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IMC Tuned PID Governor Controller for Hydro Power Plant with Water Hammer Effect

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Abstract

In the present paper a PID governor controller with Internal Model Control (IMC) tuning method for the hydroelectric power plant including water hammer effect is presented. The IMC has a single tuning parameter to adjust the performance and robustness of the controller. The proposed tuning method is very efficient in controlling the overshoot, stability and the dynamics of the speed-governing system of the hydroelectric power plant supplying an isolated/grid connected load. The results of the proposed IMC tuning method have been compared in the midst of controller with singular frequency (SF) based tuning and Ziegler-Nichols (Z-N) closed loop tuning. A remarkable improvement in stability of the system has been observed with IMC tuning justifying its applicability. Simulated results given in the paper show the feasibility and versatility of the IMC tuning technique in hydro power plant in the presence of water hammer effect.

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Keywords: Controller; Internal Model Control (IMC); Hydro plants; Singular Frequency; Speed Governor; Stability; Tuning; Water hammer

1. Introduction

Traditionally and commonly, for the hydropower station with long conduits, when the gate is partially closed, suddenly a pressure wave is set up which moves upstream. This pressure wave can cause major problems due to noise and vibration to a pipe which may lead to its collapse and consequently affects the power system [1]. The operation of a hydro-electric power system with such abnormality is very complex and need to be stabilized. Hence, the stability study of hydroelectric power plant with water hammer effect is of paramount importance and a water hammer model is essential for stability analysis [2-4]. Some of the researchers have developed a non linear model of the turbines under the effect of water hammer. However, these models are not valid for stability study in frequency domain.
The proportional integral derivative (PID) controller is the most common form of feedback in the hydro-generator speed control systems. It is an essential element of the governors and the standard tool in the process control. PID control is also an important ingredient of a distributed control system and as such these controllers come in different forms [5-7]. And also due to its efficient and robust performance with a simple algorithm, the PID (proportional, integral, and derivative) controllers have been widely accepted in most of the industrial applications [8-12]. Ziegler and Nichols have implemented and published their classical methods and also a lot of research is done along the conventional PID controller design [13]. However, the classic tuning methods involved in PID controller suffers with a few systematic design problems.

Hence, in order to compensate these internal design problems, internal model control (IMC) based tuning approach has been developed. Due to its simplicity, robustness, and successful practical applications it gained a widespread acceptance in designing the PID controller in process industries [14-18]. The analytical method based on IMC principle for the design of PID controller is developed [19-20]. The resulting structure of the control system is capable of controlling a fast dynamic process by integral control, which results in a striking improvement in performance. Its advantage is even being implemented in many of the industries. However, it has been found from the literature that the IMC-PID controller has not yet been implemented in the hydro power governing system. Consequently, the present work is a step towards implementing an IMC tuning based PID controller in hydro power plant by considering water hammer effect. The results with IMC tuned controller have been found to outperform the SF and Z-N tuned controllers.

2. Model of hydraulic turbine with water hammer

The turbine transfer function relating the mechanical power to the gate opening is derived and given in eqn. (1) by considering water hammer effect [6].

\[
\frac{\Delta P_m(s)}{\Delta G(s)} = \frac{1 - Z_p \tanh(T_{op}s)}{1 + \frac{1}{2} Z_p \tanh(T_{op}s)}
\] (1)
The above eqn. (1) contains a nonlinear term \( \tanh(T_{ep}s) \) and hence whole equation becomes nonlinear with water hammer effect. It can be linearized by using Taylor’s series expansion. From the eqn. (1) the nonlinear term is linearized and derived as eqn. (2).

\[
\tanh(T_{ep}s) = \frac{T_{ep}s - e^{-T_{ep}s}}{e^{T_{ep}s} + e^{-T_{ep}s}} = \frac{(1 + T_{ep}s)(1 - T_{ep}s)}{1 + T_{ep}s + 1 - T_{ep}s} = T_{ep}s
\]  

(2)

After substituting the eqn. (2) in (1) then the linearized transfer function of the hydraulic turbine with water hammer effect is given in eqn. (3).

\[
\frac{\Delta P_m(s)}{\Delta G(s)} = \frac{1 - Z_p T_{ep}s}{1 + \frac{1}{2} Z_p T_{ep}s}
\]  

(3)

\( Z_p \) = normalized hydraulic impedance of penstock  
\( T_{ep} \) = elastic time of penstock

