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Research Article

Adaptive Fixed-Time Fast Terminal Sliding Mode Control for Chaotic Oscillation in Power System

Caoyuan Ma,[1,2] Faxin Wang,[1,2] Zhijie Li,[1,2] Jianyu Wang,[3] Chuangzhen Liu,[1,2] Wenbei Wu,[1,2] and Yuzhou Cheng[1,2]

[1] *School of Electrical and Power Engineering, China University of Mining and Technology, Xuzhou 221116, China*
[2] *Jiangsu Province Laboratory of Electrical and Automation Engineering for Coal Mining, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China*
[3] *State Grid Taiyuan Power Supply Company, Taiyuan 030010, China*

Correspondence should be addressed to Jianyu Wang; wangjy_cumt@163.com

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The second-order chaotic oscillation system model is used to analyze the dynamic behavior of chaotic oscillations in power system. To suppress chaos and stabilize voltage within bounded time independent of initial condition, an adaptive fixed-time fast terminal sliding mode chaos control strategy is proposed. Compared with the conventional fast terminal sliding mode control strategy and finite-time control strategy, the proposed scheme has advantages in terms of convergence time and maximum deviation. Finally, simulation results are given to demonstrate the effectiveness of the proposed control scheme and the superior performance.

1. Introduction

As a typical multivariable and strongly coupled nonlinear system, power system exhibits a lot of nonlinear dynamic behaviors during operation, such as low-frequency oscillation, bifurcation, and chaos [1]. If the amplitude of the disturbance satisfies certain conditions, the power system will appear with continuous and random chaotic oscillations which may lead to instability of the system, voltage collapse, and even catastrophic blackouts [2, 3]. Therefore, it is imperative to study control schemes for chaos suppression in power system. In 1993, Chiang et al. [4] observed the chaotic behavior under different load conditions in the power system firstly. Since then, chaos control had become a hot issue of academia. The control methods of chaotic oscillation can be divided into two aspects: guiding the development of the chaotic oscillation to the expected orbit and suppressing the occurrence of system chaos [5, 6]. At present, the commonly used control methods include parameter perturbation method (OGY) [7–10], feedback control [11–14], adaptive control [15–17], fuzzy control [18–20], and backstepping control [21]. These approaches have important theoretical and practical significance to guarantee the stability and secure operation of power system while some defects did exist at the same time. For example, the backstepping control was proposed to systematize and structure the design process of the system's Lyapunov functions and controllers through the reverse design. But its structure is very complex, and the complexity of regression matrix would become stronger especially when the nonlinear damping existed for the system parameters uncertainty [22, 23]. Fuzzy control is difficult to adapt to the requirements of large-scale adjustment. It needs to constantly adjust the control rules and parameters [24–27]. Moreover, all the above control methods can only reach the asymptotic stability; that is, the convergence time cannot be allocated in advance. From the point of view of the operation of the power system, the oscillation is acceptable if it is damped within a limited time.

Fast terminal sliding mode (FTSM) control can achieve system stability in finite time. It has the advantages of strong robustness to external disturbances and parameter disturbances [28, 29]. The fast terminal sliding mode (FTSM) control can converge the system to the equilibrium point on the sliding mode surface in finite time while the traditional sliding mode control can only ensure that it reaches the sliding mode surface during the same period [30]. Finite-time control can also keep the system stable within bounded time [31]. Because the finite-time control has stronger robustness, better anti-interface, and faster convergence, it has become a research hotspot of academia in recent years. Cai et al. [32] applied the finite-time theory for the first time to deal with the generalized synchronization problem of different order chaotic systems. Khaki et al. [33] proposed a novel fuzzy finite-time variable structure controller for double integrator power systems to damp the complicated chaotic oscillations of an interconnected power system, when such oscillations can be made by load perturbation of a power system working on its stability edges. The above two control methods can make the system stable in finite time but also subject to the limitless of finite-time stability. The system stability is affected by the initial condition while it is difficult to obtain accurate parameters in practical project.

Fixed-time stability is an extension of finite-time stability. Compared with the above control approaches, fixed-time control can not only maintain stronger robustness and better anti-interference and ensure a clear upper bound of settling time, but also make the system globally uniformly ultimately bounded stable one with any initial conditions [34]. Polyakov firstly proposed the concept of fixed-time in 2012 [35]. At present, due to this attractive property, fixed-time control has begun to be widely used in hydraulic turbine governing systems [36], PMSM [37], multiagent systems [38], aircraft systems [39], chaotic systems [40], and so on. Ni et al. [40] firstly applied the STATCOM to suppress chaos of power system and authors designed a fixed-time dynamic surface high-order sliding mode control approach to achieve semiglobally fixed-timely uniformly ultimately bounded stabilization. In view of the discussion of the above control schemes, this paper presents an adaptive fixed-time fast terminal sliding mode control scheme which can accelerate the convergence, suppress chaos in the power system, and avoid voltage collapse. The main advantages of proposed controller are that it can guarantee the system stability in finite time independent of initial state and the settling time can be directly calculated.

The structure of this paper is as follows: the second section gives some theorems and lemmas to facilitate the derivation of the system control method in the later text. In the third section, an adaptive fixed-time fast terminal sliding mode control scheme is proposed to suppress chaos in the power system. The fourth section provides the simulation results in this paper to demonstrate the effectiveness of the proposed control scheme. The fifth section has made some summary conclusion based on the above work.

2. Preliminaries

In this paper, for the convenience of analysis, we firstly introduce a necessary definition and some lemmas which play an important role in design process.

Consider the following differential equation system:

$$\dot{x}(t) = f(x(t)),$$
$$x_0 = x(0) \tag{1}$$

where $x \in R^n$ is the system state variable; f: $R_+ \times R^n \longrightarrow R^n$ is a smooth nonlinear function. Assume the origin is an equilibrium point of (1).

Definition 1 (see [41–43]). The origin of system (1) is a finite-time stable equilibrium if the origin is Lyapunov stable and there exists a function T: $R^n \longrightarrow R^+$, called the settling time function, such that, for every $x_0 \in R^n$, the solution $x(t, x_0)$ of system (1) is defined on $[0, T(x_0)), x(t, x_0) \in R^n$, for all $t \in [0, T(x_0))$, and $\lim_{t\longrightarrow T(x_0)} x(t, x_0) = 0$.

