Hindawi
Complexity
Volume 2018, Article ID 8767158, 9 pages
https://doi.org/10.1155/2018/8767158

Research Article

Fixed-Time Feedback Control of the Hydraulic Turbine Governing System

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Received 25 May 2018; Revised 20 June 2018; Accepted 25 June 2018; Published 1 August 2018

Academic Editor: Diyi Chen

Dealing with convergence time and dealing with steady state are two of the most challenging problems in the field of stability of the hydraulic turbine governing system. In this paper, we solve these two challenging problems by designing fixed-time feedback controllers. The design of the controllers is based on the fixed-time theory and backstepping method. Compared with the existing controllers for fixed-time, finite-time, and other techniques, the designed controllers make the maximum convergence time of the system unaffected by the initial state. The convergence time is also shorter. Meanwhile, they are continuous and do not include any sign function, and hence, the chattering phenomenon in most of the existing results is overcome via nonchattering control. In addition, they give the system better stability and robustness to disturbances. Finally, the numerical simulation results in this paper will contribute to a better understanding of the effectiveness and superiority of the proposed controllers.

1. Introduction

Hydropower is a renewable energy source and it has high potential for economically viable utilization [1]. The past few decades have witnessed the rapid development of hydropower energy, which supplements or often replaces decommissioned coal-fired power plants [2]. The system of such a powerful hydropower plant including penstock systems, water turbines, generators, regulators, and loads, is so complex that it is difficult to control [3]. However, the stability of a hydropower system plays an important role in the stability of the whole power system and the plants themselves [4]. The hydraulic turbine governing system is one of the most important parts of a hydropower plant, which plays key roles in maintaining safety, stability, and economical operation of the hydropower plant [5]. It is also a multiparameter, high-dimension complex system with nonlinear, time-variant, and nonminimum phase characters [6]. Therefore, the study of the hydraulic turbine governing system is of great importance. In this regard, a special kind of nonlinear control technique, which combines the fixed-time control theory, feedback control theory, and backstepping method, is introduced into the controller design of the hydraulic turbine governing system in this paper.

In the past decades, many advanced control techniques have been applied to the controller design of the hydraulic turbine governing system, such as PID control [7, 8], sliding-mode control [9], nonlinear control [10–12], fuzzy control [13], fault tolerant control [14], predictive control [15, 16], finite-time control [17], and fixed-time control [18–20]. These control methods have important theoretical and practical significance for the control of a hydraulic turbine governing system, but they also have some problems in overcoming the long-term operation of the system in real-time applications. For instance, the nonlinear nature of a water turbine and the constantly varying load makes the gain schedule of the PID controller difficult to design, limiting the operating range. Sliding-mode control is a quick and powerful variable-structure approach governing the nonlinear system via a predefined switch sliding surface. However, a common drawback of the conventional sliding-mode control is the chattering phenomenon, due to the use of a discontinuous sign function. The nonlinear control is targeted, and each nonlinear control strategy is only suitable for solving some special nonlinear system control problems. Fuzzy control is difficult to adapt to the requirements of a large-scale adjustment, and it needs constant adjustment of the control rules and parameters. The convergence time of finite-time control is heavily dependent on the initial values of considered systems, which makes the maximum convergence time not fixed for different initial values. Moreover, not all the initial values of the systems are available in practice. These drawbacks prohibit the practical application of finite-time control [21]. In order to overcome the shortcomings of finite-time control, fixed-time control is proposed in [22]. The convergence time of fixed-time control can be completely determined by the parameters of a closed-loop system. Based on the advantages of fixed-time control, this control strategy has been applied to some systems [23–29]. It is worth mentioning that the sign function is indispensable for the controllers in [23–29]. It is well known that the sign function always introduces the chattering phenomenon to the system state and control signal, which damages equipment and induces undesirable effects [30]. Therefore, how to design continuous controllers without a sign function to make the system achieve fixed-time stability more rapidly has become the goal of this paper.

Motivated by the above discussions, to ensure the stability of a hydraulic turbine governing system, a set of ingenious controllers combining fixed-time control and feedback control is proposed. Compared with all the above control strategies, the designed fixed-time feedback controllers not only make the system steady in a fixed time, but also eliminate the chattering phenomenon of the system. In addition, they make the system stabilize faster and be more robust to disturbances. The rest of this paper is organized as follows. In Section 2, the model of the hydraulic turbine governing system is presented and some necessary definitions and lemmas are given. In Section 3, fixed-time feedback controllers are designed. Numerical simulations and theoretical analyses are presented to show the effectiveness of the controllers in Section 4. Finally, in Section 5, conclusions are given.

2. Preliminaries

2.1. Model of Hydraulic Turbine Governing System. The mathematical model of the hydraulic turbine governing system with the elastic water hammer has been widely studied in [12, 15, 31]. In this paper, the focus is to use an advanced control strategy to give the system better quality. Therefore, we use the nonlinear model of the hydraulic turbine governing system which is based on the previous work as follows:

$$
\begin{aligned}
\dot{x}_1 &= x_2,\\
\dot{x}_2 &= x_3,\\
\dot{x}_3 &= -a_0 x_1 - a_1 x_2 - a_2 x_3 + y,\\
\dot{\delta} &= \omega_0 \omega,\\
\dot{\omega} &= \frac{1}{T_{ab}}\left(m_t - D\omega - P_e\right),\\
\dot{y} &= \frac{y}{T_y},
\end{aligned} \tag{1}
$$

