

Nonlinear Steam Valve Adaptive Controller Design for the Power Systems

Nan Jiang, Xiangyong Chen, Ting Liu, Bin Liu, Yuanwei Jing

Faculty of Information Science and Engineering, Northeastern University, Shenyang, China

E-mail: jiangnan@ise.neu.edu.cn

Received October 21, 2010; revised December 9, 2010; accepted January 10, 2011

Abstract

Considering generator rotor and valve by external disturbances for turbine regulating system, the nonlinear large disturbance attenuation controller and parameter updating law of turbine speed governor system are designed using backstepping method. The controller not only considers transmission line parameter uncertainty, and has attenuated the influences of large external disturbances on system output. The nonlinear controller does not have the sensitivity to the influences of external disturbances, but also has strong robustness for system parameters variation, which is because of the transmission line uncertainty being considered in internal disturbances. The simulation results show that the control effect of the large disturbance attenuation controller more advantages by comparing with the control performance of conventional nonlinear robust controller.

Keywords: Power Systems, Steam Valve Control, Large Disturbance Attenuation, Backstepping, Adaptive

1. Introduction

With the development of large interconnected power systems and the use of kinds of new equipment, the size and complexity of power systems is increased, and it is inevitable that there have the influences of disturbances on the operation of power system. Meanwhile, owing to the inaccuracy of the model, the error of the parameters of the control object designed and the error of the measurement components of the controller also form the generalized disturbance of power system [1]. In order to improve the transient stability level of power system, and prevent an electric power system losing synchronism under a large sudden fault by closing the turbine regulating valve quickly to reduce the output of prime mover instantaneously, it is essential to design the strong robustness nonlinear steam valve controller to improve its reliability.

In recently years, various advanced nonlinear control technologies have been applied to excitation and steam valve controllers of power systems. Through careful investigation it is easy to see that most of these are based on some different control methods. However, these controllers suffer some flaws. Robust adaptive controller and nonlinear stabilizing controller of steam valve and excitation system design method are presented based on

Hamiltonian energy theory in [2,3], but it is difficult to solve the Hamilton-Jacobi-Isaacs (HJI) inequality. In order to avoid solving the HJI inequality, Lu [1] designed the nonlinear L2 gain disturbance attenuation excitation controller based on recursive design method for the external disturbance attenuation problem. Li [4] developed a multivariable inverse nonlinear control scheme for strongly nonlinear reheat type turbo generator steam valves, which provides whole range control to improve the transient power system stability. In [5-7], the turbine governor and excitation controller design method using no linearization methods when system parameters are precisely knowable are proposed, but the robustness of the parameters and model was not considered. For a single-machine infinite -bus system, Wang [8] designed a nonlinear robust integrated controller and a parameter-update law is obtained based on adaptive backstepping methods and Lyapunov functions of the system. The controller also has strong robustness for system parameters variation because damping coefficient uncertainty has been considered. In order to prevent an electric power system losing synchronism under a large sudden fault and to achieve voltage regulation, Wang [9] applied the Riccati equation approach, together with the direct feedback linearization (DFL) technique to design robust nonlinear controllers for transient stability enhancement

and voltage regulation of power systems under a symmetrical three-phase short circuit fault. Sun [10] designed the nonlinear adaptive controllers and parameter updating laws of the switch subsystems using the proposed modified adaptive backstepping method for a single-machine-infinite-bus system, the control input constraints are solved by introducing a switched mechanism. In [11-13], the nonlinear adaptive controllers and parameter updating laws for a single-machine-infinite-bus system with damping coefficient uncertainties in the turbine steam valve control also are proposed. However, the influences of the external unknown disturbances are not considered. Thus, how to effectively deal with the influences of the external unknown disturbances on system output for the origin system is valuable to be further studied.

Thus, in this paper we use the backstepping method to design the nonlinear disturbance attenuation controller and parameter updating law of turbine speed governor system for the uncertainty of transmission line parameters and the influences of large external disturbances on system output. In the design process, the influences of disturbances are considered while it does not use any linearization methods. Thus, the nonlinear controller does not have the sensitivity to the influences of external disturbances, but also keep the nonlinearities of systems. The simulation result demonstrates that the disturbance attenuation controller possesses superior performances by comparing with the control performance of conventional nonlinear robust controller. The design procedure based on the adaptive backstepping method is systematic and concise, it is believed that this method can be accepted with a considerable ease by engineers.

2. Model and Problem Statement

Consider the following single-machine infinite-bus system with steam valve control and the configuration of whole system is shown in **Figure 1**.