Definition 2 (see [35, 43]). The origin of system (1) is said to be fixed-time stable equilibrium point if it is globally finite-time stable with bounded convergence time $T(x_0)$; that is, there exists a bounded positive constant $T_{\max}$ such that $T(x_0) < T_{\max}$ satisfies.

Lemma 3 (see [35, 42]). *If there exists a continuous function V: $R^n \longrightarrow R_+ \mathrm{U}|0|$ such that*

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

(2) *$V(x)$ is radially unbounded,*

(3) *for some α, β, p, q, $k>0$, and $pk<1$*

any solution $x(t)$ satisfied the inequality

$$D^* V(x(t)) \leq -\left[\alpha V^p(x(t)) + \beta V^q(x(t))\right]^k \tag{2}$$

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

$$T(x_0) \leq \frac{1}{\alpha^k(1-pk)} + \frac{1}{\beta^k(qk-1)}, \quad \forall x_0 \in R^n \tag{3}$$

Lemma 4 (see [44]). *For any nonnegative real numbers, that is, $x_1, x_2, \ldots, x_N \geq 0$, the following inequality holds:*

$$\begin{aligned} &\sum_{i=1}^{N} x_i^{\eta} \geq \left(\sum_{i=1}^{N} x_i\right)^{\eta}, \quad 0 < \eta \leq 1 \\ &\sum_{i=1}^{N} x_i^{\varsigma} \geq N^{1-\varsigma}\left(\sum_{i=1}^{N} x_i\right)^{\varsigma}, \quad \varsigma > 1 \end{aligned} \tag{4}$$

3. Main Results

Ignoring the dynamic process of excitation loop and damping winding, it is assumed that the mechanical power of generator is always the same in transient process, and the transient salient effect of generator is not considered. The external factors of system, such as disturbance's influence on the system, are mainly considered. The equivalent circuit of power grid second-order chaotic oscillation system is presented in Figure 1, where G_1, G_2 and T_1, T_2 are equivalent generators and main transformers of system, respectively.

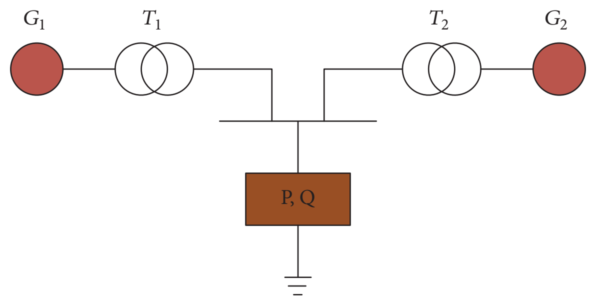

Figure 1: Equivalent circuit of power grid two-order chaotic oscillation system.

The power system is composed of two generator buses and one load bus. Here, the second-order nonlinear mathematical model of the synchronous generators used in this paper is as follows:

$$\begin{aligned} \dot{\delta} &= \omega \\ \dot{\omega} &= -\frac{1}{H}P_s \sin\delta - \frac{D}{H}\omega + \frac{1}{H}P_m + \frac{1}{H}P_e \cos\lambda t \end{aligned} \tag{5}$$

where δ and ω are state variables that denote relative angle and angular frequency between equivalent generators, respectively; H and D refer to generator inertia and damping coefficient, respectively; P_s and P_m are electromagnetic power and mechanical power of generator, respectively; P_e and λ represent amplitude and frequency of load disturbance. To simplify the model, we make the following transformation:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -a\sin x_1 - bx_2 + c + F\cos\lambda t + u \\ &= f(x) + F\cos\lambda t + u \end{aligned} \tag{6}$$

where $a = P_s/H$, $b = D/H$, $c = P_m/H$, $F = P_e/H$, $[x_1, x_2] = [\delta, \omega]$, $f(x) = -a\sin x_1 - bx_2 + c$, and u is control input.

Then the fast terminal sliding mode surface can be designed as

$$s = x_2 + \alpha_0 x_1 + \beta_0 x_1^{q_0/p_0} \tag{7}$$

where parameters satisfy $\alpha_0, \beta_0 > 0$, and q_0, p_0 are positive odd numbers. The derivative of the system (7) gives

$$\begin{aligned} \dot{s} &= \dot{x}_2 + \alpha_0\dot{x}_1 + \frac{q_0}{p_0}\beta_0 x_1^{q_0/p_0-1}x_2 \\ &= f(x) + F\cos\lambda t + u + \alpha_0 x_2 + \frac{q_0}{p_0}\beta_0 x_1^{q_0/p_0-1}x_2 \end{aligned} \tag{8}$$

For system (6), we can see that $X_0 = (z, 0)$ is a point of equilibrium of the system, where z is a constant. To realize the global stability of system (6) based on the fixed-time stability theory in the case of the equilibrium X_0, another global fast terminal sliding mode is taken as the following form:

$$\dot{s} + \phi s + \gamma s^{q/p} + k\,\mathrm{sgn}(s)|s|^\alpha + k\,\mathrm{sgn}(s)|s|^\beta = 0 \tag{9}$$

where parameters satisfy $\phi, \gamma > 0$, $0 < \alpha < 1$, $\beta > 1$, and $q < p$. p and q are positive odd numbers. According to the above analysis, we propose our main results in the following theorem.

Theorem 5. *System (6) can be stabilized in fixed-time under the following adaptive controller:*

$$\begin{aligned} u = &-f(x) - \hat{F}\cos\lambda t - \alpha_0 x_2 - \frac{q_0}{p_0}\beta_0 x_1^{q_0/p_0-1}x_2 - \phi s \\ &- \gamma s^{q/p} - k\,\mathrm{sgn}(s)|s|^\alpha - k\,\mathrm{sgn}(s)|s|^\beta \end{aligned} \tag{10}$$

where $\hat{F}$ is the estimated value of the uncertain parameter and k is the tuning parameter of the terminal attractor satisfying the following adaptive laws:

$$\begin{aligned} \dot{\hat{F}} &= s\cos\lambda t - (\hat{F} - F)^\alpha - (\hat{F} - F)^\beta \\ \dot{k} &= |s|^{\alpha+1} + |s|^{\beta+1} - (k-g)^\alpha - (k-g)^\beta \end{aligned} \tag{11}$$

where g is the arbitrary constant.

