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RESEARCH ON μ SYNTHESIS BASED HYDROTURBINE GOVERNOR DESIGN

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ABSTRACT

A novel hydroturbine governor scheme based on networked control system (NCS) is proposed. The key problem of the scheme rest with the time delay existing in the data communication in NCS as the time delay may be a detriment to governor system stability and may degrade system robustness. In order to guarantee the governor system stable with time delay, the uncertain delay model is modeled as multiplicative perturbation, and a μ synthesis based robust governor is presented. The result verifies feasibility of the robust controller.

Keywords: *NCS; μ-synthesis; robust control; governor; time delay.*

1. INTRODUCTION

The networked Control System (NCS) is the distributed control system including the functionality of computing, communication and control, which is the major trend in modern industrial system. In NCS, sensors, actuators and controllers are interconnected by communication networks [1].[1] The change of communication architecture from point-to-point to the network approach brings us enormous advantages, such as higher reliability and reconfigurability, lower maintenance cost, and flexibility of control architecture. However, the communication introduces different forms of time-delay uncertainty in the closed-loop system dynamics. Moreover, the time delays in a control application possibly degrade the performance of the control system and even result in system instability. In order to guarantee the stability and performance of NCS, both communication network and control technology are needed [2].

Nowadays, the digital ones replace the analog governors of the hydro turbines governors, and the reliability and flexibility of governors are increased [3, 4]. With the development of the intelligent sensors, intelligent actuator and NCS, NCS based governor is promising to be a new solution for the hydroturbine governor. In this event, several units would share one software based governor controller, the control rule can be realized by a software module which runs at control level in power plant automation system, and only the smart actuator is necessary besides the unit, the smart actuators of those units are connected to software governor by

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communication network. That brings the governor system lower hardware cost and higher reliability and flexibility. As the inertial time constant of the unit is larger, settling time is relative longer [5]. It is possible that soft governor replaces the governor based on hardware.

The Smith predictor is the control scheme aiming at improving the closed loop performance for systems containing time delays, which is based on the perfect prediction of delay and a known model of the system with no disturbances. Most methods were concerned with the controller design and analysis for nominal plants [6]. However, the resulting control system becomes unstable in the presence of perturbation of the plant, and, it is not easily implemented in practice. The delay element in frequency domain ($e^{-s\tau}$) is an irrational transfer function which dose not admits a finite-dimensional realization. Since most control design techniques use finite-dimension models, a finite approximation of $e^{-s\tau}$ is needed. Most methods are related to Padé approximation, so, the parameter of controller is related to maximum time delay $\tau_{\max}$ in the controlled system. But, it has been shown that controller design based on $\tau_{\max}$ may not be solution for all time-varying delays [7]. Some researchers propose gain scheduling method to accommodate different time delays for power system damping control [8], but the time delay should be measured in real time. In order to design an optimal governor which is capable of providing stability and performance for turbine operating under the range of the uncertain time delay, robust control methodology is employed in this paper.

This paper is arranged as follows, Section 2 givethe NCS based hydroturbine governor systemmodel, and model of the uncertain time delay is proposed in this section. Section 3describes the μ synthesis robust controller design approach for the NCS based governor. Section 4 gives four cases of simulation, and performance of the μ synthesis robust controller is compared with conventional PID controller. Section 5 gives the conclusion of this paper.

2. NCS BASED GOVERNOR SYSTEM MODEL

A. NCS based hydroturbine governor system scheme

According to NCS framework, the NCS based hydro turbine governor system is illustrated in fig.1