Then the model of main steam-valve control system is expressed as follows [11]:

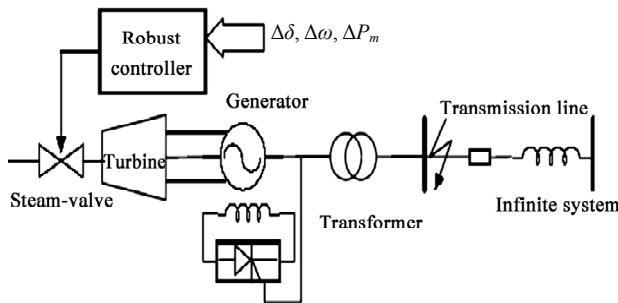


Figure 1. A single-machine infinite-bus system with the steam valve control.

$$\begin{cases} \dot{\delta} = \omega - \omega_0 \\ \dot{\omega} = \frac{\omega_0}{H}(P_H + C_{ML}P_{m0} - P_e - P_D) \\ \dot{P}_H = -\frac{1}{T_{H\Sigma}}(P_H - C_H P_{m0} + C_H u) \end{cases} \quad (1)$$

where δ is the rotor angle of generator. ω is the rotor speed of generator. P_m , P_e , P_D , P_H are mechanical power of prime motor, active power of generator, damping power and mechanical power generated by high-pressure cylinder, respectively. H is the inertial coefficient of generator. $T_{H\Sigma}$ is the equivalent time constant of valve control, the value is about 0.4. C_H is the distribution coefficient of high-pressure turbine, it is about 0.3. C_{ML} is the distribution coefficient of middle and low-pressure turbine power, it is about 0.7. P_{m0} is the initial value of mechanical power, $P_{m0} = P_{e0}$. u is the steam-valve control. And we know that:

$$P_e = \frac{E'_q V_S}{X'_{d\Sigma}} \sin \delta, \quad P_D = \frac{D}{\omega_0} (\omega - \omega_0) \quad (2)$$

where D and E'_q are damping coefficient and transient EMF of generator q axis, respectively. V_S is the infinite bus voltage. $X'_{d\Sigma}$ is the equivalent reactance between generator and infinite bus system.

Next, we will research the design of the controller when the parameter $X'_{d\Sigma}$ is unknown. For system (1), in order to transform it into the appropriate form in backstepping design, let $x_1 = \delta - \delta_0$, $x_2 = \omega - \omega_0$ and $x_3 = P_m - P_{m0}$, where δ_0 , ω_0 , P_{m0} are the initial value of corresponding variables, then system (1) can be rewritten as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{D}{H}x_2 + \frac{\omega_0}{H}(x_3 + P_{m0} + C_{ML}P_{m0} - P_e) \\ \dot{x}_3 = -\frac{1}{T_{H\Sigma}}(x_3 + P_{m0} - C_H P_{m0} + C_H u) \end{cases} \quad (3)$$

$$\text{Let } k_1 = -\frac{D}{H}, \quad k_2 = \frac{\omega_0}{H}, \quad T = -\frac{1}{T_{H\Sigma}},$$

$$a_0 = \frac{\omega_0}{H}(P_{m0} + C_{ML}P_{m0}), \quad C = -\frac{C_H}{T_{H\Sigma}},$$

and they are known constants. Further, let

$$\theta = -\frac{\omega_0 E'_q V_S}{H X'_{d\Sigma}}$$

and they are unknown parameter because of $X'_{d\Sigma}$. Finally, consider the exogenous disturbance $\varepsilon = [\varepsilon_1 \ \varepsilon_2]^T$, where ε_1 and ε_2 is the disturbance on generator rotor and steam valve, respectively. Then system (3) is trans-

formed into:

$$\dot{x}_1 = x_2 \quad (4)$$

$$\dot{x}_2 = k_1 x_2 + k_2 x_3 + a_0 + \theta k_2 \sin(\delta_0 + x_1) + \varepsilon_1 \quad (5)$$

$$\dot{x}_3 = T(x_3 - b_0) + Cu + \varepsilon_2 \quad (6)$$

$$Z = \begin{pmatrix} q_1 x_1 \\ q_2 x_2 \end{pmatrix} \quad (7)$$

where $Z = [q_1 x_1 \ q_2 x_2]^T$ is regulation output; q_1 and q_2 are the non-negative weight coefficient, which represent the weighted proportions between x_1 and x_2 .

Now we can note that the system (7) is a control system with parametric uncertainties and unknown control gain, as well as unknown bounded exogenous disturbances. Our control objective is to keep the rotor stable and the system states are stabilized simultaneously.