Proof. Firstly, substitute (10) into (8) to get the following formula which will be used directly in the process of proof:

$$\begin{aligned} \dot{s} = &F\cos\lambda t - \hat{F}\cos\lambda t - \phi s - \gamma s^{q/p} - k\,\mathrm{sgn}(s)|s|^\alpha \\ &- k\,\mathrm{sgn}(s)|s|^\beta \end{aligned} \tag{12}$$

Consider the following Lyapunov candidate function as

$$V = \frac{1}{2}s^2 + \frac{1}{2}(\hat{F} - F)^2 + \frac{1}{2}(k-g)^2 \tag{13}$$

By using the designed controller u and the appropriate tuning parameters, the time derivative of V can be obtained as

$$\begin{aligned} \dot{V}(t) = &s\dot{s} + (\hat{F} - F)\dot{\hat{F}} + (k-g)\dot{k} = s\big[F\cos\lambda t \\ &- \hat{F}\cos\lambda t - \phi s - \gamma s^{q/p} - k\,\mathrm{sgn}(s)|s|^\alpha \\ &- k\,\mathrm{sgn}(s)|s|^\beta\big] + (\hat{F} - F)\big[s\cos\lambda t - (\hat{F} - F)^\alpha \\ &- (\hat{F} - F)^\beta\big] + (k-g)\big[|s|^{\alpha+1} + |s|^{\beta+1} - (k-g)^\alpha \\ &- (k-g)^\beta\big] = -\phi s^2 - \gamma s^{p+q/p} + s(F - \hat{F})\cos\lambda t \\ &+ s(\hat{F} - F)\cos\lambda t - (\hat{F} - F)^{\alpha+1} - (\hat{F} - F)^{\beta+1} \\ &- k|s|^{\alpha+1} - k|s|^{\beta+1} + (k-g)|s|^{\alpha+1} + (k-g)|s|^{\beta+1} \\ &- (k-g)^{\alpha+1} - (k-g)^{\beta+1} = -\phi s^2 - \gamma s^{p+q/p} \\ &- g|s|^{\alpha+1} - g|s|^{\beta+1} - (\hat{F} - F)^{\alpha+1} - (\hat{F} - F)^{\beta+1} \\ &- (k-g)^{\alpha+1} - (k-g)^{\beta+1} \end{aligned} \tag{14}$$

Here, owing to the fact that p and q are positive odd numbers, the process of derivation continues:

$$\begin{aligned}
\dot{V}(t) &\leq -g|s|^{\alpha+1} - g|s|^{\beta+1} - \left(\widehat{F}-F\right)^{\alpha+1} - \left(\widehat{F}\right. \\
&\quad \left. - F\right)^{\beta+1} - (k-g)^{\alpha+1} - (k-g)^{\beta+1} \\
&= -2^{(1/2)(\alpha+1)} g \left(\frac{1}{2}s^2\right)^{(1/2)(\alpha+1)} \\
&\quad - 2^{(1/2)(\alpha+1)} \left[\frac{1}{2}\left(\widehat{F}-F\right)^2\right]^{(1/2)(\alpha+1)} \\
&\quad - 2^{(1/2)(\alpha+1)} \left[\frac{1}{2}(k-g)^2\right]^{(1/2)(\alpha+1)} \\
&\quad - 2^{(1/2)(\beta+1)} g \left(\frac{1}{2}s^2\right)^{(1/2)(\beta+1)} \\
&\quad - 2^{(1/2)(\beta+1)} \left[\frac{1}{2}\left(\widehat{F}-F\right)^2\right]^{(1/2)(\beta+1)} \\
&\quad - 2^{(1/2)(\beta+1)} \left[\frac{1}{2}(k-g)^2\right]^{(1/2)(\beta+1)} \\
&\leq -m\left\{\left(\frac{1}{2}s^2\right)^{(1/2)(\alpha+1)} + \left[\frac{1}{2}\left(\widehat{F}-F\right)^2\right]^{(1/2)(\alpha+1)}\right. \\
&\quad \left. + \left[\frac{1}{2}(k-g)^2\right]^{(1/2)(\alpha+1)}\right\} - n\left\{\left(\frac{1}{2}s^2\right)^{(1/2)(\beta+1)}\right. \\
&\quad \left. + \left[\frac{1}{2}\left(\widehat{F}-F\right)^2\right]^{(1/2)(\beta+1)} + \left[\frac{1}{2}(k-g)^2\right]^{(1/2)(\beta+1)}\right\}
\end{aligned} \tag{15}$$

where $m = \min\{2^{(1/2)(\alpha+1)}g, 2^{(1/2)(\alpha+1)}\}, n = \min\{2^{(1/2)(\beta+1)}g, 2^{(1/2)(\beta+1)}\}$. Thus, it follows from Lemma 4 that

$$\begin{aligned}
\dot{V}(t) &\leq -m\left\{\left(\frac{1}{2}s^2\right) + \left[\frac{1}{2}\left(\widehat{F}-F\right)^2\right]\right. \\
&\quad \left. + \left[\frac{1}{2}(k-g)^2\right]\right\}^{(1/2)(\alpha+1)} - 3^{(1-\beta)/2} n\left\{\left(\frac{1}{2}s^2\right)\right. \\
&\quad \left. + \left[\frac{1}{2}\left(\widehat{F}-F\right)^2\right] + \left[\frac{1}{2}(k-g)^2\right]\right\}^{(1/2)(\beta+1)} \\
&= -mV^{(1/2)(\alpha+1)} - 3^{(1-\beta)/2} nV^{(1/2)(\beta+1)}
\end{aligned} \tag{16}$$

According to Lemma 3, system (6) reaches the equilibrium within a bounded time and the bound of convergence time can be estimated by

$$\begin{aligned}
T &\leq \frac{1}{m(1-(\alpha+1)/2)} + \frac{1}{3^{(1-\beta)/2} n((\beta+1)/2-1)} \\
&= \frac{2}{m(1-\alpha)} + \frac{2}{3^{(1-\beta)/2} n(\beta-1)}
\end{aligned} \tag{17}$$

which means that the state variables of the system can stabilize when $t \geq T$. □