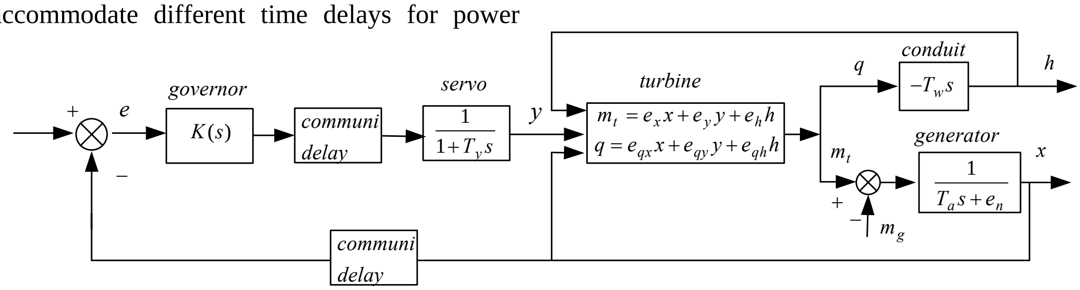

Fig.1 NCS based hydrotirbine governor system

The NCS based governor system includes intelligent sensors, intelligent actuators and networked governor, and plant comprises of turbine, generator and conduit. The intelligent sensors have three major features: data acquisition, intelligence and communication ability. The intelligent sensors acquire water blade position, the frequency of power system, the active power of unit, water head and relevant status variable of unit. Besides, the intelligent sensor has a network-capable application processor which is the interface between the sensor and network. The servo motor which has the interface to intelligent unit and communication can be served as intelligent actuator. The networked governor can be realized by the ICC (Industrial Control Computer), which has the network communication interface. The intelligent sensors, actuators and networked governor are connected by control network. Nowadays, the three typed of control network commonly implemented in industry are Ethernet-based, token-passing, and CAN-based networks [9]. Ethernet employs a simple algorithm for operation of network and has short delay at low network loads. With the realization of 802.1P prioritization protocol and switched Ethernet [10], the packet collision possibility is reduced, and the determinism of the network is improved. Therefore, Ethernet is used widely in control networks. We use the industrial Ethernet as the control network of the NCS based governor system.

In practice, a control system consists of a continuous-time process interconnected with a digital controller via a sample and hold interface. Such a system is known as a sampled-data system. Traditionally, there are two independent approaches used in digital controller design methods. The first is to design a continuous-time controller and then discretize it. The second is to design the controller in discrete-time using the discrete-equivalence of the plant. The continuous-time controller design is employed in this paper. The difficulty in the analysis and synthesis of time-delayed control system arises due to modeling of these delays. We propose a robust control approach which guarantees robust performance with assumption that the delay bounds are known.

B. The uncertain model of time delay

In industry Ethernet based NCS, the time delay between controller and actuator τ_1, the time delay between sensor and controller τ_2 can be considered determinate, i.e., it has determinate upper bound $T_{\max}$ and lower bound $T_{\min}$. Although the end-to-end data flow is a discrete-time stochastic process, the time delay is a discrete-time variable. However, in the high-speed network, we can use fluid approximation for modeling the end-to-end data flow in that it is good approximation for discrete-time models in high-speed networks [11]. In this case, the time delay τ can be modeled by:

$$\tau = \frac{1}{2}(T_{\min} + T_{\max}) + \frac{1}{2}(T_{\max} - T_{\min})\delta, \quad -1 \le \delta \le 1 \tag{1}$$

The parameter δ specifies the uncertainty region; we therefore define another parameter α as:

$$\alpha = \frac{(T_{\max} - T_{\min})/2}{T_{\max}} \tag{2}$$

The equation (1) can be written as

$$\tau = (1-\alpha)T_{\max} + \alpha T_{\max}\delta, \quad 0 \le \alpha \le 1/2 \tag{3}$$

By using the first order Padé approximate, the exponential delay transfer function is written as:

$$e^{-s\tau} = e^{-s(1-\alpha)T_{\max} - \alpha T_{\max}\delta} = e^{-s(1-\alpha)T_{\max}} e^{-\alpha T_{\max}\delta}$$
$$\approx \left(\frac{1-s(1-\alpha)T_{\max}/2}{1+s(1-\alpha)T_{\max}/2}\right)\left(\frac{1-s\alpha T_{\max}\delta/2}{1+s\alpha)T_{\max}\delta/2}\right) \tag{4}$$