3. Design of Nonlinear Adaptive Controller with Large Disturbance Attenuation

For the controlled object with the uncertain parameters and external disturbances, we can use the adaptive backstepping method to design the nonlinear robust controller of steam valve. We can design a suitable controller u by constructing the storage function $V(x)$, and then the system satisfies:

$$V(x(t)) - V(x(0)) \leq \int_0^T (\gamma^2 \|\varepsilon\|^2 - \|z\|^2) dt$$

where any $T > 0$, the L_2 gain of system less than γ , and γ is the disturbance attenuation constant.

Noticing the above-mentioned facts, the analysis method and design process of controller can be summarized as follows:

Step 1: For subsystem (4), let x_2 as the virtual control, and take stabilizing function $x_2^* = -c_1 x_1$, $c_1 > 0$ is a design constant; suppose $e_1 = x_1$, $e_2 = x_2 - x_2^*$, then subsystem (4) can be expressed as

$$\dot{e}_1 = e_2 - c_1 x_1$$

Via taking the first Lyapunov function candidate as

$$V_1 = \frac{\sigma}{2} e_1^2 \quad (8)$$

where $\sigma > 0$, then the time derivative of V_1 found is

$$\dot{V}_1 = \sigma e_1 \dot{e}_1 = \sigma e_1 (e_2 - c_1 x_1) = \sigma e_1 e_2 - \sigma c_1 e_1^2 \quad (9)$$

Step 2: By augmenting (9), the new Lyapunov function can be formed as

$$V_2 = V_1 + \frac{1}{2} e_2^2 \quad (10)$$

Suppose that

$$H_1 = \dot{V}_2 + \frac{1}{2} [\|Z\|^2 - \gamma^2 \|\varepsilon_1\|^2] \quad (11)$$

and the performance index can be supposed as follows,

$$J_1 = \int_0^\infty (\|Z\|^2 - \gamma^2 \|\varepsilon_1\|^2) dt$$

then one gets

$$\begin{aligned} H_1 &= \dot{V}_2 + \frac{1}{2} [(q_1^2 x_1^2 + q_2^2 x_2^2) - \gamma^2 \varepsilon_1^2] \\ &= \sigma e_1 e_2 - \sigma c_1 e_1^2 \\ &\quad + e_2 [k_1 x_2 + k_2 x_3 + a_0 + \theta k_2 \sin(\delta_0 + x_1) + \varepsilon_1] \\ &\quad + e_2 c_1 x_2 + \frac{1}{2} q_1^2 e_1^2 + \frac{1}{2} q_2^2 (e_2 - c_1 e_1)^2 - \frac{1}{2} \gamma^2 \varepsilon_1^2 \end{aligned} \quad (12)$$

By deviating (12) about ε_1 and supposing the first derivation is equal to 0, we can get

$$e_2 - \gamma^2 \varepsilon_1 = 0$$

then (13) can be obtained as follows,

$$\varepsilon_1^* = \frac{1}{\gamma^2} e_2 \quad (13)$$

We continue to find the second derivation of (12), one gets

$$\frac{\partial^2 H_1}{\partial \varepsilon_1^2} = -\frac{\gamma^2}{2} < 0$$

Then there is the maximum value of H_1 about ε_1 .

$$\max H_1 = \max \left\{ \dot{V}_2 + \frac{1}{2} [\|Z\|^2 - \gamma^2 \|\varepsilon_1\|^2] \right\} \quad (14)$$

Now get the integral both sides of (14), we can get

$$\begin{aligned} &\max \int_0^\infty H_1 dt \\ &= \max \left[\int_0^\infty \dot{V}_2 dt + \frac{1}{2} \int_0^\infty (\|Z\|^2 - \gamma^2 \|\varepsilon_1\|^2) dt \right] \end{aligned}$$

Let $\bar{H}_1 = \int_0^\infty H_1 dt$, then

$$\max \bar{H}_1 = \max \left[(V_2(\infty) - V_2(0)) + \frac{J_1}{2} \right]$$

Owing to $\frac{J_1}{2} = \bar{H}_1 - \Delta V_2$, one gets

$$\begin{aligned} \max \left(\frac{J_1}{2} \right) &= \max (\bar{H}_1 - \Delta V_2) \\ &\leq \max (\bar{H}_1) - \min (\Delta V_2) \end{aligned}$$

Remark 1: Suppose that the disturbance ε_1 makes V_2 reduce to 0, i.e. $\min(\Delta V_2) = 0$, that is, when the

systems have the sufficiently large disturbances, V_2 is not reduced, and then, $\max(J_1/2)$ is equivalent to $\max(\bar{H}_1)$, so ε_1 is really the worst disturbances for system.