where

$$
\begin{aligned}
P_e &= \frac{E_q' V_s}{x_{d\Sigma}'} \sin\left(\delta + \delta_0\right) + \frac{v_s^2}{2}\frac{x_{d\Sigma}' - x_{q\Sigma}}{x_{d\Sigma}' - x_{q\Sigma}} \sin\left(2\delta + 2\delta_0\right),\\
m_t &= b_3 y + \left(b_0 - a_0 b_3\right) x_1 + \left(b_1 - a_1 b_3\right) x_2 + \left(b_2 - a_2 b_3\right) x_3,\\
x_{d\Sigma}' &= x_d' + x_T + \frac{1}{2} x_L,\\
x_{q\Sigma} &= x_q + x_T + \frac{1}{2} x_L,\\
b_0 &= \frac{24 e_y}{e_{qh} h_w T_r^3},\\
b_1 &= \frac{24 e e_y}{e_{qh} T_r^2},\\
b_2 &= \frac{3 e_y}{e_{qh} h_w T_r},\\
b_3 &= \frac{e e_y}{e_{qh}},\\
a_0 &= \frac{24}{e_{qh} h_w T_r^3},\\
a_1 &= \frac{24}{T_r^2},\\
a_2 &= \frac{3}{e_{qh} h_w T_r}.
\end{aligned} \tag{2}
$$

x_1, x_2, and x_3 denote intermediate state variables, δ denotes the deviation of the generator rotor angle, ω denotes the deviation of the generator rotor speed, y denotes the deviation of the guide vane opening. The meanings of the other symbols in the system are shown in the Nomenclature.

2.2. Definition and Lemmas. In this section, for the convenience of analysis, we present the basic definition of fixed-time stability first and then introduce some useful lemmas which are necessary for controller design.

Definition 1 (see [22]). Consider the following nonlinear dynamic system.

$$\dot{x} = f(x), \tag{3}$$

where $x \in R^n$ is the system state and f is a smooth nonlinear function. If there exists a fixed convergence time T_0, which is independent of the initial condition and satisfies

$$\lim_{t \to T_0} \|x(t)\| = 0, \tag{4}$$

then this nonlinear dynamic system is said to be fixed-time stable.

Lemma 1 (see [22]). *Consider the following. If there exists a continuous radically unbounded function* $V : R^n \rightarrow R_+ \cup |0|$, *such that*

(1) $V(x) = 0 \Leftrightarrow x = 0$,

(2) *for some* $\alpha, \beta, \phi = 1 - 1/2\gamma, \varphi = 1 + 1/2\gamma$, *and* $\gamma > 1$, *any solution* $x(t)$ *satisfied the inequality*

$$D * V(x(t)) \leq -\alpha V^{\phi}(x(t)) - \beta V^{\varphi}(x(t)), \quad (5)$$

where $D^* V(x(t))$ *denotes the upper right-hand derivative of the function* $V(x(t))$, *then the origin is globally fixed-time stable and the following estimate holds*

$$T(x_0) \leq T_{\max} = \frac{\pi\gamma}{\sqrt{\alpha\beta}}, \quad \forall x_0 \in R^n. \quad (6)$$

Lemma 2 (see [32]). *If* $x_1, x_2, \ldots, x_n \geq 0$, *Then, the following two inequalities hold.*

$$\begin{aligned} &\sum_{i=1}^{n} x_i^{n} \geq \left(\sum_{i=1}^{n} x_i\right)^{\eta}, \quad 0 < \eta \leq 1, \\ &\sum_{i=1}^{n} x_i^{\theta} \geq n^{1-\theta}\left(\sum_{i=1}^{n} x_i\right)^{\theta}, \quad \theta > 1. \end{aligned} \quad (7)$$

3. Fixed-Time Feedback Controllers Design

From (1), it is known that when the system is running to the point P(0,0,0,0,0,0), the system returns to its original state of stability. In order to quickly stabilize the system to the equilibrium point P, the fixed-time controllers u_ω and u_y are added to the fifth subsystem and sixth subsystem of the system (1), respectively, and the controlled system can be described as follows:

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= x_3, \\ \dot{x}_3 &= -a_0 x_1 - a_1 x_2 - a_2 x_3 + y, \\ \dot{\delta} &= \omega_0 \omega, \\ \dot{\omega} &= \frac{1}{T_{ab}}(m_t - D\omega - P_e) + u_\omega, \\ \dot{y} &= \frac{1}{T_y}(-y + u_y). \end{aligned} \quad (8)$$

For the uncertain system (1), in order to make the hydraulic turbine governing system stabilize in fixed time, we design the controllers which are based on the fixed-time control theory, feedback control theory, and backstepping method as follows:

$$\begin{aligned} u_y &= -k_1 y - k_2 y^{m/n} - k_2 y^{p/q}, \\ u_\omega &= -\omega_0\delta - \frac{m_t - D\omega - P_e}{T_{ab}} - k_3\omega_0\omega - \frac{mk_4\omega_0\omega}{n}\delta^{(m-n)/n} \\ &\quad - \frac{pk_4\omega_0\omega}{q}\delta^{(p-q)/q} - k_3\left(\omega + k_3\delta + k_4\delta^{m/n} + k_4\delta^{p/q}\right) \\ &\quad - k_5\left(\omega + k_3\delta + k_4\delta^{m/n} + k_4\delta^{p/q}\right)^{m/n} \\ &\quad - k_5\left(\omega + k_3\delta + k_4\delta^{m/n} + k_4\delta^{p/q}\right)^{p/q}, \end{aligned} \quad (9)$$

where $k_1 > 0$, $k_2 > 0$, $k_3 > 0$, $k_4 > 0$, and $k_5 > 0$, and m, n, p, and q are positive odd integers satisfying $m < n$ and $p > q$; thus, the hydraulic turbine governing system is fixed-time stable.

Here, we will give the design process of the fixed-time feedback controllers u_y and u_ω of the hydraulic turbine governing system step by step. Consider the Lyapunov function:

$$V_1(t) = \frac{y^2}{2}. \quad (10)$$

Differentiating $V_1(t)$ along the solution of (8) gives the following:

$$\dot{V}_1(t) = y\dot{y} = \frac{y}{T_y}(-y + u_y). \quad (11)$$

According to (11), in order to achieve fixed-time stability for the $V_1(t)$, the actual fixed-time feedback control law is obtained as follows:

$$u_y = -k_1 y - k_2 y^{m/n} - k_2 y^{p/q}, \quad (12)$$

where $-k_2 y^{m/n} - k_2 y^{p/q}$ is to ensure the fixed-time stability of $V_1(t)$ and $-k_1 y$ is to speed up the stability of $V_1(t)$.