### 3. IMC-PID Controller design

Fig. 2(a) and 2(b) show the block diagrams of IMC control and equivalent classical feedback control structures, where \( G_p \) the process is, \( \tilde{G}_p \) is the process model, \( q \) is the IMC controller, \( G_c \) is the equivalent feedback controller. In the IMC control structure, the controlled variable is related as

\[
C = \frac{G_pq}{1 + q(G_p - \tilde{G}_p)} R + \left[ \frac{1 - \tilde{G}_p Q}{1 + q(G_p - \tilde{G}_p)} \right] G_D d
\]  

(4)

For the nominal case (i.e., \( G_p = \tilde{G}_p \)), the set-point and disturbance responses are simplified as

\[
\frac{C}{R} = \tilde{G}_p q
\]  

(5)
\[
\frac{C}{d} = [1 - \hat{G}_p q] G_D
\]  

(6)

According to the IMC parameterization the process model \( \hat{G}_p \) is factored into two parts:

\[
\hat{G}_p = P_M P_A
\]  

(7)

Where \( P_M \) is the portion of the model inverted by the controller; \( P_A \) is the portion of the model not inverted by the controller and \( P_A(0) = 1 \). The noninvertible part usually includes dead time and/or right half plane zeros and is chosen to be all-pass. The IMC controller is designed by

\[
q = P_M^{-1} f
\]  

(8)

where the IMC filter \( f \) is usually set as

\[
f = \frac{1}{(T_f s + 1)^n}
\]  

(9)

The ideal feedback controller equivalent to the IMC controller can be expressed in terms of the internal model, \( \hat{G}_p \), and the IMC controller, \( q \)

\[
G_C = \frac{q}{1-qG_p} = K_C \left( 1 + \frac{1}{T_i s} + T_D s \right) \frac{1}{\left( 1 + s T_f \right)^n} \]  

(10)

where \( K \), \( T_i \), and \( T_D \) are the proportional gain, integral time constant, derivative time constant of the PID controller, respectively, and \( T_f \) is the filter tuning parameters/filter time constant.

4. Results and Discussion

A standard test model as considered in [6] is taken for stability study of hydro power plant with IMC tuning controller. The test model below shown is completely designed in SISO tool. Fig. 3 shows the block diagram of speed-governing system of a hydraulic unit supplying an load. The speed governing representation includes transient droop compensation \( G_c(s) \) with governor time constant \( T_g \) of 0.5s.

![Fig. 3. Block diagram of speed governing system](image)

The generator is represented by its equation of motion with a mechanical starting time \( T_M \) of 10.0s and a system damping coefficient of 1.0 per unit. The loads on a power system consist of variety of electrical devices. Motor loads are with variable power frequency characteristics. Since motor loads are
dominant part of the electrical load, there is a need to model the effect of a change in frequency on the net load drawn by the system. The relation between changes in load due to the change in frequency is given by

$$\Delta P_L = D \Delta \omega \quad \text{or} \quad D = \frac{\Delta P_L}{\Delta \omega} \quad (11)$$

Where $D$ expressed as percent change in load divided by percent change in frequency.

To show the robustness of the speed governing system with IMC tuning controller, various cases as given below have been considered. The cases considered have been simulated and verified in SISO tool MATLAB/SIMULINK ver 7.6 [21].

Case a: Singular frequency based design tuning
Case b: Ziegler-Nichols closed loop design tuning
Case c: IMC based design tuning

It is mentioned here that the designed values are taken same as have been provided in [6].

4.1 Case a: Singular frequency based design tuning

To get the singular frequency based design tuning the Fig. 3 is simulated in SISO tool. The frequency response for such a system is computed using the linear approximation (Bode plot). The magnitude and phase as a function of frequency of such a system are plotted in Fig. 4(a). From the plotted graph the gain crossover frequency $\omega_{gc}$ is 0.314 rad/sec and phase crossover frequency $\omega_{pc}$ is 2.41 rad/sec. The gain and phase margins are $m_G = 7.74$ dB and $m_I = 27.8$ deg, $\omega_{gc}$ is less than $\omega_{pc}$ since $\omega_{gc}$ should not be greater than $\omega_{pc}$ for stability of the system. The speed governing system with singular frequency based design tuning is stable.