Remark 2: Based on the equivalent analysis of $\max(\bar{H}_1)$ and $\max(J_1/2)$, ε_1 make \bar{H}_1 get the maximum value means that ε_1 makes J_1 also obtain maximum. While our ultimate goal is to make J_1 minimum, then explain ε_1 on the system's performance damage is the largest. If we substitute disturbances with such damage degree into systems, based on which we design the controller, and ensure the stability of the closed-loop system. Thus it shows that the system is not sensitivity for the influences of disturbances in theory.

Substituting (13) into (12), there is

$$\begin{aligned} H_1 = & \sigma e_1 e_2 - \sigma c_1 e_1^2 \\ & + e_2 [k_1 x_2 + k_2 x_3 + a_0 + \theta k_2 \sin(\delta_0 + x_1)] \\ & + e_2 c_1 x_2 + \frac{1}{2} \gamma^2 e_2^2 + \frac{1}{2} q_1^2 e_1^2 + \frac{1}{2} q_2^2 e_2^2 \\ & - q_2^2 e_2 c_1 e_1 + \frac{1}{2} q_2^2 c_1^2 e_1^2 \end{aligned}$$

Suppose that

$$\begin{aligned} \alpha &= \sigma c_1 - \frac{1}{2} q_1^2 - \frac{1}{2} q_2^2 c_1^2, \\ h_1 &= \sigma + \frac{1}{2} q_2^2 c_1 + \frac{1}{2 \gamma^2} c_1, \\ h_2 &= \frac{1}{2 \gamma^2} + c_1 + \frac{1}{2} q_2^2 + k_1 \end{aligned}$$

Then

$$H_1 = -\alpha e_1^2 + e_2 [h_1 x_1 + h_2 x_2 + k_2 x_3 + a_0 + \theta k_2 \sin(\delta_0 + x_1)]$$

Consider x_3 as the virtual control, and define that $e_3 = x_3 - x_3^*$, then choosing the new virtual stabilization function as follows,

$$x_3^* = \frac{1}{k_2} [-h_1 x_1 - h_2 x_2 - a_0 - \theta k_2 \sin(\delta_0 + x_1) - c_2 e_2]$$

Let $n_1 = k_2 \sin(\delta_0 + x_1)$, where c_2 is a positive number to be selected.

$$x_3^* = \frac{1}{k_2} [-h_1 x_1 - h_2 x_2 - a_0 - \bar{\theta} n_1 - c_2 e_2]$$

We can obtain

$$H_1 = -\alpha e_1^2 - c_2 e_2^2 + e_2 \tilde{\theta} k_2 \sin(\delta_0 + x_1)$$

where $\tilde{\theta} = \theta - \bar{\theta}$, $\bar{\theta}$ is the estimated value of θ .

Step 3: By augmenting V_2 , the new Lyapunov function can be formed as

$$V_3 = V_2 + \frac{1}{2} e_3^2 + \frac{1}{2 \rho} \tilde{\theta}^2 \quad (15)$$

where $\rho > 0$ is the adaptive gain coefficient.

Define that

$$H_2 = \dot{V}_3 + \frac{1}{2} [\|Z\|^2 - \gamma^2 \|\varepsilon\|^2]$$

and the performance index as follows,

$$J_2 = \int_0^\infty (\|Z\|^2 - \gamma^2 \|\varepsilon\|^2) dt$$

Because $\dot{V}_3 = \dot{V}_2 + e_3 \dot{e}_3 + \frac{1}{\rho} \tilde{\theta} \dot{\tilde{\theta}}$, and

$$\begin{aligned} \dot{x}_3^* &= \frac{1}{k_2} [-h_1 \dot{x}_1 - (h_2 + c_2) \dot{x}_2 - \dot{\tilde{\theta}} n_1 - (\bar{\theta} n_2 + c_1 c_2) x_2] \\ &= \frac{1}{k_2} \left\{ -h_1 \dot{x}_1 - (h_2 + c_2) [k_1 x_2 + k_2 x_3 + a_0 \right. \\ &\quad \left. + \theta k_2 \sin(\delta_0 + k_2) + \frac{1}{\gamma^2} e_2] - \dot{\tilde{\theta}} n_1 - (\bar{\theta} n_2 + c_1 c_2) x_2 \right\} \end{aligned}$$

