developed using MATLAB/Simulink.

General simplifications are made to the governor’s servo-system and the generator-load unit to simplify the frequency study. Considering the linearized dynamic equation of the generator as:

\[ H \frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e - \beta \Delta \omega \]  

Assumptions are made: \( \beta = 0 \) (\( \beta \) damping coefficient) and \( \Delta P_e = k \Delta \omega \). The transfer function of the generator-load model becomes:

\[ \frac{G_{\text{Gen-Load}}(s)}{s+\alpha} = \frac{1}{Hs+\alpha} \]  

\( H \) and \( \alpha \) are, respectively, the inertia time constant and the load-frequency sensitivity of the unit.

Presently available speed governors’ types for hydraulic turbines are essentially electro-hydraulic mainly as shown in Figure 1. The speed sensing, permanent droop, temporary droop and other measuring and computing functions can be performed electrically in this type of governor. The electric components provide greater flexibility and improved performance with regard to dead bands and time lags. The dynamic characteristics of electric governors are usually adjusted to be similar to those of the mechanical–hydraulic governors.

Some electro-hydraulic governors are provided with three-term controllers with proportional-integral-derivative (PID) action to allow the possibility of higher response speeds by providing both transient gain reduction and transient gain increase. The common PID type governor shown in Fig. 1 is considered in this paper. One should note that this specific type is just used for demonstration purpose, but the method is not restricted to any PID type. Its transfer function is:

\[ G_{\text{PID}}(s) = K_p + \frac{K_i}{s} + K_d \]
For the governor:

\[
G_{\text{gov}}(s) = \frac{1}{T_s s + 1}
\]  

(4)

Kp, Ki, Kd are initially all manually set but yet to be optimized (Section 3).

Figure 1. PID governor

Figure 2. Hydraulic turbine regulating system

In the below equation, the pressure waves traveling in the penstock, thereby inducing the water-hammer effect, are taken into account inside the expression of the governor gate-opening to the turbine mechanical power transfer function:

\[
\frac{\Delta P_w(s)}{\Delta G_{\text{gov}}(s)} = \frac{1 - (T_{wp}/T_{ep}).\tanh(T_{ep}.s)}{1 + \frac{1}{2}(T_{wp}/T_{ep}).\tanh(T_{ep}.s)}
\]  

(5)

\(T_{wp}\) is the water starting-time of the hydropower plant.

\(T_{ep}\) is the elastic time of the penstock.

2.2. Proposed Gate-Turbine modelling method

The expression showed in (5), however, is irrational in s and, therefore, needs to be linearized, with respect to the complex frequency, in order to make it fit into a linear system model. Thanks to the work of R. E. Goodson and Gingold et al. (1988)[8] on mathematical power product expansions[9], the hyperbolic tangent function is turned into its infinite product expansion equivalent:

\[
\tanh(T_{ep}.s) = \left(1 - e^{-2T_{ep} s}\right) \left(1 + e^{-2T_{ep} s}\right)^{-1}
\]  

(6)

\[
\tanh(T_{ep} s) = s.T_{ep} \left[ \prod_{n=1}^{\infty} \left(1 + \left(\frac{s T_{ep}}{n \pi}\right)^2\right) \right]^{-1} \left[ \prod_{n=1}^{\infty} \left(1 + \left(\frac{2s T_{ep}}{(2n-1) \pi}\right)^2\right) \right]^{-1}
\]  

(7)

The final transfer function becomes a rational fraction of two \([4n-3]\)-th degree polynomials. Considering the fact that numerical solvers mainly don’t simplify the similar denominator expression in the hyperbolic tangent function present both in the numerator and the denominator of expression (5):
\[
\frac{\Delta P_n(s)}{\Delta G_{gov}(s)} = \frac{p_{4n-3}(s)}{q_{4n-3}(s)}
\]  

(8)

First, the transfer function block parameters are defined as two different row-vector variables: NumCoeff and DenomCoeff, which contain respectively the coefficients of \( p_{4n-3}(s) \) and \( q_{4n-3}(s) \) ranked from the lowest to the highest order coefficient. Second, the elements of NumCoeff and DenomCoeff are passed to them from a script. This so designed script now only needs the freely chosen order \( n \) as main input and also the HPP’s elastic time and water starting time as variables to define the governor gate-opening to turbine mechanical power transfer function.

As high as the approximation order \( n \) might be chosen, the main task is now reduced to obtaining the coefficients of \( p_{4n-3}(s) \) and \( q_{4n-3}(s) \).