In NCS, the uncertain time delay can be considered as a disturbing block. So, in order to utilize the robust control synthesis, the uncertain part in equation (4) can be expressed in complex multiplicative uncertainty as:

$$\frac{1-s\alpha T_{\max}\delta/2}{1+s\alpha T_{\max}\delta/2} = 1 - \frac{s\alpha T_{\max}\delta}{1+s\alpha T_{\max}/2} = 1 + W_\tau(s)\Delta_\tau \tag{5}$$

Where $W_\tau(s) = \dfrac{\alpha T_{\max} s}{1 + \alpha T_{\max} s / 2}$.

As $W_\tau(s)$ cannot cover all possible plant in the frequency domain, we use the multiplicative uncertainty weight function $W_m(s)$ [12], which can cover the uncertain delay.

$$W_m(s) = \frac{\alpha T_{\max} s}{1 + \alpha T_{\max} s / 3.465} \tag{6}$$

In this case, the uncertain exponential delay transfer function can be expressed as the multiplicative uncertainty structure, which is illustrated in Figure.2

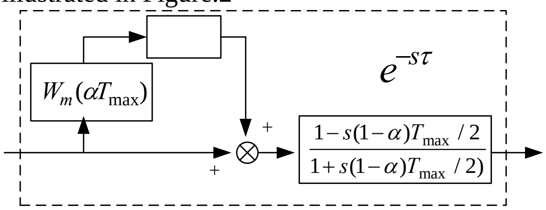

Fig. 2 multiplicative certainty model of delay

C. μ Synthesis based robust control

The fundamental requirement of a NCS based governor system is the stability, i.e., the unit should operate stably when the frequency perturbation or load perturbation occurs. In addition to stability, the governor should meet some control system specifications such as performance specifications and robustness specifications. According to the performance specifications the governor system should accurately track the command inputs. Meanwhile the robustness specifications limit the degradation in performance due to variations in the system and disturbances such as variation of the operation condition and load perturbation.

From a robust control theory perspective, the two-section time delay can be considered as two individual uncertain blocks of the model in NCS. If two sections of delays can be combined together, and the small gain theorem is used to design the robust controller, the controller will be conservative because the perturbation set is enlarged. Doyle proposed the structured singular value (SSV) in 1982 [13], and established the μ control theory. The basic idea of this theory lies in that the sufficient and necessary condition of the robust stability is achieved after the multiple bounded perturbation block are transferred into diagonal perturbation structure .The μ control theory realizes great balance of stability robustness and performance robustness. The standard $\Delta - M$ model structure of μ control theory is stated in Fig. 3, the controller can be evaluated by D-K iterative approach [14].

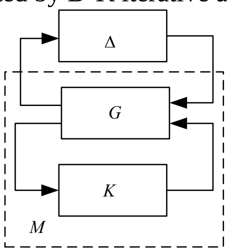

Fig.3. The standard μ synthesis structure

A comparison among various known control methods for time-delayed system shows that a combination of finite dimension of finite dimensional approximation techniques and optimal control theory is the most suitable approach for delayed systems [15]. Therefore, the μ synthesis based robust controller design approach is employed in this paper.

3. NCS BASED μ SYNTHESIS ROBUST GOVERNOR DESIGN

After the uncertain time delay is modeled by the above-mentioned approach, the NCS based hydroturbine governor system is modeled in fig.4. Considering the non-elastic water hammer and water inertia of conduit system, the hydroturbine and the conduit system transfer function can be written as:

$$G_t(s) = \frac{M_t(s)}{Y(s)} = \frac{e_y - (e_{qy}e_h - e_y e_{qh})T_w s}{1 + e_{qh}T_w s} = \frac{e_y - (e_{qy}e_h - e_{qh}e_y)T_w s}{e_{qh}T_w s + 1} \quad (7)$$