4. Numerical Simulations

In this section, numerical simulations are performed to demonstrate the effectiveness and the superiority of the proposed control method. System (6) is selected for simulation. Without loss of generality, the system parameters are a =1, b =0.02, and c =0.2 and controller parameters are α_0 =1, β_0 =2, q_0 =5, p_0 =9, ϕ=20, γ=15, α=0.5, β=1.5, p=3, q=1, g=0.3, and $k(0)$=0.2. The initial values of the state variable are $S(\delta_0, \omega_0)$ = (0.43,0.003). In the power system, the damping coefficient and the inertial coefficient of the generator are often constant, and the variation of the load disturbance can usually cause the chaotic oscillation of the power system. Further, when amplitude of periodic load disturbance F varies to 0.2593, the power system exhibits chaotic oscillations which are displayed in Figures 2 and 3. As the parameters are selected, Lyapunov exponents can be calculated as $(\lambda_1,\lambda_2,\lambda_3)$ =(0.0174, 0, −0.0374). There is one positive Lyapunov exponent, which validates the existence of chaotic attractor. Figure 2 is the phase portrait of chaotic power system and it shows chaotic behavior of the power system clearly. Figure 3 shows the time responses of state variables in chaotic power system. As can be seen from Figure 3, the time responses of state variables are in an irregular and aperiodic oscillatory state and their trajectories are unpredictable after a long period of time.

The chaotic oscillation state has great harm to the power system. Circuit voltage and current waveform distortion caused by the oscillation, particularly over voltage, will cause severe local instability with potentially serious impact and damage to the power system. Therefore, an immediate control action needs to be activated to suppress chaos. Simulations are conducted to examine the proposed controller performance in terms of suppressing chaos in power system and stabilizing the power system to its desired operating point. The time responses of state variables and the phase portrait of chaotic power system under proposed controller are presented in Figures 4 and 5, respectively. Figures 6 and 7 are the time response of tuning parameter of the terminal attractor and the time response of the proposed controller u. As Figure 7 shows, the controller was added at 50s. Further, the bound of convergence time T can be calculated by taking the controller parameters we selected into (17). After calculation, we get T=14.59s. Therefore, the theoretical limit of stabilization time in the numerical simulations is t_1=64.59s. Figure 4 shows that the control objectives have been controlled to the stability value. The system state variables δ and ω reached stable states at 59.2s and 53.3s, respectively, and they are all smaller than t_1. Figure 5 depicts that the control objective has been stabilized to its desired operating point and the chaotic oscillation has been suppressed completely, which verifies the effectiveness of proposed controller.

To explore the influence of different initial conditions on the control effect, the simulation has been done. Figure 8 shows the time responses of state variables when the initial states of system are $S1$=(0.43,0.003), $S2$=(0.45,0.005), and $S3$=(0.47,0.007). As can be seen from Figure 8, the oscillation amplitude and overshoot are different, but the difference between the settling times is very small. The system state

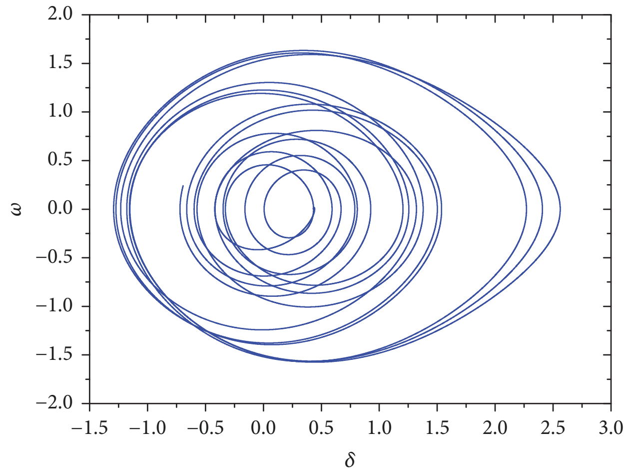

Figure 2: Phase portrait of chaotic power system.

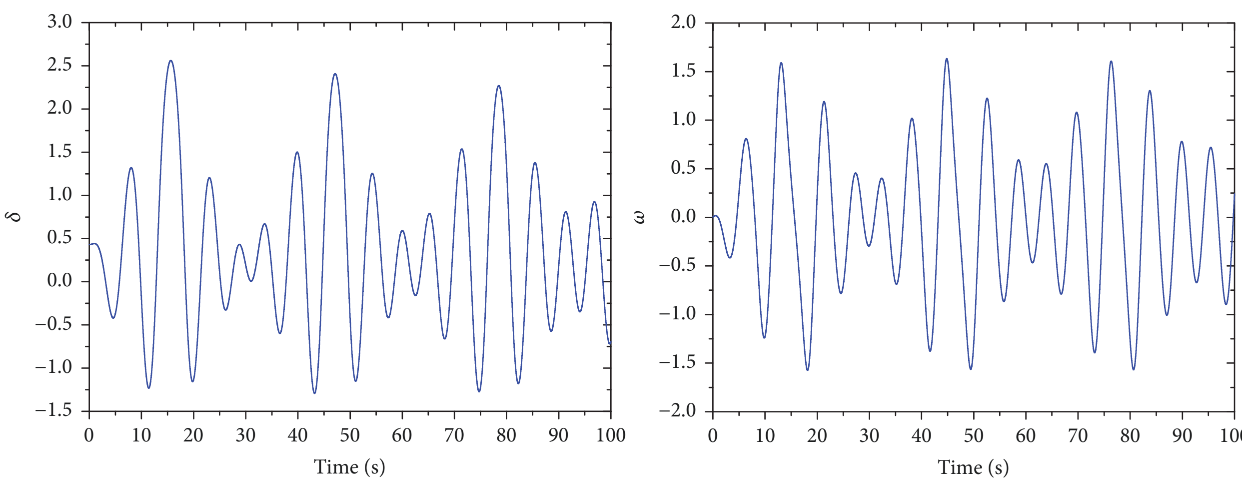

Figure 3: Time responses of state variables in chaotic power system.