To bring (12) into $V_1(t)$, the following can be obtained:

$$\begin{aligned} \dot{V}_1(t) &= \frac{y}{T_y}\left(-y - k_1 y - k_2 y^{m/n} - k_2 y^{p/q}\right) \\ &= -\frac{1}{T_y}\left(y^2 + k_1 y^2 + k_2 y^{(m+n)/n} + k_2 y^{(p+q)/q}\right) \\ &\leq -\frac{k_2}{T_y}\left[\left(y^2\right)^{(m+n)/2n} + \left(y^2\right)^{(p+q)/2q}\right] \\ &= -\frac{k_2}{T_y}\left[\left(\frac{y^2}{2}\right)^{(m+n)/2n} \cdot \left(\frac{1}{2}\right)^{-(m+n)/2n} \right. \\ &\quad \left. + \left(\frac{y^2}{2}\right)^{p+q/2q} \cdot \left(\frac{1}{2}\right)^{-p+q/2q}\right] \\ &= -\frac{k_2}{T_y} \cdot 2^{(m+n)/2n} V_1^{(m+n)/2n}(t) - \frac{k_2}{T_y} \cdot 2^{p+q/2q} V_1^{p+q/2q}(t), \end{aligned} \quad (13)$$

where $\alpha_1 = k_2/T_y \cdot 2^{(m+n)/2n}$, $\beta_1 = k_2/T_y \cdot 2^{(p+q)/2q}$, $\phi_1 = (m+n)/2n$ and $\varphi_1 = (p+q)/2q$. According to Lemma 1, we know that the sixth subsystem of (8) is stable in fixed time

$$t_1 = \frac{T_y \pi q n}{k_2 (pn - mq) \cdot 2^{(qm+pn-2qn)/4qn}}, \tag{14}$$

which means that the system state variable y satisfies the following relation $y = 0$ when $t \geq t_1$. And

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= x_3, \\ \dot{x}_3 &= -a_0 x_1 - a_1 x_2 - a_2 x_3, \\ \dot{\delta} &= \omega_0 \omega, \\ \dot{\omega} &= \frac{1}{T_{ab}} (m_t - D\omega - Pe) + u_\omega. \end{aligned} \tag{15}$$

For the system (15), the desired controllers u_ω can be worked out by the following steps.

Step 1. Define the tracking errors as follows: $e_1 = \delta$, $e_2 = \omega - \omega_d$, in which $\omega_d = -k_3 \delta - k_4 \delta^{m/n} - k_4 \delta^{p/q}$. Then, their derivatives can be written as $\dot{e}_1 = \dot{\delta} = \omega_0 \omega$, $\dot{e}_2 = \dot{\omega} - \dot{\omega}_d$, in which ω is the virtual controller and ω_d is the virtual stabilization function. Then, the derivative of e_1 can be written as

$$\dot{e}_1 = \omega_0. \tag{16}$$

A Lyapunov candidate function $V_2(t)$ for stability analysis is defined as follows:

$$V_2(t) = \frac{e_1^2}{2}. \tag{17}$$

Differentiating $V_2(t)$ with respect to time, there is

$$\begin{aligned} \dot{V}_2(t) &= e_1 \dot{e}_1 \\ &= \omega_0 \left(e_1 e_2 - k_3 e_1^2 - k_4 e_1^{(m+n)/n} - k_4 e_1^{(p+q)/q} \right). \end{aligned} \tag{18}$$

From (18) we can know $\dot{V}_2(t) \leq 0$ when $e_2 = 0$.

Step 2. Then, going one step ahead provides the candidate Lyapunov function $V_3(t)$ as follows:

$$V_3(t) = V_2(t) + \frac{e_2^2}{2}. \tag{19}$$

Differentiating $V_3(t)$ with respect to time yields

$$\begin{aligned} \dot{V}_3(t) &= \dot{V}_2(t) + e_2 \dot{e}_2 \\ &= \omega_0 \left(e_1 e_2 - k_3 e_1^2 - k_4 e_1^{(m+n)/n} - k_4 e_1^{(p+q)/q} \right) \\ &\quad + e_2 (\dot{\omega} - \dot{\omega}_d) \\ &= \omega_0 \left(-k_3 e_1^2 - k_4 e_1^{(m+n)/n} - k_4 e_1^{(p+q)/q} \right) \\ &\quad + e_2 \left[\omega_0 e_1 + \frac{1}{T_{ab}} (m_t - D\omega - P_e) + u_\omega \right. \\ &\quad + k_3 \omega_0 \omega + \frac{m k_4 \omega_0 \omega}{n} \cdot \delta^{(m-n)/n} \\ &\quad \left. + \frac{p k_4 \omega_0 \omega}{q} \cdot \delta^{(p-q)/q} \right]. \end{aligned} \tag{20}$$

In order to achieve fixed-time stability for the $V_3(t)$, the actual fixed-time feedback control law is obtained as

$$\begin{aligned} u_\omega = &-\omega_0 \delta - \frac{1}{T_{ab}} (m_t - D\omega - P_e) - k_3 \omega_0 \omega - \frac{m k_4 \omega_0 \omega}{n} \delta^{(m-n)/n} \\ &- \frac{p k_4 \omega_0 \omega}{q} \delta^{(p-q)/q} - k_3 e_2 - k_5 e_2^{m/n} - k_5 e_2^{p/q}. \end{aligned} \tag{21}$$