Where e_y is the coefficient of hydro turbine torque to water blade position, e_h is the coefficient of hydro turbine torque to water head, e_{qh} is the coefficient of hydro turbine stream to water head, e_{qy} is the coefficient of hydro turbine stream to water blade position, T_w is the water starting time. When a load or frequency perturbation occurs, the regulation time of hydroturbine is about 8-20 seconds, so, the transfer function of generator and load is given by a inertia function as:

$$G_g(s) = \frac{X(s)}{M_t(s)} = \frac{1}{T_a s + e_n} \quad (8)$$

Where T_a unit inertia time is constant, e_n is the unit synthesis self-tune coefficient. Only considering the pilot servo system, the servo can be modeled as:

$$G_s(s) = \frac{1}{T_y s + 1} \quad (9)$$

Where T_y is the inertia time constant of the pilot servo.

In order to get μ synthesis standard structure, we should choose the exterior signal, control signal, controlled output signal and controller input signal. One task of governor is to guarantee the unit accurately tracking the frequency set point during the generator startup. To minimize the signal tracking error, the error signal z_e is chosen as the controlled output signal, and the reference input r is the exterior input signal. Besides, the two disturbing block output signals w_u , w_y are also exterior signal. $w_e(s)$ is the weight transfer function between error and output, which exhibits the performance of disturbance rejection in the control system. Generally, it is determined by the steady-state error and transient response performance. Because the uncertainty of the controlled system plays a main role in the high frequency part, the $W_e(s)$ should be designed as a low pass filter.

According to equation (6),the time delay τ_u (between governor and actuator) can be expressed by $w_u(s)$, Δ_u and $(1-0.5*s(1-\alpha)T_{u\max})/(1+0.5*s(1-\alpha)T_{u\max})$,the time delay τ_y (between sensor and governor) can be expressed by $w_y(s)$, Δ_y and

$(1-0.5*s(1-\alpha)T_{y\max})/(1+0.5*s(1-\alpha)T_{y\max})$, which is illustrated in fig. 4 finally, we obtain the closed-loop diagram of the NCS based governor, where G is the general control plant, z_e, z_u, z_y are controlled output signals, e is the input signal of controller, u is the control signal of general plant. Then, the closed-loop system can be expressed as the standard μ synthesis diagram, which is illustrated in fig.5. Utilizing the μ analysis and synthesis toolbox in MATLAB [14], we can design the robust controller, which owns the stability robustness and performance robustness.

4. THE DIGITAL SIMULATION OF THE NCS BASED GOVERNOR

In order to validate the NCS based governor, we choose a Francis turbine in a hydro power plant, and design a governor by utilizing the above-mentioned robust controller, the hydraulic-electric unit parameter is chosen as $T_a=9.06$, $T_w=1.27$, $T_y=0.2$. The hydro turbine operation condition is given as follows: $e_x=-1.2714$ $e_y=1.0487$ $e_h=1.3817$ $e_{qx}=-0.20$ $e_{qy}=0.8403$ $e_{qh}=0.4780$, $e_n=0.7286$. We call those as operation condition I in this paper, and the governor is designed based on this operation condition. $W_e(s)$ is chosen as a low pass filter:

$$We(s)=\frac{1}{0.0002}\cdot\frac{s+1}{10000s+1} \tag{10}$$

We assume that the maximum delay between controller and servo is 80 millisecond (τ_1 called in this paper), and the maximum delay between sensor and controller is 80 millisecond (τ_2 called in this paper). By virtue of the μ synthesis toolbox in MATLAB, we obtain the controller K given as:

$$\frac{271.4s^8+1.07*10^5s^7+1.285*10^7s^6+4.595*10^8s^5+6.303*10^9s^4+3.147*10^{10}s^3+5.516*10^{10}s^2+2.917*10^{10}s+4.044*10^9}{s^9+1008s^8+1.856*10^5s^7+7.816*10^6s^6+1.28*10^8s^5+9.066*10^8s^4+3.204*10^9s^3+7.814*10^9s^2+3.212*10^9s+3.211*10^5} \tag{11}$$