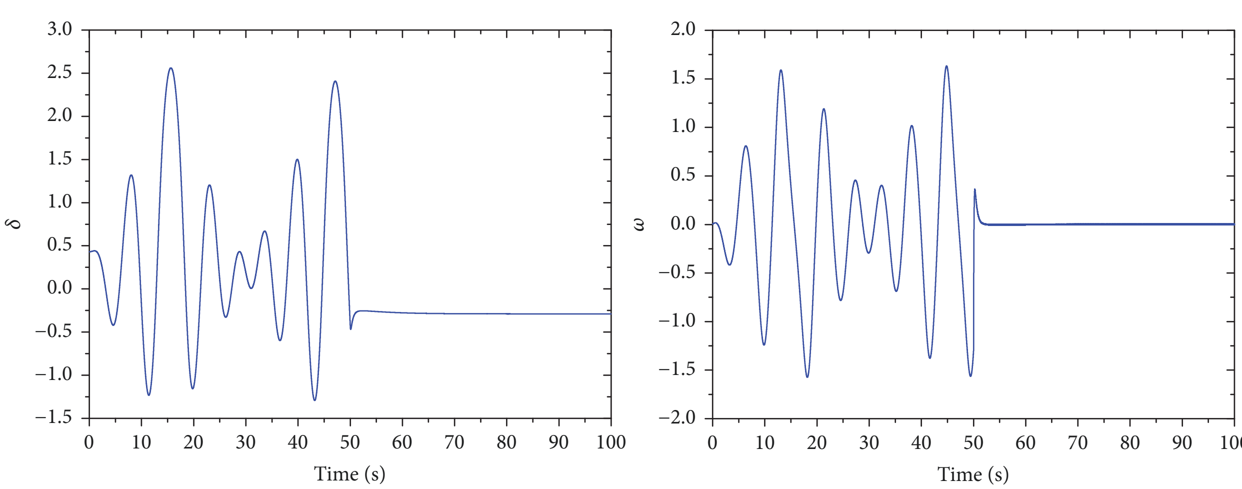

Figure 4: Time responses of state variables in chaotic power system with proposed controller.

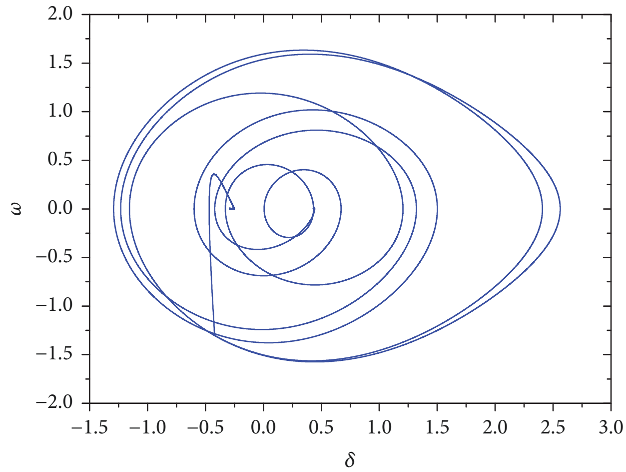

FIGURE 5: Phase portrait of chaotic power system with proposed controller.

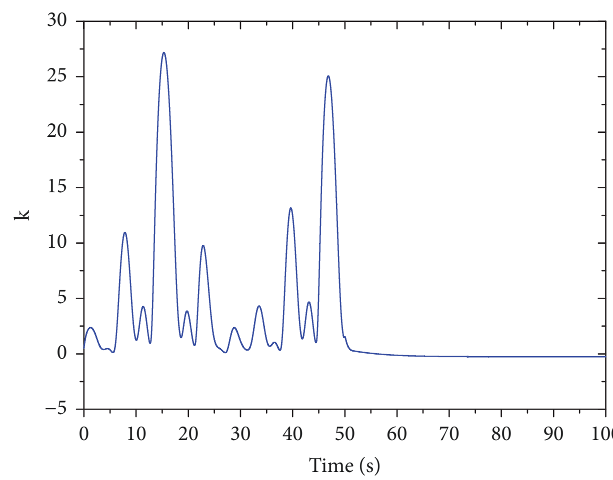

FIGURE 6: Tuning parameter of terminal attractor k.

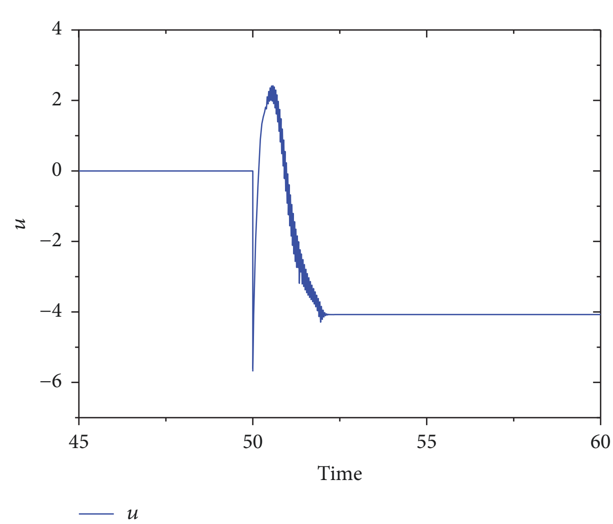

FIGURE 7: Time response of the proposed controller u.

