

A H_∞ robust control strategy of hydro turbine speed Governor with surge tank

According to hydraulic subsystem speciality of hydro turbine speed governor system, the hydro turbine governor system control model with surge tank for hydraulic structure: reservoir-tunnel-surge tank-penstock-generator was established for the first time. The H_∞ double loop hydro turbine speed governor system robust controller was designed considering the character of hydraulic and power load disturbance. The system parameters and power load disturbance simulation results demonstrate that the controller can effectively restrain impact of system parameters and power load disturbance, keep output speed stable, possess nice robust performance, compared to traditional PID controller, which has more excellent regulating ability of speed and rejection load disturbance performance.

Keywords: Hydro turbine speed governor system; surge tank; double loop; H_∞ robust control; PID

1.0 Introduction

The increasing system complexity has ensured the governor design of hydro turbine remains a challenge and important problem. The performances of hydro turbine governor is one of primary factories which effect power system stability. Plant models are always inaccurate, so the controller has to manage the difference between the true plant model and nominal model used in a design. Many classical advanced control techniques should be applied in governor area in order to realize to full potential of plant over a wide range of operating conditions, The classical control techniques include PID controller, such as chaotic optimization algorithm PID[1][2], neural network-artificial fish algorithm PID[3][3], genetic algorithm PID[4], particle swarm algorithm PID[5]. The advance control strategies consist of dynamic matrix control (DMC)[6], nonlinear control [7-10], variable structure control [11], robust control [12-14] and adaptive control [15-18]. In all the published hydro turbine paper, the hydro turbine is modelled by the ideal hydro

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turbine model, whose complex conduit system is simplified as reservoir-penstock-generator (no surge tank). In fact, when the penstock is longer than 300-500m, the surge tank is set in conduit system. So the hydraulic conduit system composed of reservoir-surge tank-penstock-generator (with surge tank). Because of surge tank existence, the hydraulic power system transient process, water hammer, governor regulator characteristic and power system stability performance show distinct difference compared to that of ideal hydro turbine model. So it is necessary to model the hydro turbine speed governor with surge tank and research its control strategy.

In this paper, the hydro turbine speed governor with surge tank is modelled considering unelastic water column effect. The H_∞ robust control strategy of hydro turbine speed governor is designed in order to improve the control performance of load disturbance and system parameters excursion.

2.0 System model

2.1 HYDRO TURBINE MODEL

In order to partially or outrightly damp water hammer wave transmission, improve hydraulic system stability, the surge tank is constructed in water conduit system. The hydropower plant scheme is shown in Fig.1. Water from the reservoir enters the tunnel, arrives to the surge tank node, then flows through the penstock before reaching to hydro turbine inlet. Next it flows into scroll casing, which evenly distributes around the runner bladers, The runner is mounted on a common shaft with electric generator. The water flows into turbine is regulated by means of wicket gates, opened and closed by electricity-oil servomechanism controlled by governor. The governor acts upon whenever there is mismatch between the torque developed and electrical demand on the generator.

In Fig.1: h_0 : reservoir water head; h_r : surge tank water head; h_t : turbine head; h_{lc} : tunnel water head losses; h_{ls} : surge tank water head losses; h_{lt} : penstock water head losses; h_{lq} : turbine head losses.

q_c : tunnel flow; q_s : surge tank flow; q_i : penstock flow

For modelling system, the hydropower system with surge tank is divided into two subsystems: the first is reservoir-

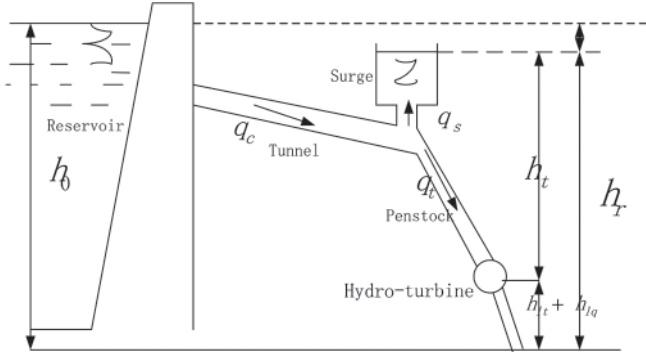


Fig.1: Layout of hydropower plant

tunnel-surge tank, the second is surge tank-penstock-hydro turbine. The transfer function between hydro turbine power flow and power head is [19]:

$$G_{tp}(s) = -\frac{1 + \frac{G(s)}{Z_p} \tanh(T_{ep}s)}{\Phi_p + G(s) + Z_p \tanh(T_{ep}s)} \quad \dots (1)$$

where, $G(s)$ denotes transfer function of the first subsystem between flow and head, and $G(s)$ is:

$$G(s) = \frac{\Phi_c + Z_c \tanh(T_{ec}s)}{1 + sC_s \Phi_c + Z_c \tanh(T_{ec}s) s C_s} \quad \dots (2)$$

Supposing water hammer effect is unelastic, for $n=0$, the hyperbolic tangent function is truncation as: $\tanh(T_{ep}s) = T_{ep}s$, $\tanh(T_{ec}s) = T_{ec}s$.

the equation (1), (2) can simplified as:

$$G_{tp}(s) = -\frac{1 + \frac{G(s)}{Z_p} T_{ep}s}{\Phi_p + G(s) + Z_p T_{ep}s} \quad \dots (3)$$

$$G(s) = \frac{\Phi_c + T_{wc}s}{1 + sC_s \Phi_c + T_{wc}s^2 C_s} \quad \dots (4)$$

where:

T_{wp} : water starting time of penstock; T_{wc} : water sharing time of tunnel; T_{ep} : elastic time of penstock; T_{ec} : elastic time of tunnel; C_s : storage constant of surge tank; f_p : water head losses coefficient of penstock; f_t : water head losses coefficient of tunnel; f_s : water head losses coefficient of surge tank; Φ_p : friction coefficient of penstock; Φ_c : friction coefficient of tunnel; Z_p : hydraulic surge impedance of penstock; Z_c : hydraulic surge impedance of tunnel

Replace equation (4) into (3) the transfer function of unelastic water hammer effect between hydro turbine output power and changes in guide vane position is [19][20]:

$$G_t(s) = \frac{\Delta P_m}{\Delta G} = \frac{1 - \Phi_p - Z_p T_{ep}s + \frac{G(s)}{Z_p} T_{ep}s - G(s)}{1 + 0.5\Phi_p + 0.5Z_p T_{ep}s + \frac{G(s)}{Z_p} T_{ep}s + 0.5G(s)} \quad \dots (5)$$

Ignoring Φ_p and Φ_c , equation (4), (5) can be written as:

$$G(s) = \frac{sT_{wc}}{1 + s^2 T_{wc} C_s} \quad \dots (6)$$

$$G_t(s) = \frac{1 - Z_p T_{ep}s + \frac{G(s)}{Z_p} T_{ep}s - G(s)}{1 + 0.5Z_p T_{ep}s + 0.5G(s) + \frac{G(s)}{Z_p} T_{ep}s} \quad \dots (7)$$

2.2 GENERATOR MODEL

The generator model may be given as:

$$G_g(s) = \frac{1}{Hs + D} \quad \dots (8)$$

where H is the inertia, D is the generator damping.

2.3 SERVO MOTOR MODEL

The servo motor model is given as:

$$G_s(s) = \frac{1}{(T_p s + 1)(T_s s + 1)} \quad \dots (9)$$

Where T_p is the pilot motor time constant, T_s is the gate servo motor time constant.

3.0 Governor control system design

The main outer disturbances of hydro turbine speed controls system include hydraulic disturbance arose by water conduit system and power system load disturbance. Applied robust control theory, the controller whose design is based on the nominal model of the plant should provide stability and performance requirements in the presence of uncertainty. Considering the hydraulic subsystem complexity, the control system is designed as two loops framework as is shown in Fig.2, the inner loop regulator $C_1(s)$ keeps the water wicket gate position stable, the out loop regulator $C_2(s)$ adjusts the power system frequency in given value range.