A linearized model of hydro-electric plant with water hammer effect can hence be developed by considering \( n \)-th order approximation for stability analysis.

![Gate-Turbine modelling method](image)

Figure 3. Gate-Turbine modelling method

In this model, the measured synchronous generator speed is fed back and compared with the reference speed signal. The resulting speed deviation is used as an input for the PID speed-governor. The governor then produces the control signal, causing a change in the gate opening. The turbine produces the mechanical torque driving the synchronous machine generating the electrical power as output. PID controller gain values are fixed by hand-tuning according to the required response of control system. Load disturbances are modelled through \( \Delta P_e \) in Figure 2.
Figure 4. Accuracy of the first-six orders lumped-parameter approximations of the frequency response of the governor gate-opening to the turbine mechanical power transfer function considering the water-hammer effects (the higher the order, the more accurate the frequency response).

3. Plant Model

The optimization method is based on the hydraulic system incorporating the improved gate-turbine model block and aims to control the system’s frequency using PSO algorithm.

3.1. Objective function

Designers have the choice between a number of criteria to assess PID controllers’ performance in the frequency-domain analysis such as integral squared error (ISE), integral time-weighted square error (ITSE), integral absolute error (IAE), integral time-weighted absolute error (ITAE). Each of these integral performance criteria has its own drawbacks and advantages regarding error minimization aggressivity, rise time, settling time, steady-state error, complexity and time-consumption of the analytical formula. Among those performance criteria, the ITAE criterion presents a good compromise between a comparatively higher time performance (rise time) and a comparatively lower error-minimization performance (overshoot). Its formula is as follows:

\[
ITAE = \int_0^\infty t |e(t)| \, dt
\]  

In this paper, the ITAE criterion is used for evaluating the PID controller performance[10]. A set of good control parameters Kp, Ki and Kd will come with a minimal computed value of the chosen performance criterion in the time domain including the overshoot, rise time, settling time, and steady-state error. Therefore, having to control the dynamic frequency response of the system, the objective function (fitness or cost) to be minimized is the ITAE of the speed deviation due to a unit step input:

\[
\text{fitness}_{\text{ITAE}} = \int_0^\infty t |\Delta \omega - \Delta \omega(t)| \, dt
\]  

3.2. Constraints

The search-space, defined by the control parameters needs to be bounded. Furthermore, we should ensure the three controller parameters to stay non-zero during all the optimization process so as to guarantee both the proportional, integral and derivative actions on the system. Therefore, the constraints are followingly defined:

\[
0.1 \leq Kp \leq 5, \\
0.1 \leq Ki \leq 5, \\
0.1 \leq Kd \leq 5.
\]
The optimization model does not require any specific governor models and generally applies to various models with different sets of control parameters. It uses at final step the PSO algorithm to fitness the objective function then returns the tuned parameters.

3.3. PSO algorithm

Inspired from social models of adaptation, Particle Swarm Optimization (PSO) algorithm is an evolutionary optimization technique offering strong ability in solving problems featuring nonlinearity and non-differentiability, multiple optima, and high dimensionality. Its procedure derives from research on swarm intelligence such as flocks of birds, fish shoals or insects swarming. PSO algorithm was initially introduced by Kennedy and Eberhart in 1995[11].

A group of N individuals called particles move together in steps throughout a bounded-defined region or solution space. At each step \( k \), the same objective function is evaluated for each particle then recorded along with its current position \( x_i \). Before moving to the next step, the algorithm adjusts the velocity vector \( v_i \) of each particle properly towards a new position determined by the best position found so far by the swarm \( g_b \) (Gbest), and also by the best position found by the particle itself \( p_b \) (Pbest).

Many studies have subsequently been introduced to improve the performance of the PSO with respect to the speed of convergence and to make sure that the algorithm will not get stuck in a local minimum[12,13].

The velocities and the positions of the particles can be updated using the following equations:

\[
\begin{align*}
    v_i^{k+1} &= w v_i^k + c_1 r_1 (p_b - x_i^k) + c_2 r_2 (g_b - x_i^k) \\
    x_i^{k+1} &= x_i^k + v_i^{k+1}
\end{align*}
\]

(11) (12)

\( v_i \) is the particle velocity, \( x_i \) is the current position of the particle in the search-space (solution). \( p_b \) and \( g_b \) are defined as stated before. \( r_{1,2} \) are generated random numbers between (0,1). \( c_{1,2} \) are the learning factors either defined by the practitioner or generated by the algorithm itself in case of recent adaptive-PSO methods.