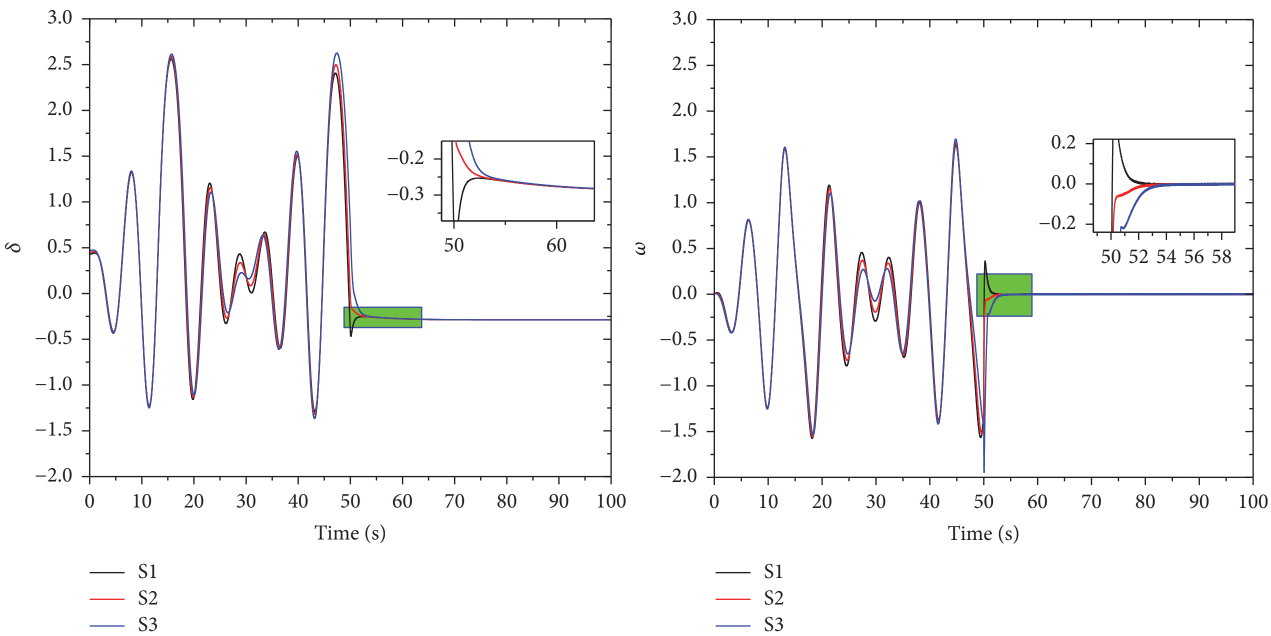

Figure 8: The time responses of state variables with different S.

Table 1: Record of the numerical values of the settling time and the maximum deviation.

System state variable		Settling time	Maximum deviation
δ	Proposed control	12.06s	-0.0236
	FTSM control	12.76s	-0.0480
	Finite-time control	12.31s	-0.0304
ω	Proposed control	11.47s	0.0787
	FTSM control	11.97s	0.1662
	Finite-time control	11.81s	0.1353

variable δ achieves stable state at 59.2s, 59.4s, and 59.7s, respectively, and the system state variable ω achieves stable state at 53.3s, 53.6s, and 53.7s, respectively. They will always be less than the theoretical derivation time t_1.

Figures 9(a)–9(d) show the variations of the system state variables δ and ω with different values of α and β. The simulated condition for the controllers is chosen to be the same. In Figures 9(a) and 9(b), where $\beta = 1.5$ and $\alpha = 0.6$, 0.7, 0.8, 0.9, it is shown that, for both δ and ω, the smaller the value of α is, the faster the convergence rate is. In Figures 9(c) and 9(d), where $\alpha = 0.6$ and $\beta = 1.5$, 1.6, 1.7, 1.8, it is shown that the law of β is the same as that of α. In other words, the convergence time is a decreasing function of the values of α and β for both δ and ω, which is consistent with the theoretical analysis of the maximum stable time T of the system in the previous section. In addition, it is found from Figures 9(a) and 9(c) that the values of α and β affect the stability value of the system state variable δ. Therefore, we can get the stability value of the system state variable δ we need by adjusting the values of the controller parameters α and β.

Figures 10(a) and 10(b) are the comparisons of time responses of state variables in chaotic power system with the proposed controller, the fast terminal sliding mode (FTSM) controller, and finite-time controller. To make a fair comparison, the initial conditions, parameters, and the tuning parameters are identical. The simulation time is set to 20s, and the controllers are added at 10s. Figures 10(a) and 10(b) show that the settling time of proposed control scheme is smaller than that of the other two. Moreover, the time response curves of system state variables δ, ω under proposed control scheme have smaller maximum deviation than that under the other two, which demonstrates the proposed controller has better control effect. Table 1 records the exact numerical values of the settling time and maximum deviation in the simulation results, which verifies the conclusion more accurately.

5. Conclusion

In this paper, to investigate the problem of chaos suppression and voltage stabilization in chaotic power system, a new