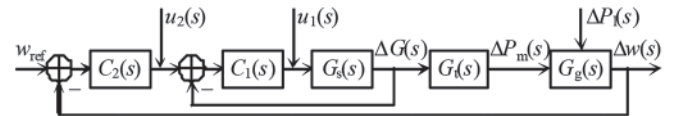


Fig.2: Dual-loop control system of hydroturbine speed governor

Where $u_1(s)$ is inner loop regulator output signal, $u_2(s)$ is out loop regulator output signal, w_{ref} is the given reference speed signal, $\Delta G(s)$ is incremental water gate position deviation, $\Delta P_1(s)$ is incremental power load deviation.

4.0 Case study

For illustration the control system performance, the values of the plant parameters for a typical turbine are assumed to be [19][20]:

$$T_{wc} \in [1.5 \ 5.79], T_{ep} \in [0.25 \ 0.42], D \in [0 \ 1],$$

$$Z_p \in [3.942 \ 4.217], C_s \in [138.22 \ 170.7],$$

$$T_s \in [0.05 \ 0.6], T_p \in [0.005 \ 0.02], H_e \in [4 \ 13.2],$$

During the course of simulation, the parameters is assumed to be:

$$T_{wc} = 4, T_{ep} = 0.35, Z_p = 4.187, C_s = 138.22, T_s = 0.1,$$

$$T_p = 0.25, H = 10, D = 1. Equation (7) may be written as:$$

$$G_r(s) = \frac{-810.1266s^3 + 553.2123s^2 - 5.4654s + 1}{405.0633s^3 + 553.2123s^2 + 2.7327s + 1} \quad \dots (10)$$

4.1. ANALYSIS OF INNER REGULATOR

According to H_∞ robust control design theory, the weights are chosen as:

$W_1 = \frac{0.088s + 3.5}{s + 0.001}$, $W_2 = 0.01$, $W_3 = 0.002 + 0.0001s$, the inner loop regulator $C_1(s)$ may be designed by use of MATLAB7.0.

$$C_1(s) = \frac{9867.8567(s+4)(s+100)}{(s+854.8)(s+189.4)(s+0.001)} \quad \dots (11)$$

In order to evaluate the effectiveness of the proposed robust design, the regulator frequency response characteristics is performed as in Figs.3 and 4. The results show that the regulator has concave low gain round $\omega = 3.17$ rad/s, this low gain can reject outer disturbance. The regulator also fulfills condition of H_∞ robust control requirement $\|WIS\|_\infty < 1$.