To bring u_ω into $\dot{V}_3(t)$ the following can be obtained:

$$\begin{aligned} \dot{V}_3(t) = &\ \omega_0 \left(-k_3 e_1^2 - k_4 e_1^{(m+n)/n} - k_4 e_1^{(p+q)/q} \right) \\ &- k_3 e_2^2 - k_5 e_2^{(m+n)/n} - k_5 e_2^{(p+q)/q} \\ \leq &-k_4 \omega_0 e_1^{(m+n)/n} - k_5 e_2^{(m+n)/n} - k_4 \omega_0 e_1^{(p+q)/q} - k_5 e_2^{(p+q)/q} \\ \leq &-k_m \left(e_1^{(m+n)/n} + e_2^{(m+n)/n} \right) - k_m \left(e_1^{(p+q)/q} + e_2^{(p+q)/q} \right) \\ = &-k_m \left[\left(\frac{e_1^2}{2} \right)^{(m+n)/2n} \left(\frac{1}{2} \right)^{-(m+n)/2n} \right. \\ &\left. + \left(\frac{e_2^2}{2} \right)^{(m+n)/2n} \left(\frac{1}{2} \right)^{-(m+n)/2n} \right] \\ &- k_m \left[\left(\frac{e_1^2}{2} \right)^{(p+q)/2q} \left(\frac{1}{2} \right)^{-(p+q)/2q} \right. \\ &\left. + \left(\frac{e_2^2}{2} \right)^{(p+q)/2q} \left(\frac{1}{2} \right)^{-(p+q)/2q} \right] \\ = &-k_m 2^{(m+n)/2n} \left[\left(\frac{e_1^2}{2} \right)^{(m+n)/2n} + \left(\frac{e_2^2}{2} \right)^{(m+n)/2n} \right] \\ &- k_m 2^{(p+q)/2q} \left[\left(\frac{e_1^2}{2} \right)^{(p+q)/2q} + \left(\frac{e_2^2}{2} \right)^{(p+q)/2q} \right] \\ \leq &-k_m 2^{(m+n)/2n} V_3^{(m+n)/2n}(t) - 2 k_m V_3^{(p+q)/2q}(t), \end{aligned} \tag{22}$$

Table 1: The system and controllers parameters.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
D	0.5	E'_q	1.35	$x'_{d\sum}$	1.15	e_y	1
e	0.7	h	2	$x_{q\sum}$	1.474	T_{ab}	8
e_{qh}	0.5	T_y	0.1	T_r	1	V_s	1
ω_0	314	δ_0	30	x_L	0.08	k_1	2.5
k_2	0.5	k_3	0.05	k_4	0.05	k_5	1
m	11	n	15	p	11	q	7

where $k_m = \min(k_4\omega_0, k_5)$, $\alpha_2 = k_m 2^{(m+n)/2n}$, $\beta_2 = 2k_m$, $\phi_2 = (m+n)/2n$, and $\varphi_2 = (p+q)/2q$. According to Lemma 1, we know that $\dot{V}_3(t)$ is stable in fixed time.

$$t_2 = \frac{\pi q n}{k_m(pn - mq)\cdot 2^{(m-n)/4n}}, \tag{23}$$

which means $V_3(t) = 0$ when $t \geq t_2$. It also means $e_1 = 0$, $e_2 = 0$, $\delta = 0$, and $\omega = 0$, and the system reaches steady state. To sum up, when $t \geq t_3$, the hydraulic turbine governing system is stable under the action of fixed-time feedback controllers u_ω and u_y, where $t_3 = t_1 + t_2$. In other words, the system is stable in the fixed time.

4. Simulation Results and Analyses

In this section, the simulation results are provided to verify the validity and effectiveness of the proposed fixed-time feedback control strategy. Based on some published papers, the value of system parameters are selected from [18] and the system parameters and controller parameters of this paper are shown in Table 1.

Figures 1(a)–1(c) display the transient responses of the system state variables δ, ω, and y after the controllers u_ω and u_y are applied to the hydraulic turbine governing system, respectively. From Figure 1, it can be seen that when the system is coupled with u_ω and u_y, the system state variable y reaches steady state at 0.11 s, and the system state variables δ and ω reach steady state at 0.18 s, simultaneously. The convergence time of δ, ω, and y is much smaller than the theoretical estimate $t_3 = 4.634$ s, which is calculated by the values of the parameters of the fixed-time feedback controllers. The simulation results show that the system can reach the steady state rapidly under the action of fixed-time feedback controllers u_ω and u_y, and the control effect is achieved.

In this part, in order to prove the validity and superiority of the fixed-time feedback controllers proposed in this paper, we compared the control effect of the fixed-time feedback controllers and the feedback controllers. From Section 3, we know that the fixed-time feedback controllers are composed of two parts of the fixed-time control part and the feedback control part, and the feedback control part can also bring the hydraulic turbine governing system to a stable state in theory. The feedback controllers used for comparison are the feedback control part of the fixed-time feedback controllers. In order to make a fair comparison between fixed-time feedback control and feedback control, we select the same initial conditions and system parameters. The parameters of the feedback controllers are exactly the same as those of the feedback control part of the fixed-time feedback controllers and these parameters have been given in Table 1. Figures 2(a)–2(c) show the dynamic responses of the system state variables under the action of fixed-time feedback controllers and feedback controllers. From Figure 2, it can be found that the performance of the system state variables δ, ω, and y with fixed-time feedback controllers is much better than the performance of the system state variables δ, ω, and y with the feedback controllers. Under the action of fixed-time feedback controllers, the system state variables δ, ω, and y are stable at 0.18 s, 0.18 s, and 0.11 s, respectively. And under the action of feedback controllers, the system state variables δ, ω, and y are stable at 1.08 s, 1.08 s, and 0.25 s, respectively. The fixed-time controllers stabilize the nonlinear system faster than feedback controllers do. In other words, compared with the feedback control, the fixed-time feedback control has better control effect on the hydraulic turbine governing system.