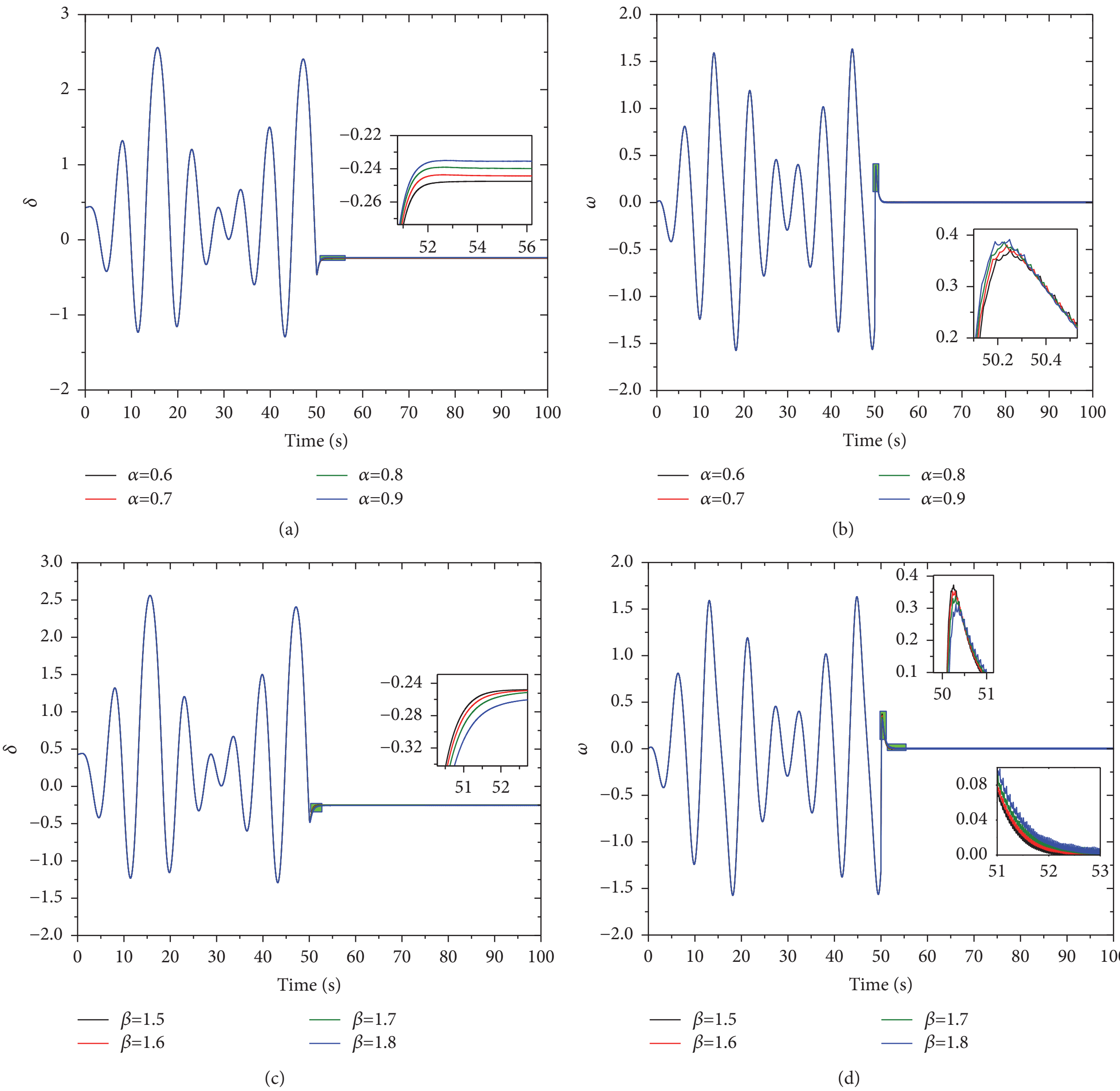

Figure 9: The time responses of state variables with different values of α and β.

control scheme based on the fixed-time stability theory is proposed. An adaptive fixed-time fast terminal sliding mode chaos control strategy is presented to design controller. Simulation results illustrate the effectiveness and superiority of the proposed controller. Compared with the conventional fast terminal sliding mode control strategy and finite-time control strategy, the proposed controller has more advantages in the aspect of convergence time and maximum deviation. Moreover, the settling time is independent of the initial state and can be directly calculated. Note that the present study did not consider the effect of noise perturbation; future research will extend the proposed control strategy to high-order system with noise perturbation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

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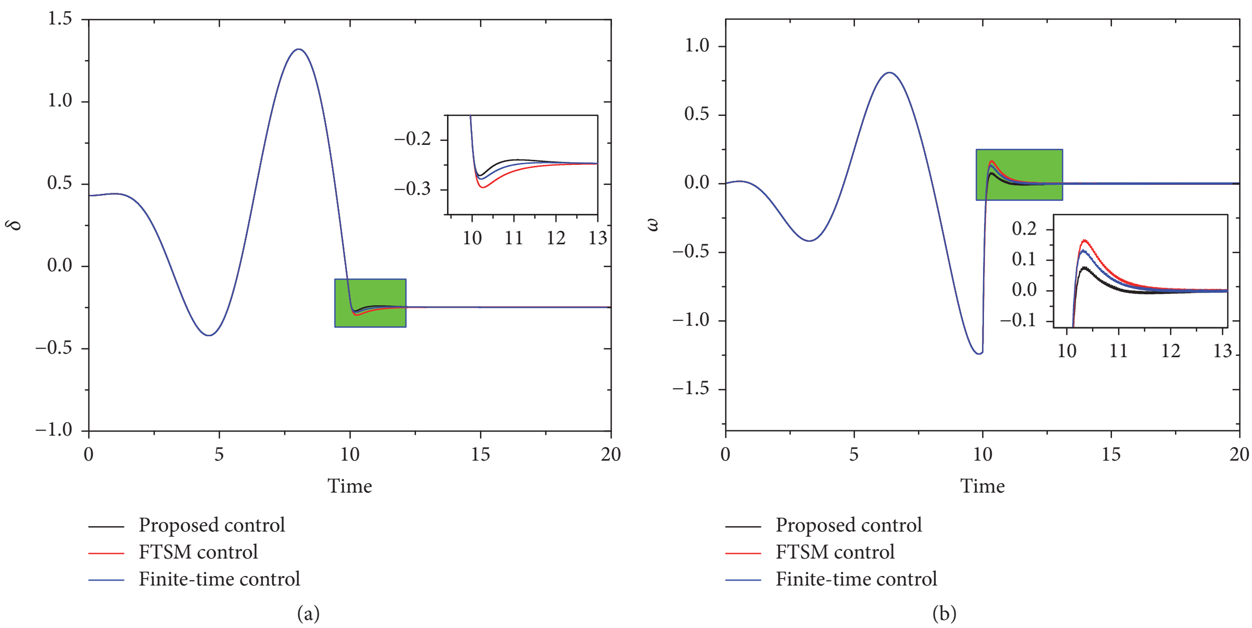

FIGURE 10: Time responses of state variables in chaotic power system with different controllers.

References

[1] H. O. Wang, E. H. Abed, and A. M. A. Hamdan, "Bifurcations, chaos, and crises in voltage collapse of a model power system," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 41, no. 4, pp. 294–302, 1994.

[2] Q. Lu, S. W. Mei, and Y. Z. Sun, *Power system nonlinear control*, Tsinghua University Press, Beijing, China, 2008.

[3] K. Yamashita, S.-K. Joo, J. Li, P. Zhang, and C.-C. Liu, "Analysis, control, and economic impact assessment of major blackout events," *European Transactions on Electrical Power*, vol. 18, no. 8, pp. 854–871, 2008.

[4] H.-D. Chiang, C.-W. Liu, P. P. Varaiya, F. F. Wu, and M. G. Lauby, "Chaos in a simple power system," *IEEE Transactions on Power Systems*, vol. 8, no. 4, pp. 1407–1417, 1993.

[5] X. Chen, W. Zhang, and W. Zhang, "Chaotic and Subharmonic Oscillations of a Nonlinear Power System," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 52, no. 12, pp. 811–815, 2005.