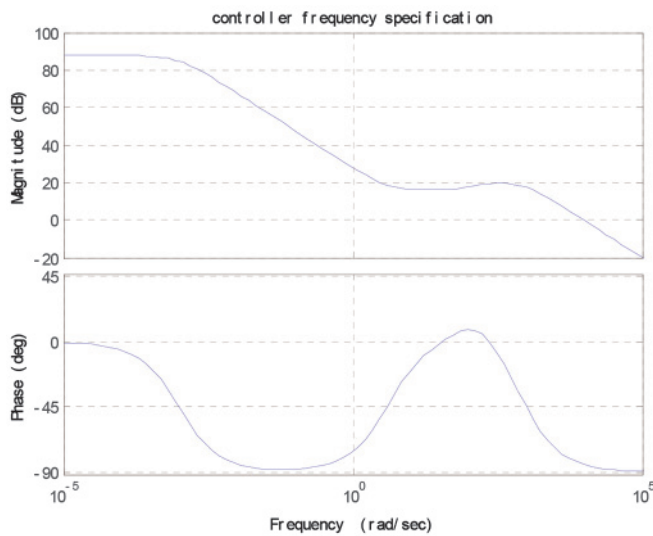


Fig.3: Frequency speciality of controller C1

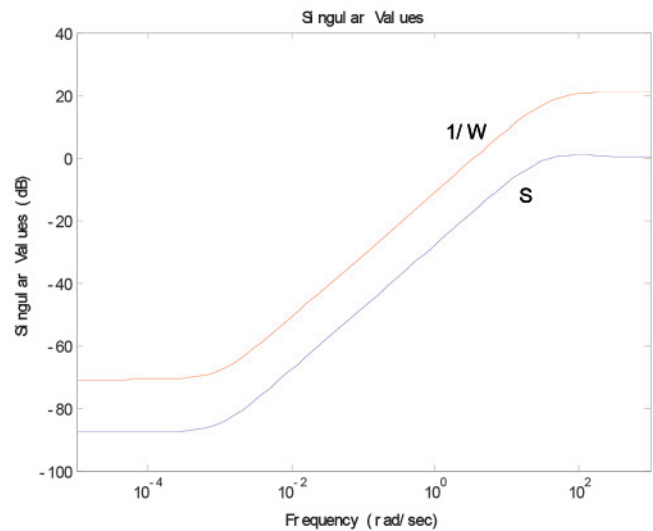


Fig.4: Frequency specialities of S and 1/W1 of inner-loop controller

4.2. ANALYSIS OF OUTER REGULATOR

After design the inner loop regulator, the outer loop regulator $C_2(s)$ is designed in MATLAB7.0 when the weight functions are chosen as:

$$W_1 = \frac{0.0035s^2 + 0.87842s + 0.05858}{s^2 + 10.1s + 0.01}, \quad W_2 = 0.01,$$

$$W_3 = \frac{0.002s^2 + 0.0001s + 0.00477}{s + 0.0487},$$

the designed $C_2(s)$ is: ... (12)

$$C_2 = \frac{27.5744(s+1.362)(s+0.075)(s+0.0487)(s^2+0.003621s+0.001812)}{(s+0.04399)(s+0.00099)(s^2-0.1528s+0.01519)(s^2+4.748s+17.61)}$$

The regulator frequency response characteristics is performed as in Figs.5 and 6. The results show that the regulator has concave low gain round $\omega = 0.067$ rad/s, this low gain can reject outer disturbance. The regulator also fulfills condition of robust control requirement $\|WIS\|_\infty < 1$. The unit step response of hydro turbine governor system is shown in Fig.7.