In order to explore the effect of different initial conditions on system stability under the action of fixed-time feedback controllers, we compared the responses of three different initial conditions of the hydraulic turbine governing system. In this section, the initial values of the hydraulic turbine governing system are shown as follows: $S1 = (0.02, 0.02, 0.02, 0.02, 0.02, 0.02)$, $S2 = (0.05, 0.05, 0.05, 0.05, 0.05, 0.05)$, and $S3 = (0.08, 0.08, 0.08, 0.08, 0.08, 0.08)$. From Figure 3, we can see that as the initial values increase, the convergence time gradually increases when the system is coupled with u_ω and u_y, but they all do not exceed the theoretical estimate $t_3 = 4.634$ s. And no matter how the initial value changes, the system achieves the ideal steady state. That is to say, the simulation results are consistent with the theoretical derivation and the actual situation.

Figures 4(a)–4(c) show the dynamic responses of the system state variables when the system is subjected to external disturbances. In order to verify the robustness of the controlled system to disturbance, this paper gives δ and y a disturbance in 0.5 s and 1 s, respectively. From Figure 4, it can be found that the system achieves steady state under the action of fixed-time feedback controllers before 0.5 s. When the system is disturbed in 0.5 s, δ and ω quickly

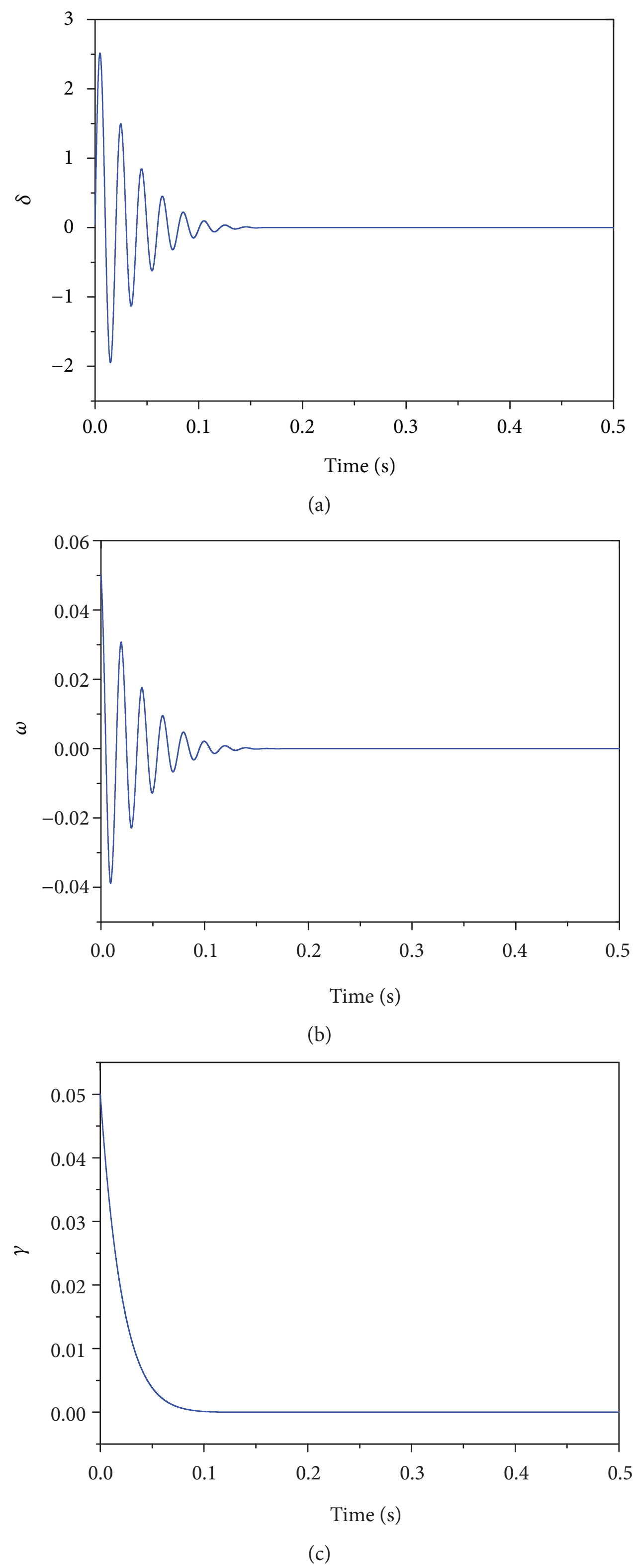

FIGURE 1: The response of the system variables δ, ω, and y with fixed-time feedback controllers.

increase, whose maximum deviations reach to 2.51 and 0.05, respectively. But under the action of the controller u_{ω}, the state of y has not changed. As time goes on, δ and ω gradually