The step response of the speed governing system with singular frequency tuning in time domain analysis is given in Fig. 4(b). The whole simulation is done for 100s. The rise time $T_r = 3.27$s, peak time $T_p = 9.77$s the peak overshoot $\% M_p = 43$ and settling time $T_s = 51.6$s for this case are obtained. The damping factor ($\xi$) value explains the stability of the system. In general, if $\xi$ value increases then the poles of the transfer function moves towards the left hand side of the s-plane near to the real axis. Hence the damped frequencies of oscillations are decreased. The rise time and peak time of the system increases and peak overshoot decreases. From Fig. 4(b) it has been determined that the peak overshoot in this case has more.

![Fig. 4. (a) Frequency response for SF based design tuning; (b) Responses of the system to a step input with SF based design tuning](image-url)
4.2 Case b: Ziegler-Nichols closed loop design tuning

To achieve such a system of speed governing, the Fig. 3 is simulated in SISO tool. For this system also the frequency response is computed using the linear approximation (Bode plot). The magnitude and phase as a function of frequency are plotted and is as shown in Fig. 5(a). From Fig. 5(a), it is determined that gain crossover frequency $\omega_{gc}$ is 0.57 rad/sec and phase crossover frequency $\omega_{pc}$ is 1.08 rad/sec for this case. The gain and phase margins are $G_m = 5.16$ dB and $\phi_m = 21.2$ deg. Since, $\omega_{gc}$ is less than $\omega_{pc}$ and hence in this case also the speed governing system is stable.

The step response of the Ziegler-Nichols design tuning in time domain analysis is as given in Fig. 5(b). The whole simulation is done for 100s. Rise time $T_r = 1.15$ s, peak time $T_p = 4.87$ s, peak overshoot $\% M_p = 73.8$ and settling time $T_s = 21.2$ s are obtained.

4.3 Case c: Internal Model Control (IMC) based design tuning

This tuning design can be obtained when the Fig. 3 is simulated in SISO tool. The magnitude and phase as a function of frequency for this case are plotted in Fig. 6(a). It is seen from the figure that gain crossover frequency $\omega_{gc}$ is 0.166 rad/sec and phase crossover frequency $\omega_{pc}$ is 0.724 rad/sec. The gain and phase margins are $G_m = 11.8$ dB and $\phi_m = 67.8$ deg. Since $\omega_{gc}$ is less than $\omega_{pc}$ (phase crossover frequency) then the magnitude and phase values of the bode plot are more and positive. The speed governing system with IMC design tuning is stable.

Fig. 5. (a) Frequency response for ZN based design tuning; (b) Responses of the system to a step input with ZN based design tuning

Fig. 6. (a) Frequency response for IMC design tuning; (b) Responses of the system to a step input with IMC design tuning
The step response of the IMC based design tuning in time domain analysis is as shown in Fig. 6(b). For which the rise time $T_r = 7.18s$, peak time is 29.1s, peak overshoot $\%M_p = 0.0028$ and settling time $T_s = 14s$.

Time and frequency domain responses have been determined to investigate the effectiveness of the proposed controller in IMC design tuning. It has been determined that the IMC tuning with controller governor provides the required stability and performance specifications. Frequency-response characteristics allow good insight into the tuning of the control systems compared to time domain responses. The results show that the gain and phase margins are significantly improved with 11.8dB gain margin and 67.8° phase margin. These are obtained from the frequency response of the open-loop system and are as given in Fig. 6(a). It is found from Fig. 6(a) that the phase margin is significantly improved at the critical frequency of inter-area modes between 0.166rad/sec and 0.724rad/sec. On the other hand, 7.74dB and 5.16dB gain margins for the Singular Frequency and Ziegler-Nichols tuning controllers are obtained which are low compared with the IMC tuning controller. Detailed results are as summarized in Table 1.

Table 1. Frequency Domain Results

| Specifications            | S F Based Tuning | Z-N Closed loop Tuning | IMC Based Tuning |
|---------------------------|------------------|------------------------|------------------|
| Gain Margin               | 7.74dB           | 5.16dB                 | 11.8dB           |
| Gain crossover Frequency  | 0.314r/s        | 0.57r/s                | 0.166r/s        |
| Phase margin              | 27.8°           | 21.2°                  | 67.8°           |
| Phase crossover Frequency | 2.41r/s         | 1.08r/s                | 0.724r/s        |

The time domain results for closed loop system are presented in Table 2. Improved results have been obtained with IMC design tuning controller. Generally, a lower peak overshoot and lower settling time are preferred for the better performance of the system.