one gets

$$\begin{aligned} H_2 &= \dot{V}_2 + e_3 \dot{e}_3 + \frac{1}{\rho} \tilde{\theta} \dot{\tilde{\theta}} + \frac{1}{2} (q_1^2 x_1^2 + q_2^2 x_2^2) - \frac{1}{2} \gamma^2 (\varepsilon_1^2 + \varepsilon_2^2) \\ &= -\alpha e_1^2 - c_2 e_2^2 + e_2 \tilde{\theta} k_2 \sin(\delta_0 + x_1) + \frac{1}{\rho} \tilde{\theta} \dot{\tilde{\theta}} - \frac{1}{2} \gamma^2 \varepsilon_2^2 \\ &\quad + e_3 [T(x_3 - b_0) + cu + \varepsilon_2] + e_3 \frac{1}{k_2} \left\{ -h_1 \dot{x}_2 - (h_2 + c_2) \right. \\ &\quad \left. \times \left[k_1 x_2 + k_2 x_3 + a_0 + \theta k_2 \sin(\delta_0 + x_1) + \frac{1}{\gamma^2} e_2 \right] \right. \\ &\quad \left. - \dot{\tilde{\theta}} n_1 - (\bar{\theta} n_2 + c_1 c_2) x_2 \right\} \end{aligned} \quad (15)$$

By deviating (15) about ε_2 and supposing the first derivation is equal to 0, we can get

$$\varepsilon_2^* = \frac{1}{\gamma^2} e_3 \quad (16)$$

To find the second derivation of (15), we can obtain

$$\frac{\partial^2 H_2}{\partial \varepsilon_2^2} = -\frac{\gamma^2}{2} < 0,$$

So there is the maximum value of H_2 about ε_2 . Then, we know that ε_2^* is the most disturbance of system to make a performance cost J_2 be the largest value.

Substituting (16) into (15), then

$$\begin{aligned} H_2 &= -\alpha e_1^2 - c_2 e_2^2 + e_2 \tilde{\theta} k_2 \sin(\delta_0 + x_1) \\ &\quad + \frac{1}{\rho} \tilde{\theta} \dot{\tilde{\theta}} - \frac{1}{2 \gamma^2} e_3 + e_3 \left[T(x_3 - b_0) + cu + \frac{1}{\gamma^2} e_3 \right] \end{aligned}$$

$$+ \frac{e_3}{k_2} \left\{ -h_1 x_2 - (h_2 + c_2) [k_1 x_2 + k_2 x_3 + a_0 + \theta k_2 \sin(\delta_0 + x_1) + \frac{e_2}{\gamma^2}] - \dot{\theta} n_1 - (\bar{\theta} n_2 + c_1 c_2) x_2 \right\}$$

Choosing the feedback control as follows,

$$u = \frac{1}{c} \left\{ -T(x_3 - b_0) - \frac{e_3}{\gamma^2} - \frac{1}{k_2} [-h_1 x_2 - (h_2 + c_2) \times (k_1 x_2 + k_2 x_3 + a_0 + \bar{\theta} n_1 + \frac{e_2}{\gamma^2}) - \dot{\theta} n_1 - (\bar{\theta} n_2 + c_1 c_2) x_2] c_3 e_3 \right\}$$

then,

$$H_2 = -\alpha e_1^2 - c_2 e_2^2 + e_2 \tilde{\theta} k_2 \sin(\delta_0 + x_1) + \frac{1}{\rho} \tilde{\theta} \dot{\tilde{\theta}} - \frac{e_3^2}{2\gamma^2} - c_3 e_3^2 - \frac{e_3}{k_2} (h_2 + c_2) \tilde{\theta} n_1$$

In order to ensure that $H_2 \leq 0$, suppose that

$$e_2 \tilde{\theta} k_2 \sin(\delta_0 + x_1) + \frac{1}{\rho} \tilde{\theta} \dot{\tilde{\theta}} - e_3 (h_2 + c_2) \tilde{\theta} \sin(\delta_0 + x_1) = 0$$

$$\tilde{\theta} \left(e_2 n_1 - \frac{1}{\rho} \dot{\tilde{\theta}} - e_3 (h_2 + c_2) \sin(\delta_0 + x_1) \right) = 0$$

Choosing the parameter update law

$$\dot{\tilde{\theta}} = \rho [e_2 n_1 - e_3 (h_2 + c_2) \sin(\delta_0 + x_1)]$$

By choosing the appropriate coefficient σ , so $\alpha \geq 0$, then

$$H_2 = -\alpha e_1^2 - c_2 e_2^2 - c_3 e_3^2 \leq 0$$

Let $V(x) = 2V_3(x)$, one gets

$$\dot{V}(x) \leq \gamma^2 \|\varepsilon\|^2 - \|z\|^2 \quad (17)$$

where $\varepsilon = [\varepsilon_1 \ \varepsilon_2]^T$. When $x(0) = 0$, we get the integral both sides to satisfy the inequality (17), so there are the gain from disturbance to output.

Remark 3: when the system operates normally, then $0^\circ < \sigma < 180^\circ$, and we can know that $\sin(\delta_0 + x_1) \neq 0$, so the control is defined.