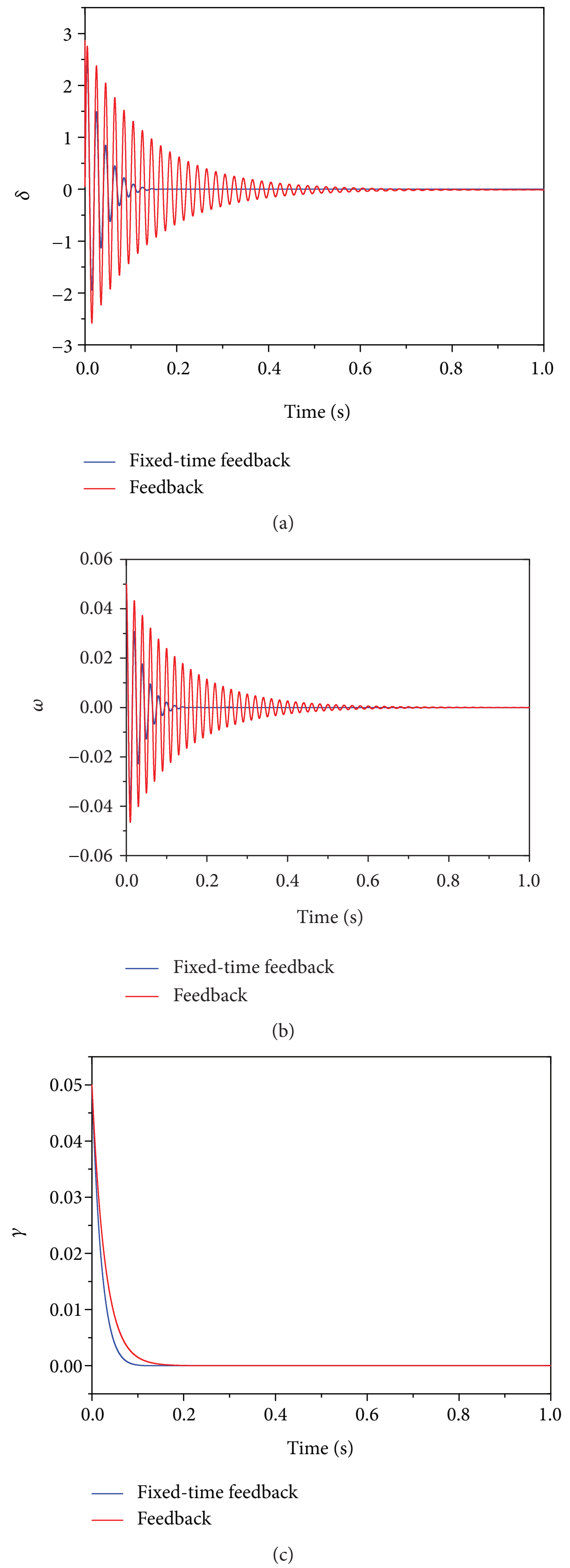

FIGURE 2: Comparison of converging speed of fixed-time feedback and feedback controllers.

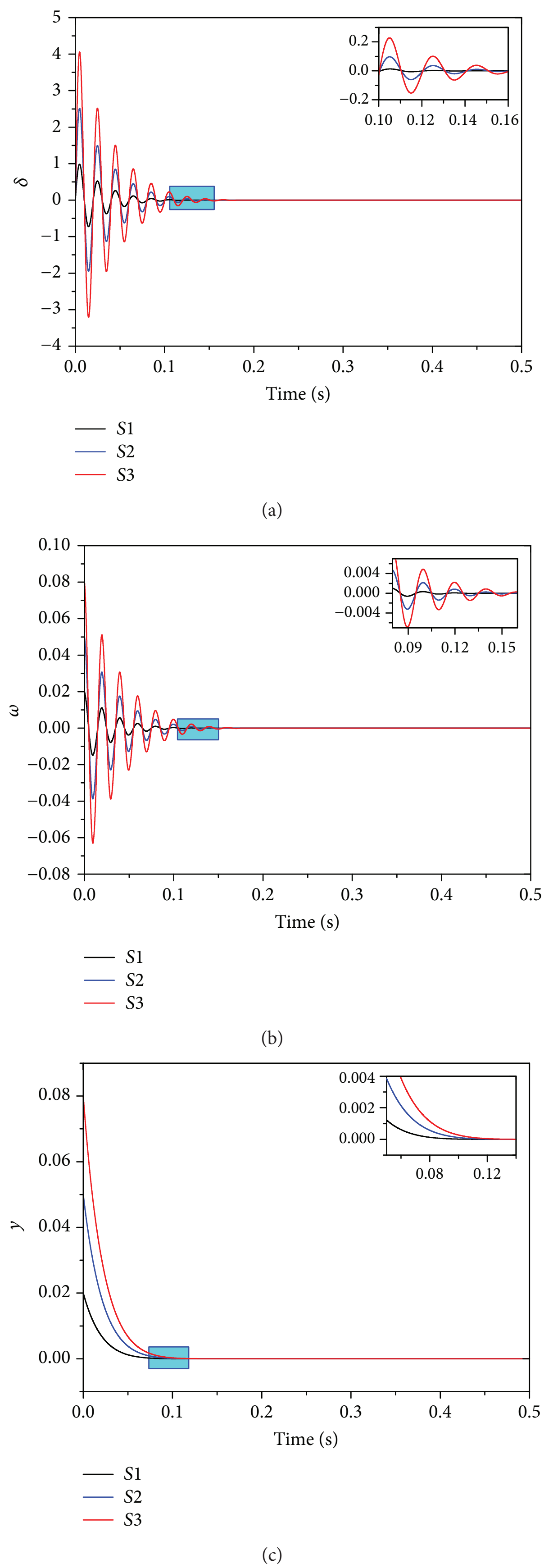

Figure 3: The response of the system with the different S.