Table 2. Time Domain Results

| Specifications          | S F Based Tuning | Z-N Closed loop Tuning | IMC Based Tuning |
|-------------------------|------------------|------------------------|------------------|
| Rise time               | 3.27s            | 1.15s                  | 7.18s            |
| Peak time               | 9.77s            | 4.87s                  | 29.1             |
| Overshoot               | 43%              | 73.8%                  | 0.0028%          |
| Settling time (1%)      | 51.6s            | 21.2s                  | 14s              |
From the Table 2 it has been seen that for SF based tuning peak overshoot is 43% and settling time is 51.6s, for Z-N based tuning peak overshoot is 73.8% and settling time is 21.2s and for IMC tuning peak overshoot is 0.0028% and settling time is 14s. From the above it is observed that when compare to SF and Z-N tuning methods IMC tuning method obtained better settling time and peak overshoot, thereby justifying the suitability of the proposed IMC tuning for hydro-electric system with water hammer effect. The time domain responses of all types of tuning methods controller with hydraulic speed governing system comparison are as shown in Fig. 7 for a step set-point speed signal change.

![Fig.7. Responses of the system to a step input with all tuning algorithm controllers](image)

5. Conclusions

A robust IMC tuning based PID controller is proposed for hydro power system with water hammer effect. The proposed tuning method has been found to enhance the stability of the hydraulic unit. Different cases have been considered and compared to justify the suitability of the IMC tuning controller. From Table 1 it is found that the gain margins IMC tuning controller is 4.06dB higher compared with SF tuning controller and 6.64dB higher when compared with Z-N tuning controller, similarly, peak overshoot and settling time has improved with IMC tuning controller with water hammer effect.

References

1. Kamanbadast AA, Shahosseini M, Aghamajidi R. Evaluation of Numerical Method to Analyzed Hammer Effects in a Turbine Penstock Pipe in Hydro Power Plant. *World Applied Science Journal* 2010; 9: 689-94.
2. Vournas CD, Papaioannou G. Modelling and stability of a Hydro Plant with Two Surge Tanks. *IEEE Trans. on Energy Conversion* 1995; 10: 368-75.
3. Parmakian J. *Water Hammer Analysis*. Dover Publications: New York; 1963.
4. Paynter HM. *A Palimpsest on the Electronic Analogue Art*. A. Philbrick Researches:Boston: Mass.
5. Vrancic D, Kristiansson B, Strmcnik S, Oliveira PM. Improving performance/activity ratio for PID controllers. Int. Conf. Control and Automation 2005; p. 834-839.
6. [8] Astrom KJ, Panagopoulos H, Hagglund T. Design of PI controllers based on non-convex optimization. *Automatica* 1998; 34: 585-601.

7. Seborg DE, Edgar TF, Mellichamp DA. Process dynamics and control. John Wiley & Sons, Second edition. New York; 2004.

8. [11] Smith CL., Corripio AB, Martin JJ. Controller tuning from simple process model. *Instrumentation Technological* 1975; 22: 39-45.

9. Ziegler JG, Nichols NB. Optimum settings for automatic controller. *Transactions ASME* 1942; 64: 759-766.

10. Chien IL, Fruehauf. Consider IMC tuning to improve controller performance. *Chemical Engineering Program* 1990; 86: 33-38.

11. Aidan O, Dwyer. *Handbook of PI and PID controller tuning rules*. Imperial College Press: London; 2003.

12. Horn IG, Arulandu JR, Christopher JG, VanAntwerp JG, Braatz RD. Improved filter design in internal model control. *Industrial Engineering Chemical Research* 1996; 35: 33-37.

13. Lee Y, Park S, Lee M. Consider the generalized IMC-PID method for PID controller tuning of time-delay processes. *Hydrocarbon Processing* 2006; p. 87-91.

14. Lee Y, Park S, Lee M, Brosilow C. PID controller tuning for desired closed-loop responses for SISO systems. *AICHE Journal* 1998; 44: 106-15.

15. Morari M, Zafiriou E. *Robust Process Control*. Prentice Hall, Englewood Cliffs; NJ; 1989.

16. Rivera DE, Morari M, Skogestad S. Internal model control, 4. PID controller design. *Industrial Engineering Proceeding Design Deu* 1986; 25: 252-58.

17. Shamsuzzohal M, Lee M. IMC Based Control System Design of PID Cascaded Filter. *SICE-ICASE International Joint Conference* 2006: p.2485-2490.

18. MATLAB/SIMULINK ver. 7.6