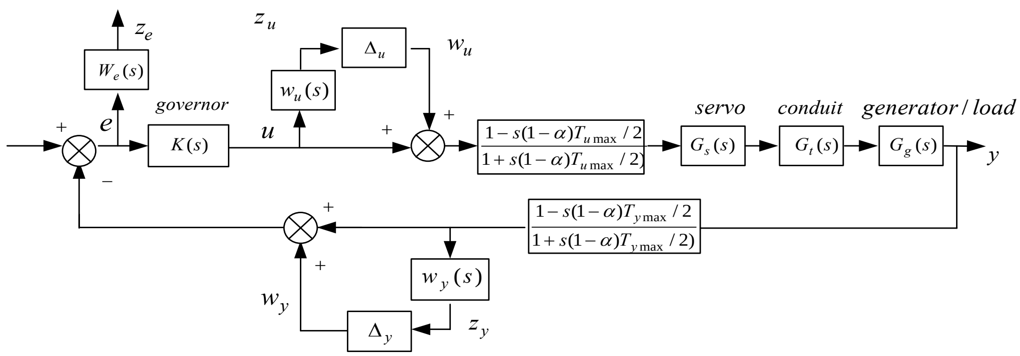

Fig.4.NCS based hydro turbine governor system with uncertain delay

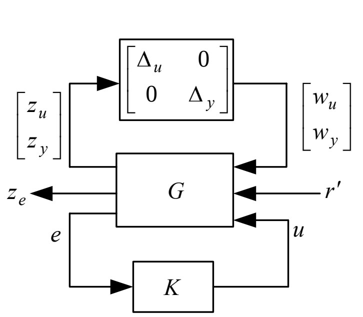

Fig 5 NCS based governor system μ synthesis structure

The controller in equation (10) is obviously too complicate for a reliable implementation in practice. Therefore, a practical solution is to obtain a reduced order for K using optimal model reduction techniques. Since the model reduction involves approximation of high order system by a low order one, it should be emphasized that the reduced-order controller is only a sub-optimal one as far are concerned. However, if the frequency responses of the two controllers match reasonable well in the frequency performance degradation, one would not expect too much performance degradation in the closed-loop system even with the reduced order controller. In this paper, we employed the balance model hankel norm approximation to solve the reduced controller [16, 17]. Then, we obtain the third-order controller as follows:

$$K(s)=\frac{59.51s^2+78.1s+18.41}{s^3+4.02s^2+14.61s+0.001461} \quad (12)$$

The comparison of robust controller and a reduced order controller is given in fig.6.

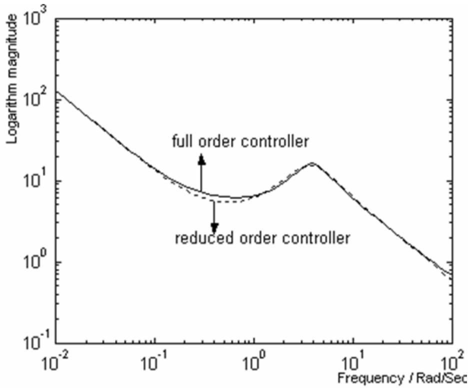

Fig. 6 Comparison of robust controller and reduced order controller

To demonstrate the feasibility of this robust controller, four cases are studied with τ_1 experiencing 40 milliseconds and $\tau 2$ experiencing 40 milliseconds.

A. Case1- load and frequency perturbation simulation

As the unit should endure perturbation of exterior environment during the normal operation condition, it is necessary to verify whether the unit owns robust by the control rule of the governor. In this case, we carry out the 8% and 5% frequency perturbation simulation under the operation condition I, and obtain the frequency response curve in fig.7. The settling-time is about 10 seconds in the event of 5% frequency perturbation, and the overshoot value is about 1.0%. For an 8% frequency perturbation, the settling-time is about 12 seconds, and the overshoot value is about 1.1%.