In this paper, a PSO-PID controller is used to find the optimal parameters of the speed-governor. Fig. 5 shows a block diagram to schematize the optimal control process.

![Figure 5. Optimal PID control](image)
Run simulation model for each particle

Initialize population of 3 dimensional particles (Kp, Ki, Kd)

Evaluate particles’ new fitness function

Evaluate particles’ Pbest

Evaluate population’s Gbest

Record then Update particles’ velocities, positions, particles’ Pbest and population’s Gbest

Max Iteration or Min Fitness tolerance reached?

Yes

No

Start

Stop

Return final Gbest and matching position

Figure 6. Flow-chart of PSO algorithm

4. Simulation results

This simulation is carried out using MATLAB\Simulink. The test system is as shown in Fig. 2 with the compensator replaced by the PID governor shown in Fig. 2. Typical parameters are chosen as H=10s, α=1 and Tg=2s. Kp, Ki, and Kd are initially randomly set to 3, 0.7, and 0.5, respectively.

The main task consists to compute the coefficients of \( p_{n-3}(s) \) and \( q_{n-3}(s) \) as stated before. That is made possible in MATLAB\Simulink using the Simulink Model Callback functions [10]. First, the transfer function block parameters are defined as two different row-vector variables: NumCoeff and DenomCoeff, which contain respectively the coefficients of \( p_{n-3}(s) \) and \( q_{n-3}(s) \) ranked from the lowest to the highest order coefficient. Second, the elements of NumCoeff and DenomCoeff are passed to them from a script through the Simulink\Model Callbacks function InitFcn or, in the case of optimization simulation needing successive automatic model running, through StartFcn. The Callback script now only needs the freely chosen order \( n \) inside the Callback script and the HPP’s elastic time and water starting time as variables to define the governor gate-opening to the turbine mechanical power transfer function. For simulation sake, \( n \) is just taken to 7, that corresponds to an accurate frequency range from 0 to over 30Hz (see figure 4).

As given per our algorithm, the coefficients of the s-domain transfer function of the gate-turbine model become:
Table 1. Coefficients

| Degree | $p_{4e-3}(s)$  | $q_{4e-3}(s)$  |
|--------|---------------|---------------|
| 25     | -1.168e22     | 5.841e21      |
| 24     | 2.296e23      | 2.296e23      |
| 23     | -7.495e25    | 3.747e25      |
| 22     | 1.296e27      | 1.296e27      |
| 21     | -2.059e29    | 1.029e29      |
| 20     | 3.115e30      | 3.115e30      |
| 19     | 3.177e32      | 1.588e32      |
| 18     | 4.174e33      | 4.174e33      |
| 17     | -3.04e35      | 1.52e35       |
| 16     | 3.434e36      | 3.434e36      |
| 15     | 1.879e38      | 9.396e37      |
| 14     | 1.802e39      | 1.802e39      |
| 13     | -7.587e40    | 3.794e40      |
| 12     | +6.072e41     | 6.072e41      |
| 11     | -1.98e43      | 9.9e42        |
| 10     | 1.293e44      | 1.293e44      |
| 9      | 3.236e45      | 1.618e45      |
| 8      | 1.668e46      | 1.668e46      |
| 7      | -3.124e47     | 1.562e47      |
| 6      | 1.209e48      | 1.209e48      |
| 5      | -1.607e49     | 8.034e48      |
| 4      | +4.297e49     | 4.297e49      |
| 3      | 3.631e50      | 1.816e50      |
| 2      | 5.532e50      | 5.532e50      |
| 1      | -2.29e51      | 1.145e51      |
| 0      | 2.29e51       | 2.29e51       |

The result after running the simulation shows an ITAE value equal to 13.19. The corresponding optimized PID-governor parameters are $K_p=3.845$, $K_i=0.254$, $K_d=4.099$.

The response of the system with tuned parameters to step load disturbances ($\Delta P$, as system input perturbation) is compared to the response of a system controlled with literature recommended parameter values for the PID-governor[1].