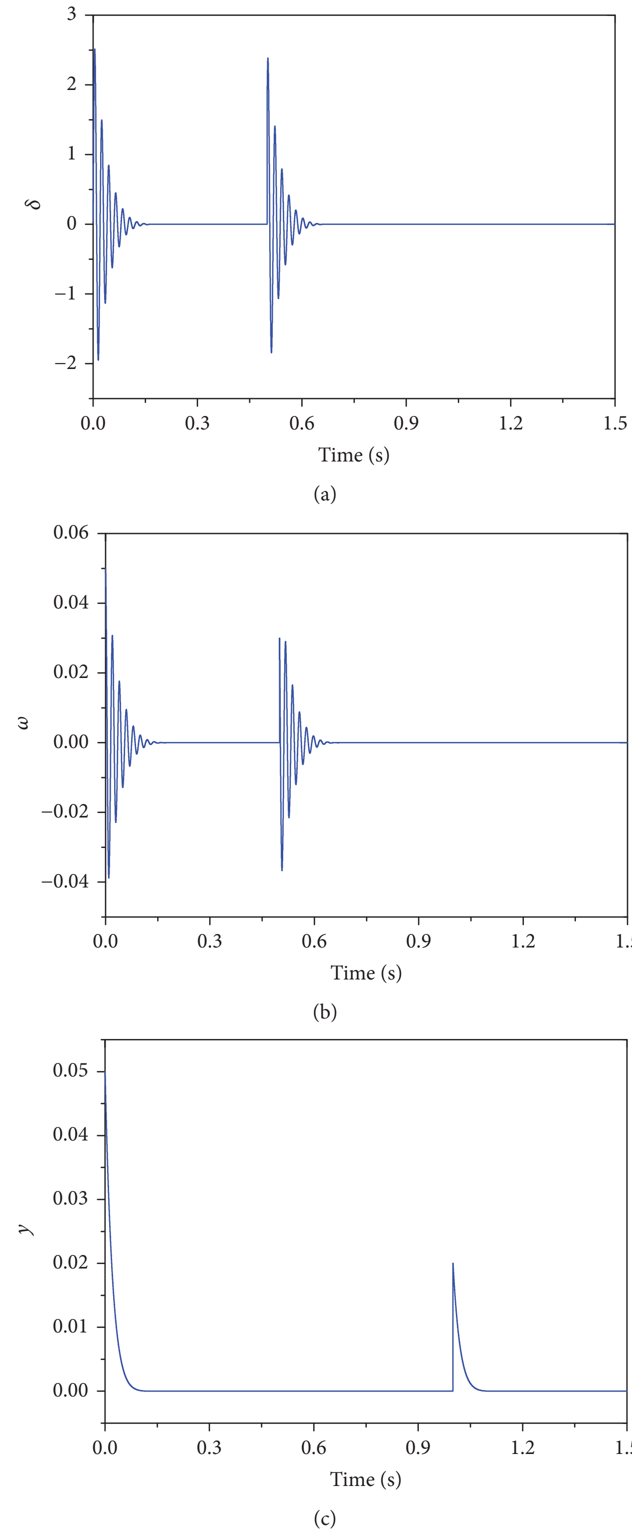

Figure 4: The response of the system with the different disturbances.

reach the steady state, which indicate that the hydraulic turbine governing system remains in a stable state under the appropriate control of the fixed-time feedback controller u_{ω}. When the system is disturbed in 1 s, y gradually decreased from the disturbance and eventually stabilized to zero. There is no change in the state of δ and ω in the controlled system. Therefore, the simulation results are consistent with the theoretical derivation and show that the system has good robustness to external disturbances under the action of fixed-time feedback controllers.

5. Conclusions

The control problem of a nonlinear hydraulic turbine governing system is studied in this paper. In order to give the system better quality, the fixed-time feedback controllers were designed by combining fixed-time control and feedback control and compared with the feedback controllers. The designed controllers are without sign function, which means the chattering phenomenon will not appear in the system. The fixed-time feedback control inherits the advantages of the fixed-time control, so that the maximum convergence time of the system is not affected by the initial state of the system. The introduction of feedback control of the fixed-time feedback control makes the controlled system achieve a steady state faster. The fixed-time feedback controllers also give the system robustness to external disturbances. Finally, simulations were carried out in the presence of various situations to evaluate the effectiveness of the proposed fixed-time feedback controllers, where the results demonstrated the effectiveness and superiority of the proposed controllers.

Nomenclature

- D: Generator damping coefficient
- e: Intermediate variable
- e_{qh}: First-order partial derivative value of flow rate with respect to water head
- e_y: First-order partial derivative value of torque with respect to wicket gate
- E'_q: The transient internal voltage of armature
- h_ω: The characteristic coefficient of the pipeline
- m_t: The deviation of the mechanical torque of the hydro-turbine
- P_e: The electromagnetic power of generator
- T_y: The engager relay time constant
- T_r: The reflection time of the penstock
- T_{ab}: The mechanical starting time
- x'_d: The direct axis transient reactance
- x_q: The quartered axis reactance
- x_T: Short circuit reactance of the transformer
- x_L: Reactance of the electric transmission line
- $x'_{d\Sigma}$: Direct axis transient reactance
- $x_{q\Sigma}$: Quadrature axis reactance
- V_s: The voltage of infinite bus
- δ_0: Initial generator rotor angle
- ω_0: Synchronous angular speed.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Caoyuan Ma and Chuangzhen Liu conceived and designed the experiments. Chuangzhen Liu and Xuezi Zhang performed the experiments and analyzed the data. Chuangzhen Liu and Xuezi Zhang wrote the paper. Caoyuan Ma and Chuangzhen Liu contributed equally to this work.

References

[1] C. L. Chen, H. C. Chen, and J. Y. Lee, "Application of a generic superstructure-based formulation to the design of wind-pumped-storage hybrid systems on remote islands," *Energy Conversion and Management*, vol. 111, pp. 339–351, 2016.

[2] B. B. Alagoz, A. Kaygusuz, and A. Karabiber, "A user-mode distributed energy management architecture for smart grid applications," *Energy*, vol. 44, no. 1, pp. 167–177, 2012.

[3] M. Mahmoud, K. Dutton, and M. Denman, "Design and simulation of a nonlinear fuzzy controller for a hydropower plant," *Electric Power Systems Research*, vol. 73, no. 2, pp. 87–99, 2005.

[4] C. Li, J. Zhou, S. Ouyang, X. Ding, and L. Chen, "Improved decomposition-coordination and discrete differential dynamic programming for optimization of large-scale hydropower system," *Energy Conversion and Management*, vol. 84, pp. 363–373, 2014.

[5] C. Li and J. Zhou, "Parameters identification of hydraulic turbine governing system using improved gravitational search algorithm," *Energy Conversion and Management*, vol. 52, no. 1, pp. 374–381, 2011.

[6] C. Jiang, Y. Ma, and C. Wang, "PID controller parameters optimization of hydro-turbine governing systems using deterministic-chaotic-mutation evolutionary programming (DCMEP)," *Energy Conversion and Management*, vol. 47, no. 9-10, pp. 1222–1230, 2006.

[7] C. Li, N. Zhang, X. Lai, J. Zhou, and Y. Xu, "Design of a fractional-order PID controller for a pumped storage unit using a gravitational search algorithm based on the Cauchy and Gaussian mutation," *Information Sciences*, vol. 396, pp. 162–181, 2017.

[8] Y. Xu, J. Zhou, X. Xue, W. Fu, W. Zhu, and C. Li, "An adaptively fast fuzzy fractional order PID control for pumped storage hydro unit using improved gravitational search algorithm," *Energy Conversion and Management*, vol. 111, pp. 67–78, 2016.