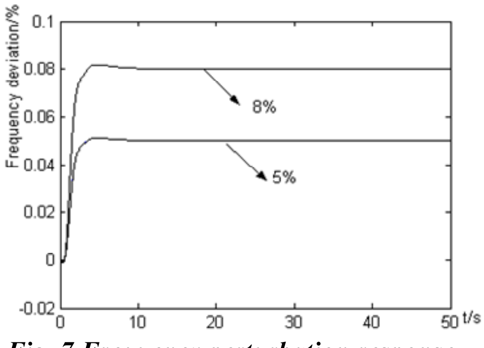

Fig. 7 Frequency perturbation response

The frequency of the unit should return the normal operation condition after the load perturbation occurs. Therefore, we accomplish the 10%, 50, 75% load perturbation simulation and obtain response curve in fig.8.

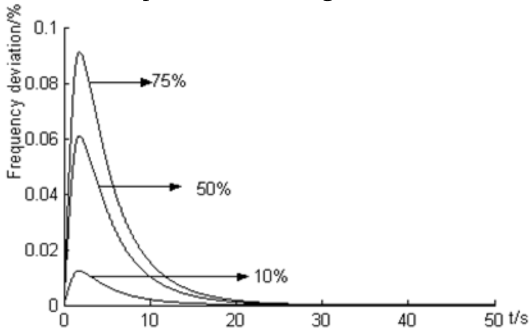

Fig. 8 Load perturbation response

The fig.8 states that the unit owns robust stability under the three type of load perturbation, and the unit frequency can return normal at 20-30 seconds.

B. Case2- The variance of operation condition simulation

In practice, most of electric-hydraulic type of governor employ PID (Proportional, Integral, and Derivative) controller, and the parameters of the controller are obtained by the linearization model at the typical operation condition. These parameters are still used when the unit operates under other condition. However, electric-hydraulic unit exhibits the time-varying nonlinear characteristic among all the operation conditions. In this case, the PID controller designed by this approach cannot achieve the perfect performance. In contrast, the robust controller owns robust performance to attenuate the operation condition parameter perturbation, thus, the robust controller obtain optimal performance among all the operation condition.

To validate the adaptability of robust governor, we choose another operation condition, (we call it the operation condition II in this paper), $e_x=-0.9179$, $e_y=0.9755$ $e_h=0.4853$, $e_{qx}=-0.0815$, $e_{qy}=0.8284$, $e_{qh}=0.3431$, $e_n=2.1821$. Because the e_n in the operation condition II is bigger than it in operation condition I, it implies that the operation condition of the electric-hydraulic unit varies greatly. We use the controller designed under the operation condition I to work under operation condition II, and carry out the 8% frequency perturbation and 75% load perturbation simulation, the result is showed in Fig. 9 and 10.

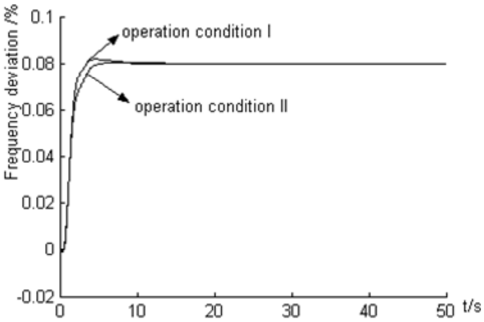

Fig.9 8% Frequency perturbation response

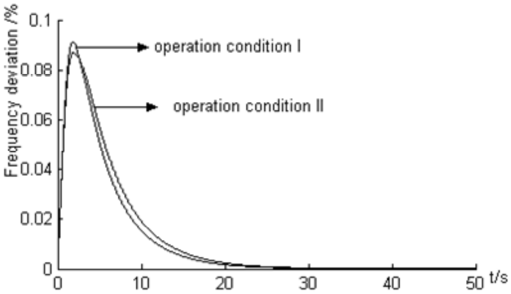

Fig. 10 75% Load perturbation response

Fig.9 and Fig.10 show that the setting-time and overshoot of the two operation condition almost keep invariant, although the operation condition varies greatly. It verifies that the robust governor owns robust performance to parameter perturbation brought by the operation condition alteration.