Now get the integral both sides of (17), the dissipation inequality can be obtained as follows,

$$V(x(t)) - V(x(0)) \leq \int_0^t (\gamma^2 \|\varepsilon\|^2 - \|z\|^2) dt$$

so there is L2 gain from disturbance to the output of system. And when $\varepsilon = 0$, the closed-loop error control system is asymptotic stable with the feedback control law u , then the closed-loop control system can be expressed as

follows,

$$\begin{cases} \dot{e}_1 = e_2 - c_1 e_1 \\ \dot{e}_2 = -c_2 e_2 - e_1 + \frac{n_1 \tilde{\theta}}{k_2^2} \\ \dot{e}_3 = -c_3 e_3 + \frac{(c_1 + k_1 + c_2) n_1}{k_2^2} \tilde{\theta} \\ \dot{\tilde{\theta}} = -\dot{\theta} = \gamma \left[\frac{e_2}{k_2} + \frac{(c_1 + k_1 + c_2) e_3}{k_2^2} \right] n_1 \end{cases} \quad (18)$$

4. Simulation Examples

In this section, we firstly analyze the stability of the system by analyzing the state responses of system, which is generated by Simulink. Further, when the system parameters change under the fault that occurs, we observe the stability time of system with the influence of nonlinear steam valve adaptive robust controller, so we can analyze the stability of nonlinear steam valve adaptive robust controller of power system based on adaptive backstepping method, and the bounded ness of the state of system and whether to suppress the influences of large external disturbances on system output also can be analyzed.

4.1. Simulation of General Nonlinear Robust Controller

In this subsection, we can give the simulation analysis of general nonlinear robust controller, and the transient responding curves of the system output state and the controller output can be shown in **Figure 2** and **Figure 3**.

The general nonlinear robust steam valve controller can be designed using the general backstepping method. As this robust controller, the time of the stability of system is longer and it will keep a slow convergence. Moreover, it will maintain the small oscillation stability within a certain range, and the control is ineffective.

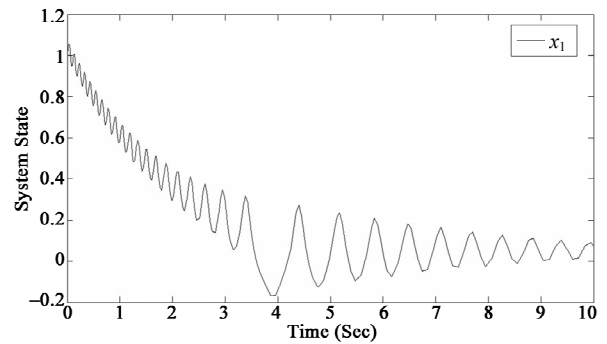


Figure 2. The transient responding curves of the system state x_1 .

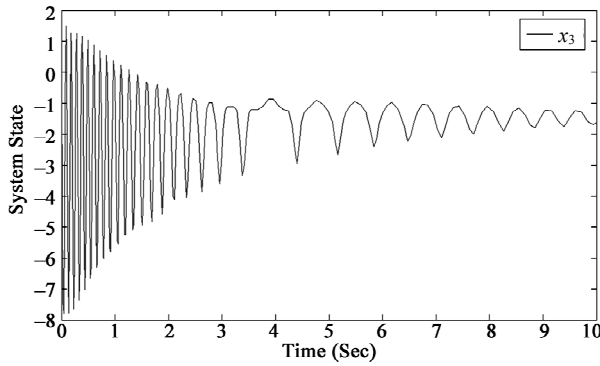


Figure 3. The transient responding curves of the system state x_3 .

4.2. Simulation of the Closed-Loop Error System

According to the design results of foregoing section, we simulate system (18) using MATLAB. The simulation parameters can be supposed as follows: $D = 5$, $H = 8$, $c_1 = 2$, $c_2 = 2$, $c_3 = 2$, $\gamma = 1$, $\rho = 2$, $q_1 = 0.4$, $q_2 = 0.6$, $\sigma = 1$, $\omega_0 = 314.159$ rad/s, $P_{m0} = 0.8$ pu. And the responses of state can be obtained as Figure 4.

From the responding curves of the system states, we can see that the system have very good convergent performance and the closed-loop system goes into steady state quickly. When $t \rightarrow \infty$, then $e_1 \rightarrow 0$, $e_2 \rightarrow 0$, $e_3 \rightarrow 0$. According to the definition of x_1 , x_2 , x_3 and x_2^* , x_3^* , x_1 , x_2 and x_3 will be convergent to zero.