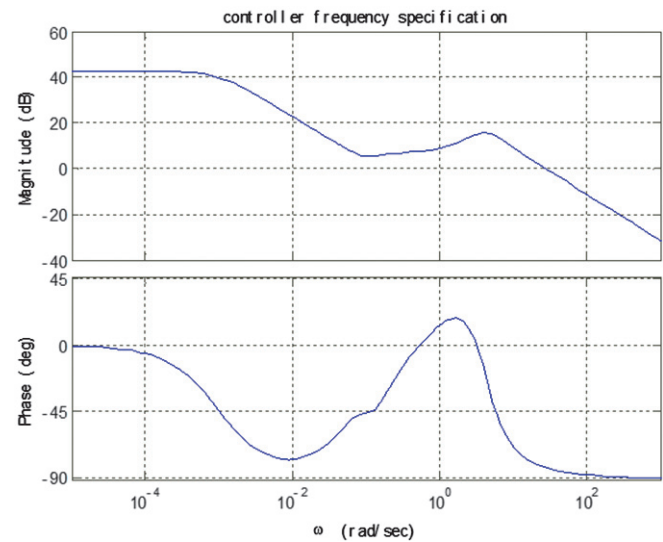


Fig.5: Frequency speciality of controller C2

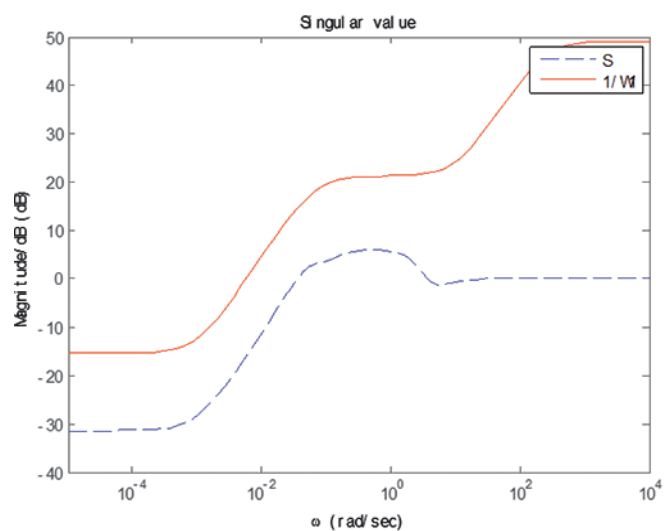


Fig.6: Frequency specialities of S and 1/W1 of outer-loop controller

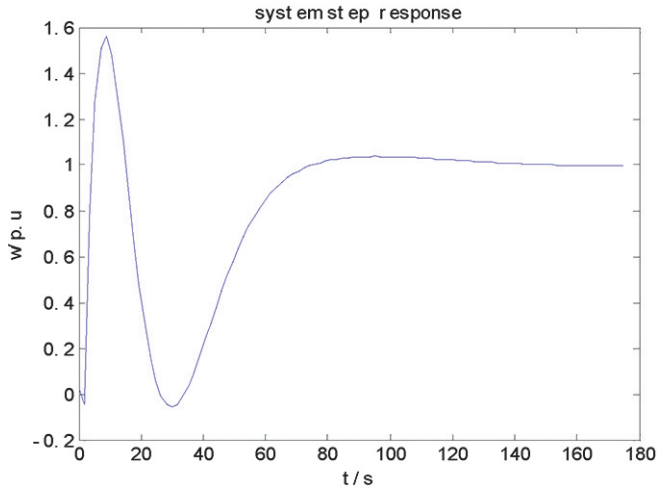


Fig.7: Step response curve for system

4.3 ANALYSIS OF LOAD REJECTION

The power system load disturbance is the main outer disturbance for hydro turbine speed regulator system which can lead in power frequency variation.

When system is stable, the 20%, 100% load step variation is given in system. The relevant system speed response curve is shown in Fig.8. Insight into the response curve, the designed H_∞ double loop control system can tune system speed on the given value for two times regulation. the designed H_∞ double loop control system can effectively improve the system control precision and ability of disturbance rejection.

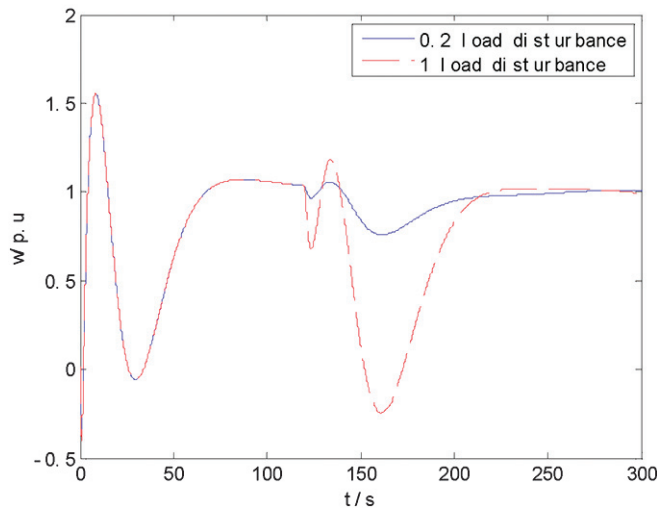


Fig.8: Generator speed after 20%, 100% load injected

4.4 ANALYSIS OF SYSTEM PARAMETER EXCURSION

When the system parameters T_{ep} , T_{wc} , T_s , T_p , H , D are changed in finite range

$T_{wc} \in [1.5 \ 5.79]$, $T_{ep} \in [0.25 \ 0.42]$, $T_s \in [0.05 \ 0.5]$, $T_p \in [0.005 \ 0.02]$, $H \in [4 \ 13.2]$, $D \in [0 \ 1]$. Considering the system working in extreme condition, the two group

parameters is obtained, one is max parameters (parameters I): $T_{wc} = 5.79$, $T_{ep} = 0.42$, $T_s = 0.5$, $T_p = 0.02$, $H = 13.2$, $D = 1$, the other is min parameters (parameters II): $T_{wc} = 1.5$, $T_{ep} = 0.25$, $T_s = 0.05$, $T_p = 0.05$, $H = 4$, $D = 10^{-5}$. The designed H_∞ double loop control system speed response curve is shown in Fig.9.

Insight into Fig.9, when system exist parameter disturbances, the designed H_∞ system can swiftly tune the speed on the stable given value. When the system works in natural operating condition, the system speed response curve lies between the bound of parameters I and parameters II.