[9] X. Yuan, Z. Chen, Y. Yuan, Y. Huang, X. Li, and W. Li, "Sliding mode controller of hydraulic generator regulating system based on the input/output feedback linearization method," *Mathematics and Computers in Simulation*, vol. 119, pp. 18–34, 2016.

[10] H. Mesnage, M. Alamir, N. Perrissin-Fabert, and Q. Alloin, "Nonlinear model-based control for minimum-time start of hydraulic turbines," *European Journal of Control*, vol. 34, pp. 24–30, 2017.

[11] D. Chen, C. Ding, Y. Do, X. Ma, H. Zhao, and Y. Wang, "Nonlinear dynamic analysis for a Francis hydro-turbine governing system and its control," *Journal of the Franklin Institute*, vol. 351, no. 9, pp. 4596–4618, 2014.

[12] H. Li, D. Chen, H. Zhang, F. Wang, and D. Ba, "Nonlinear modeling and dynamic analysis of a hydro-turbine governing system in the process of sudden load increase transient,"

Mechanical Systems and Signal Processing, vol. 80, pp. 414–428, 2016.

[13] S. Simani, S. Alvisi, and M. Venturini, "Data-driven design of a fault tolerant fuzzy controller for a simulated hydroelectric system," *IFAC Papers OnLine*, vol. 48, no. 21, pp. 1090–1095, 2015.

[14] S. Simani, S. Alvisi, and M. Venturini, "Fault tolerant control of a simulated hydroelectric system," *Control Engineering Practice*, vol. 51, pp. 13–25, 2016.

[15] R. Zhang, D. Chen, and X. Ma, "Nonlinear predictive control of a hydropower system model," *Entropy*, vol. 17, no. 12, pp. 6129–6149, 2015.

[16] Z. Xiao, S. Meng, N. Lu, and O. P. Malik, "One-step-ahead predictive control for hydroturbine governor," *Mathematical Problems in Engineering*, vol. 2015, Article ID 382954, 10 pages, 2015.

[17] B. Wang, L. Yin, S. Wang, S. Miao, T. Du, and C. Zuo, "Finite time control for fractional order nonlinear hydroturbine governing system via frequency distributed model," *Advances in Mathematical Physics*, vol. 2016, Article ID 7345325, 9 pages, 2016.

[18] C. Ma, C. Liu, X. Zhang, Y. Sun, W. Wu, and J. Xie, "Fixed-time stability of the hydraulic turbine governing system," *Mathematical Problems in Engineering*, vol. 2018, Article ID 1352725, 10 pages, 2018.

[19] Y. Liu, W. Qian, Q. Lan, H. Chu, and C. Qian, "Universal finite-time observer design and adaptive frequency regulation of hydraulic turbine systems," *IET Control Theory and Applications*, vol. 10, no. 4, pp. 363–370, 2016.

[20] W. Zhu, Y. Zheng, J. Dai, and J. Zhou, "Design of integrated synergetic controller for the excitation and governing system of hydraulic generator unit," *Engineering Applications of Artificial Intelligence*, vol. 58, pp. 79–87, 2017.

[21] X. Yang, J. Lam, D. W. C. Ho, and Z. Feng, "Fixed-time synchronization of complex networks with impulsive effects via non-chattering control," *IEEE Transactions on Automatic Control*, vol. 62, no. 11, pp. 5511–5521, 2017.

[22] A. Polyakov, "Nonlinear feedback design for fixed-time stabilization of linear control systems," *IEEE Transactions on Automatic Control*, vol. 57, no. 8, pp. 2106–2110, 2012.

[23] H. Hong, W. Yu, G. Wen, and X. Yu, "Distributed robust fixed-time consensus for nonlinear and disturbed multiagent systems," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 7, pp. 1464–1473, 2017.

[24] J. Gao and Y. Cai, "Fixed-time control for spacecraft attitude tracking based on quaternion," *Acta Astronautica*, vol. 115, pp. 303–313, 2015.

[25] X. Ding, J. Cao, A. Alsaedi, F. E. Alsaadi, and T. Hayat, "Robust fixed-time synchronization for uncertain complex-valued neural networks with discontinuous activation functions," *Neural Networks*, vol. 90, pp. 42–55, 2017.

[26] C. Hu, J. Yu, Z. Chen, H. Jiang, and T. Huang, "Fixed-time stability of dynamical systems and fixed-time synchronization of coupled discontinuous neural networks," *Neural Networks*, vol. 89, pp. 74–83, 2017.

[27] J. Cao and R. Li, "Fixed-time synchronization of delayed memristor-based recurrent neural networks," *Science China Information Sciences*, vol. 60, no. 3, article 032201, 2017.

[28] J. Ni, L. Liu, C. Liu, X. Hu, and S. Li, "Fast fixed-time nonsingular terminal sliding mode control and its application to chaos suppression in power system," *IEEE Transactions on Circuits and Systems II-Express Briefs*, vol. 64, no. 2, pp. 151–155, 2017.

[29] Y. Yang, C. Hua, J. Li, and X. Guan, "Fixed-time coordination control for bilateral telerobotics system with asymmetric time-varying delays," *Journal of Intelligent & Robotic Systems*, vol. 86, no. 3-4, pp. 447–466, 2017.

[30] X. Yang, D. W. C. Ho, J. Lu, and Q. Song, "Finite-time cluster synchronization of T-S fuzzy complex networks with discontinuous subsystems and random coupling delays," *IEEE Transactions on Fuzzy Systems*, vol. 23, no. 6, pp. 2302–2316, 2015.

[31] X. Yuan, Z. Chen, Y. Yuan, and Y. Huang, "Design of fuzzy sliding mode controller for hydraulic turbine regulating system via input state feedback linearization method," *Energy*, vol. 93, pp. 173–187, 2015.

[32] H. K. Khalil and J. W. Grizzle, *Nonlinear Systems Third Edition*, Prentice Hall, Upper Saddle River, 2002.