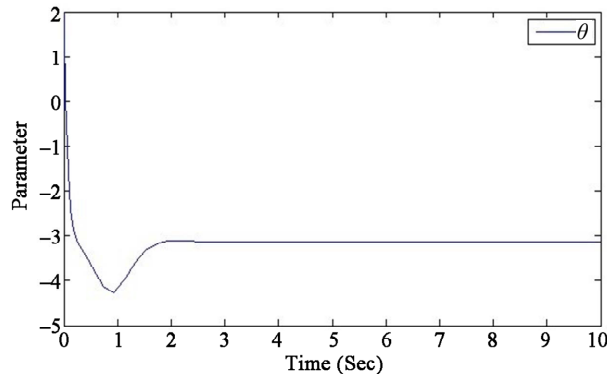
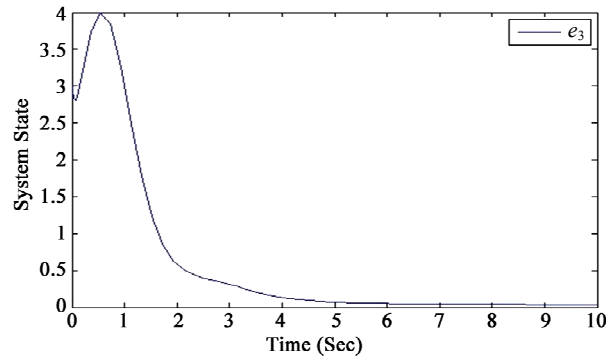
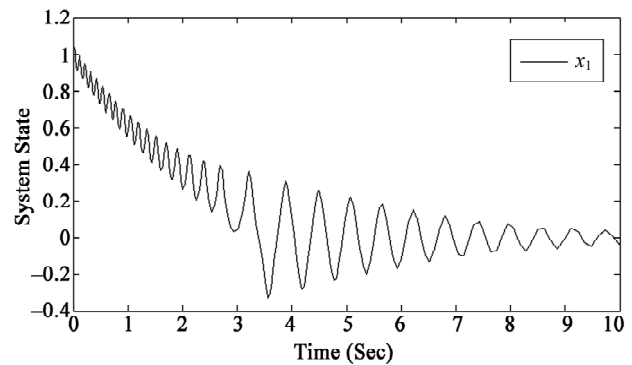
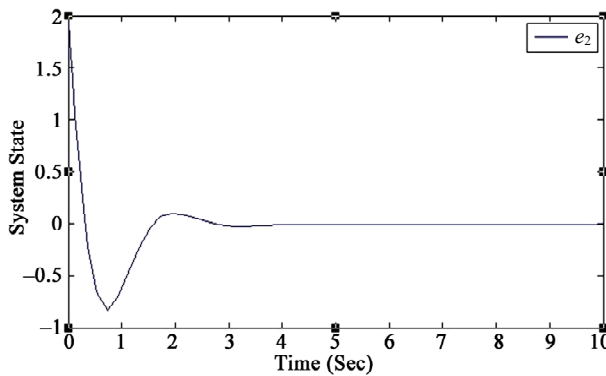
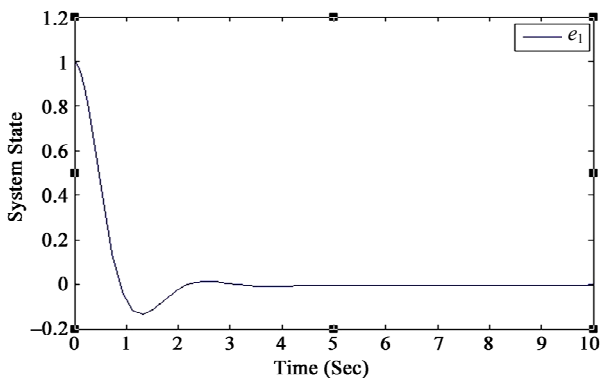


Figure 4. The state responding curves of the system.

4.3. Simulation of Nonlinear Steam Valve Robust Controller

In order to demonstrate superior performances of the controller designed by adaptive backstepping method, the external unknown disturbances of the generator rotor and steam valve are considered. And the transient responding curves of the controller can be shown in Figure 5.

From the responding curves of the system states, we can see that the system have very good convergent performance though being subjected to the influence of the maximum external disturbances, the speed that the closed-loop system goes into steady state is very quickly.