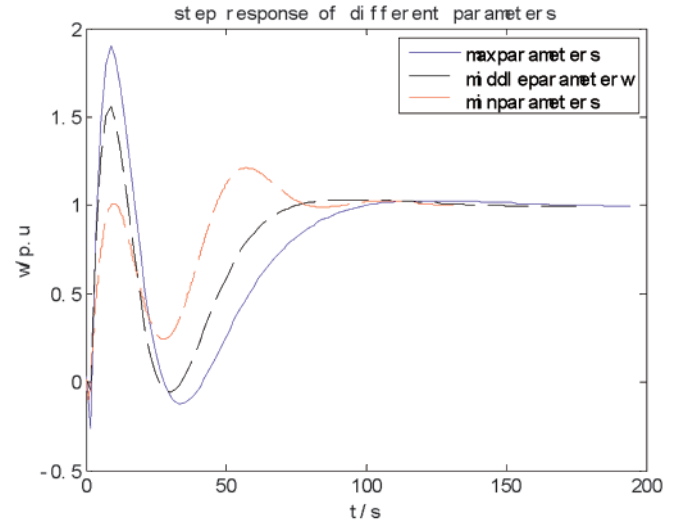


Fig.9: Generator speed after parameters disturbed

In order to validate the designed control system de synthesis rejection ability of parameters excursion and load disturbance, supposed, after the system working in extreme condition (parameters I and parameters II), at $t=150s$ and $t=180s$, the 20%, 050% step variation are applied to the system, the results are illustrated in Figs.10 and 11 respectively.

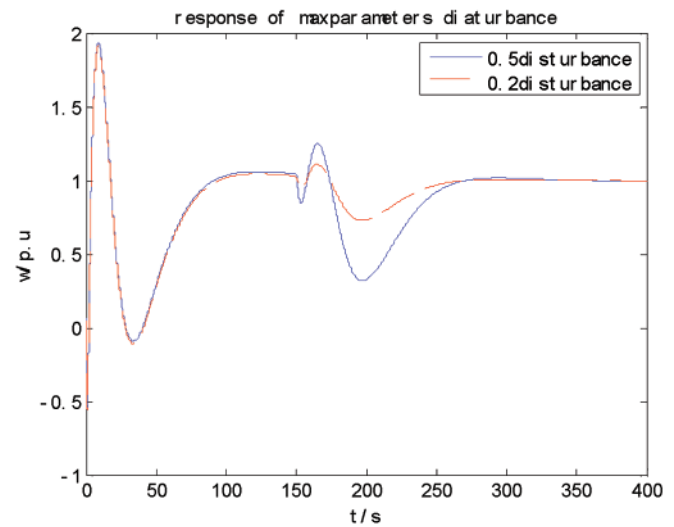


Fig.10: Generator speed after load injected with disturbed parameters I

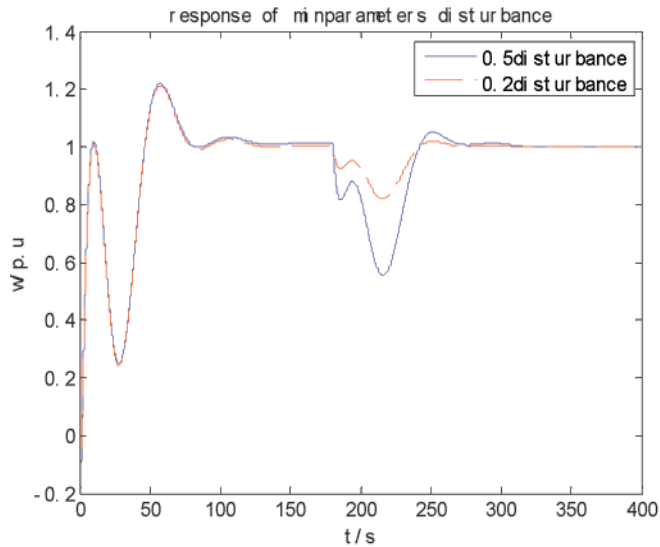


Fig.11: Generator speed after load injected with disturbed parameters II

Insight into Figs.10 and 11, when system working in extreme condition, the system has excellent ability of load disturbance rejection also. The response curves illustrate that the designed H_{∞} double loop control system has strong robustness which is in favor of power system frequency stability.