Time response of the generator speed deviation output to a step load disturbance (in p.u. x10-2Hz):
Figure 7. Comparative time-domain simulations at steady-state

Bode diagram of the system:

Figure 8. Comparative frequency responses

Table 2. Time-domain response characteristics

|                          | Post-tuning frequency response | Literature recommended parameters’ time response |
|--------------------------|-------------------------------|-----------------------------------------------|
| Rise time                | - 0.314                       | 3.15                                          |
| Peak time                | 5.28                          | 5.19                                          |
| Peak Overshoot           | - 0.314                       | - 0.326                                       |
| Settling time 2%         | 57.7                          | 101                                           |
Table 3. Frequency-domain characteristics

| Post-tuning frequency response | Literature recommended parameters’ frequency response |
|-------------------------------|-------------------------------------------------------|
| Peak gain                     | -4.54 dB                                               |
| Gain margin                   | 3.7 dB                                                 |
| Gain margin                   | 6.28 dB                                                 |
| Phase margin                  | -3.5 dB                                                 |
| Phase margin                  | ∞                                                      |
| Gain Crossover-frequency      | 629.9 deg                                              |
| Phase Crossover-frequency     | 0.286 rad/s                                            |
| Phase Crossover-frequency     | 0.325 rad/s                                            |
| Phase Crossover-frequency     | 0.322 rad/s                                            |
| Closed loop Stability?        | Yes                                                    |
| Closed loop Stability?        | No                                                     |

5. Conclusion
In this paper, a computing method for obtaining n-order approximation to the exact irrational hydraulic turbine transfer function in the entire or desired frequency range of electromechanical oscillations was proposed. The traveling waves inducing the water-hammer can be more accurately represented thus reducing the risk of having unpredicted disturbances in the HPP. The model is built and implemented in MATLAB/Simulink software package. Post-optimization results and final plots showing time-domain and frequency-domain responses and characteristics prove its feasibility. Further studies could mainly focus on reducing the computational cost, different optimization algorithms and exploring the effect of non-linearities associated with governor dead-bands.

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References
[1] Kundur, P. (1994) Power System Stability and Control. McGraw-Hill Education, New York.
[2] Bergant A, Mazij J and Karadžić U (2018) Design of water hammer control strategies in hydropower plants. Appl. Eng. Lett., 3:2466–4847. 10.18485/aletters.2018.3.1.5.
[3] IEEE Transactions on Power Systems (1992) Hydraulic turbine and turbine control models for system dynamic studies. IEEE Trans. Power Syst., 7:167–79. 10.1109/59.141700.
[4] Anil, Naik, K., Srikanth, P., Chandel, A., K. (2011) A novel governor control for stability enhancement of hydro power plant with water hammer effect. 2011 International Conference on Emerging Trends in Electrical and Computer Technology, ICETECT 2011, pp. 40–5. 10.1109/ICETECT.2011.5760088.
[5] Vournas, C., D., (1990) Second order hydraulic turbine models for multimachine stability studies. IEEE Trans. Energy Convers., 5:239–44. 10.1109/60.107216.
[6] Ghosal, S., Darbar, R., Neogi, B., Das, A., Tibarewala D., N. (2012) Application of Swarm Intelligence Computation Techniques in PID Controller Tuning: A Review. Springer, Berlin, Heidelberg, pp. 195–208. 10.1007/978-3-642-27443-5_23.
[7] Chen, L., Lu, X., Min, Y., Zhang, Y., Chen Q., Zhao Y., Ben, C. (2018) Optimization of Governor Parameters to Prevent Frequency Oscillations in Power Systems. IEEE Trans. Power Syst., 33:4466–74. 10.1109/TPWRS.2017.2778506.
[8] Goodson, R., E. (1970) Distributed system simulation using infinite product expansions. Simulation, 15:255–63. 10.1177/003754977001500603.
[9] Gingold, H., Gould, H., W., Mays, M., E. (1988) Power product expansions. Utilitas Mathematica, 34:143-161.
[10] Martins, F., G. (2005) Tuning PID controllers using the ITAE criterion. Int. J. Eng. Educ, 21:867–73.
[11] Eberhart, R., Kennedy, J. (1995) A new optimizer using particle swarm theory. MHS’95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science
[12] Shi, Y., Eberhart, R. (1998) Modified particle swarm optimizer. IEEE International Conference on Evolutionary Computation Proceedings. IEEE World Congress on Computational Intelligence (Cat. No.98TH8360) (IEEE), pp. 69–73. 10.1109/ICEC.1998.699146

[13] Shi, Y., Eberhart, R., C. (1999) Empirical study of particle swarm optimization. Proceedings of the 1999 Congress on Evolutionary Computation-CEC99 (Cat. No. 99TH8406) (IEEE), pp. 1945–50. 10.1109/CEC.1999.785511.