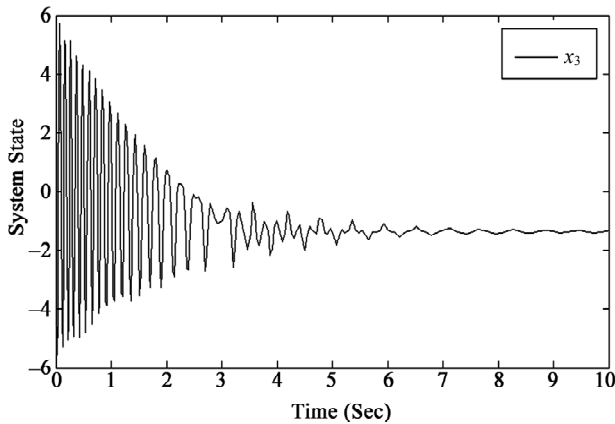


Figure 5. The response curve of the system state.

Thus all of these do verify the design process in this paper.

5. Conclusion

In this paper, we apply the nonlinear adaptive robust control scheme to turbine speed governor system. Nonlinear adaptive robust controller of steam-valve with the large external disturbances attenuation technique is designed by combining adaptive backstepping method. The essential nonlinear nature of the systems is entirely preserved because of no use of any kind of linearization on the original nonlinear system model. Owing to the fact that both internal and external disturbances in controller design are considered together, we compared the designed controller with the more conventional, not only the designed nonlinear controller does not have the sensitivity to the influences of external disturbances, but also has strong robustness for system parameters variation. The further simulations demonstrated the controller has superior adaptability and robustness.

6. Acknowledgements

This work is supported by the Fundamental Research Funds for the Central Universities, under grant 090304004, and the National Natural Science Foundation of China, under grant 60274009, and Specialized Research Fund for the Doctoral Program of Higher Education, under grant 20020145007.

7. References

- [1] Q. Lu, S. W. Mei, T. L. Shen, *et al.*, "Recursive Design of Nonlinear H_∞ Excitation Controller," *Science in China (Series E)*, Vol. 30, No. 1, 2000, pp. 70-78.
- [2] S. J. Li, Z. Yu and G. Wang, "Adaptive H-Infinity Control of Synchronous Generators with Steam Valve via Hamiltonian Function Method," *Journal of Control Theory and Applications*, Vol. 4, No. 2, 2006, pp. 105-110. doi:10.1007/s11768-006-5059-6
- [3] J. Ma, Z. R. Xi, S. W. Mei, *et al.*, "Nonlinear Stabilizing Controller Design for the Steam-Valuing and Excitation System Based on Hamiltonian Energy Theory," *Proceedings of the CSEE*, Vol. 22, No. 5, 2002, pp. 88-93.
- [4] H. R. Ri, D. H. Li and L. Q. Li, "Reheat-Type Turbo Generator Steam Valve Whole-Range Non-linear Control," *Journal of Tsinghua University (Science and Technology)*, Vol. 40, No. 10, 2000, pp. 89-92.
- [5] Y. Z. Sun, Q. Lu and C. X. Sun, "On the Study of Power System Nonlinear Robust Control," *Proceedings of the CSEE*, Vol. 16, No. 6, 1996, pp. 361-365.
- [6] Y. Z. Sun, X. Li and H. P. Dai, "Nonlinear Excitation Controller to Improve both Power System Stability & Voltage Regulation Accuracy," *Proceedings of the CSEE*, Vol. 16, No. 5, 1996, pp. 332-335.
- [7] Q. Lu and Y. Z. Sun, "Nonlinear Control of Power Systems," Science Press, Beijing, 1993.
- [8] B. H. Wang, C. W. Yang, Q. Zhang, *et al.*, "Integrated Nonlinear Adaptive Backstepping Controller for Synchronous Generator," *Control Theory & Applications*, Vol. 23, No. 1, 2006, pp. 60-64.
- [9] Y. Y. Wang and J. David, "Robust Nonlinear Coordinated Control of Power Systems," *Automatica*, Vol. 32, No. 4, 1996, pp. 611-618. doi:10.1016/0005-1098(95)00186-7
- [10] Li. Y. Sun and J. Zhao, "Nonlinear Adaptive Control for the Turbine Steam Valve with Input Constraints," *Control Theory & Applications*, Vol. 6, No. 6, 2009, pp. 601-606.
- [11] W. L. Li, Y. W. Jing and M. S. Wang, "Stability Control in Power Systems: A Survey," *Control and Decision*, Vol. 17, No. 6, 2002, pp. 1-6.
- [12] W. L. Li, Y. W. Jing and X. P. Liu, "Adaptive Robust Backstepping Design for Nonlinear Steam Valve Controller," *Proceedings of the CSEE*, Vol. 23, No. 1, 2003, pp. 155-158.
- [13] W. L. Li, "Study on the Nonlinear Adaptive Robust Control for Power Systems," Ph.D. Thesis, Northeastern University, Shenyang, 2003.