C. Case3- The variance of time delay simulation

To validate the robust owning less conservativeness, we do 75% load perturbation simulation on five scenarios, which the τ_1 and τ_2 experience 40 milliseconds, 80 milliseconds, 100 milliseconds, 400 milliseconds and 600 milliseconds delay respectively. The response curve is showed in fig. 11, which demonstrates that the transient performance (rise time, percent overshoot, peak time, settling time) is debased with the time delay lengthened. Because the governor is designed under the operation condition $\tau_1 = \tau_2 = 80$ milliseconds, the controller can guarantee the governor system stable if delay is within this region. However, the performance will not be guaranteed if the delay exceeds the maximum bound.

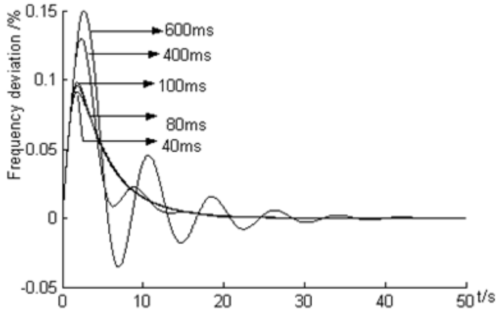

Fig. 11 75% load perturbation with different delay

D. Case4- Comparison with PID controller simulation

In order to compare with the conventional PID controller, we choose the parameters of PID controller as: $b_t = 0.32$, $T_d = 4.3$, $T_n = 0.63$. It can make the hydraulic-electric unit achieve optimal performance under the PID control rule since these parameters are obtained by optimization calculation. We assume that the robust controller and PID controller experience the same time delay .The 75% load perturbation response curve is given in fig.12, which shows that the frequency deviation under the robust controller is less than that under the PID controller, and the settling-time is also shorter than that under the PID controller. As a consequence, the robust controller exhibits the good performance of perturbation rejection.

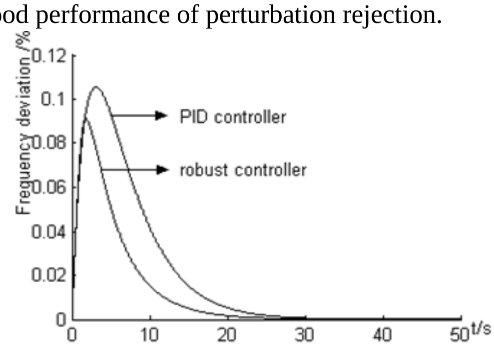

Fig. 12 75% Load perturbation response

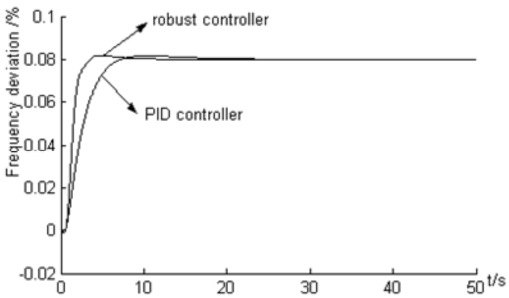

Fig. 13 8% Frequency perturbation response

The 8% frequency perturbation response is illustrated in fig.13. As seen, the settling-time under the robust controller is shorter than that under the PID controller, which also proves that robust controller, is better than PID controller.

5. CONCLUSION

A NCS based hydroturbine governor and its robust control strategy have been presented and analyzed in this paper. The proposed NCS based hydroturbine governor system comprises of the intelligent servo motor, the intelligent sensors and a networked governor. This system owns simpler installation and maintenance, information source share and higher reliability.

Digital simulations demonstrate that the μ synthesis based governor owns stability robustness and performance robustness no mater if the operation parameter perturbation or delay perturbation occurs. And the μ synthesis based controller can achieve better performance than the conventional PID controller.

In order to realize the NCS based governor in practice, we can discretize the continuous-time controller after the controller is evaluated.

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