4.5 COMPARISON TO PID CONTROLLER

After elaborate testing, the traditional PID controller transfer function is chosen as:

$$G(s)_{PID} = 4.18 + \frac{4.18}{4.485s} + 1.2s \quad \dots (13)$$

Given the same model parameters, the unit step response and 100% load rejection response curves of traditional PID controller and H_{∞} double loop control system are shown as Figs.12 and 13 respectively.

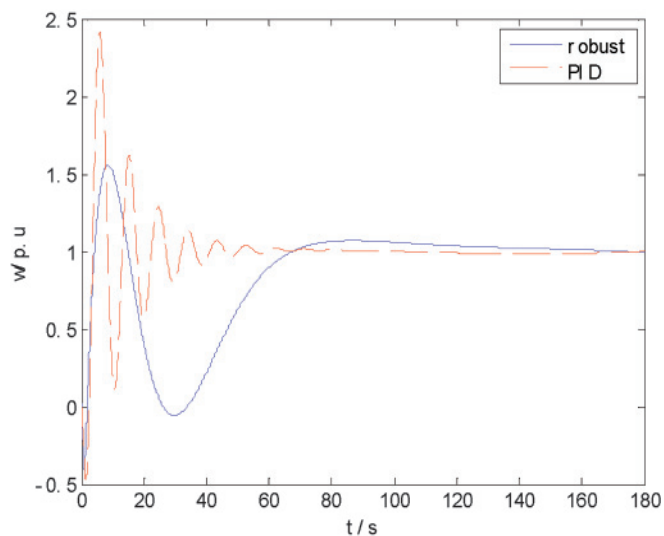


Fig.12: Step response of PID and H_{∞} controllers

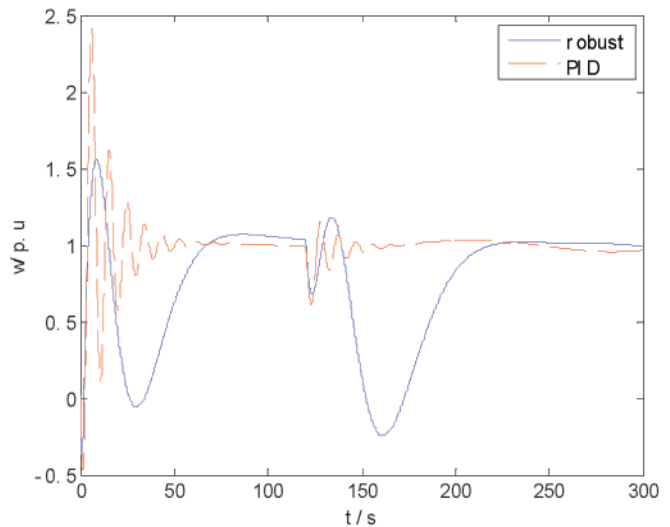


Fig.13: Response of PID and H_{∞} controllers after 100% load injected

From Figs.12 and 13, whether unit step response or 100% load rejection response curves, the designed H_{∞} double loop control system can tune the system speed to stable given value in two times, but traditional PID controller can tune system speed to stable given value after acutely vibrating for many times. The response curves illustrated that the designed H_{∞} double loop control system has excellent robustness performance.

5.0 Conclusions

In this paper, a new hydro turbine governor system model was presented for hydropower generating system constructed as: reservoir-surge tank-penstock-generator. In comparison with classical hydro turbine governor system model without surge tank, the important effect of surge tank for water hammer and hydro turbine output speed was synthetically considered in the proposed new model. Based on the new hydro turbine governor system model, moreover, detailedly took the characteristic of hydraulic disturbance and power load disturbance into account, the H_{∞} double loop robust control system was designed. In comparison with traditional PID controller, designed H_{∞} double loop robust control system possesses excellent disturbance rejection robust performance. The simulation results demonstrate that the designed hydro turbine governor system has nicer dynamic stability performance which could keep the power system frequency in given range.

6.0 Acknowledges

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