[6] J. Ni, C. Liu, K. Liu, and X. Pang, "Variable speed synergetic control for chaotic oscillation in power system," *Nonlinear Dynamics*, vol. 78, no. 1, pp. 681–690, 2014.

[7] G. L. Li, C. Y. Li, X. Y. Chen, and X. W. Zhang, "Chaos control of SEPIC converter based on resonant parametric perturbation method," *Acta Physica Sinica*, vol. 62, no. 21, pp. 210505-210505, 2013.

[8] A. Jimenez-Triana, C. Gonzalez-Cotrino, and G. Chen, "A parametric perturbation method for controlling discrete hyperchaotic systems," in *Proceedings of the 54th IEEE Conference on Decision and Control, CDC 2015*, pp. 6692–6697, December 2015.

[9] S. P. Nangrani and S. S. Bhat, "Numerical study of optimized fractional-order controller for chaos control of nonlinear dynamical power system," *International Transactions on Electrical Energy Systems*, vol. 27, no. 8, article e2336, 2017.

[10] A. Jimenez-Triana, G. Chen, and A. Gauthier, "A parameter-perturbation method for chaos control to stabilizing UPOs," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 62, no. 4, pp. 407–411, 2015.

[11] H. Zhao, Y. Ma, and Y. Yue, "Improved Delayed Feedback Suppression of Chaotic Oscillation in Power System," in *Proceedings of the 2010 2nd International Conference on Information Engineering and Computer Science (ICIECS)*, pp. 1–4, Wuhan, China, December 2010.

[12] S. L. de Souza, I. L. Caldas, R. L. Viana, J. M. Balthazar, and R. M. Brasil, "A simple feedback control for a chaotic oscillator with limited power supply," *Journal of Sound and Vibration*, vol. 299, no. 3, pp. 664–671, 2007.

[13] Q. Lin and X. Wu, "The sufficient criteria for global synchronization of chaotic power systems under linear state-error feedback control," *Nonlinear Analysis: Real World Applications*, vol. 12, no. 3, pp. 1500–1509, 2011.

[14] Y. Deng, H. Hu, W. Xiong, N. N. Xiong, and L. Liu, "Analysis and Design of Digital Chaotic Systems with Desirable Performance via Feedback Control," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 45, no. 8, pp. 1187–1200, 2015.

[15] D. Q. Wei and X. S. Luo, "Passivity-based adaptive control of chaotic oscillations in power system," *Chaos, Solitons & Fractals*, vol. 31, no. 3, pp. 665–671, 2007.

[16] Y. Zhang, Z. Zhang, and T. Li, "Adaptive terminal sliding mode control for chaos oscillation of power system," *Lecture Notes in Electrical Engineering*, vol. 138, pp. 1847–1853, 2012.

[17] W. D. Huang, F. H. Min, Z. L. Wang, and Z. J. Chu, "Chaotic Oscillation Suppression of the Interconnected Power System Based on the Adaptive Back-Stepping Sliding Mode Controller," in *Proceedings of the 2015 14th International Symposium on Distributed Computing and Applications for Business Engineering and Science (DCABES)*, pp. 463–467, Guiyang, China, August 2015.

[18] M. M. Zirkohi, T. Kumbasar, and T.-C. Lin, "Hybrid adaptive type-2 fuzzy tracking control of chaotic oscillation damping of

power systems," *Asian Journal of Control*, vol. 19, no. 3, pp. 1114–1125, 2017.

[19] A. S. A. Abadi and S. Balochian, "Chaos control of the power system via sliding mode based on fuzzy supervisor," *International Journal of Intelligent Computing and Cybernetics*, vol. 10, no. 1, pp. 68–79, 2017.

[20] S. Song and X. Song, "T-S fuzzy control for fractional order Liu chaotic system with uncertain parameters," in *Proceedings of the 2016 IEEE International Conference on Information and Automation, IEEE ICIA 2016*, pp. 228–233, August 2016.

[21] M. Shukla K and B. Sharma B, "Stabilization of a class of uncertain fractional order chaotic systems via adaptive backstepping control," in *Proceedings of the Control Conference*, pp. 462–467, IEEE, 2017.

[22] C. Kwan and F. L. Lewis, "Robust backstepping control of nonlinear systems using neural networks," *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, vol. 30, no. 6, pp. 753–766, 2000.

[23] D. M. Dawson, J. J. Carroll, and M. Schneider, "Integrator Backstepping Control of a Brush DC Motor Turning a Robotic Load," *IEEE Transactions on Control Systems Technology*, vol. 2, no. 3, pp. 233–244, 1994.

[24] S. Bououden, M. Chadli, and H. R. Karimi, "Fuzzy sliding mode controller design using Takagi-Sugeno modelled nonlinear systems," *Mathematical Problems in Engineering*, vol. 2013, Article ID 734094, 7 pages, 2013.

[25] A. Akhenak, M. Chadli, J. Ragot, and D. Maquin, "Design of a sliding mode fuzzy observer for uncertain Takagi-Sugeno fuzzy model: application to automatic steering of vehicles," *International Journal of Vehicle Autonomous Systems*, vol. 5, no. 3-4, pp. 288–305, 2007.

[26] M. Chadli and I. Zelinka, "Chaos synchronization of unknown inputs Takagi-Sugeno fuzzy: application to secure communications," *Computers & Mathematics with Applications*, vol. 68, no. 12, pp. 2142–2147, 2014.

[27] T. Youssef, M. Chadli, H. R. Karimi, and M. Zelmat, "Chaos synchronization based on unknown input proportional multiple-integral fuzzy observer," *Abstract and Applied Analysis*, vol. 2013, Article ID 670878, 11 pages, 2013.

[28] L. Yuan, K.-Y. Wei, B.-X. Hu, and N. Wang, "Nonsingular terminal sliding-mode controller with nonlinear disturbance observer for chaotic oscillation in power system," in *Proceedings of the 35th Chinese Control Conference, CCC 2016*, pp. 3316–3320, July 2016.

[29] J. Ni K, C. Liu X, and X. Pang, "Fuzzy fast terminal sliding mode controller using an equivalent control for chaotic oscillation in power system," *Acta Physica Sinica*, vol. 62, no. 19, article 190507, Article ID 07, 1905.

[30] M. Zhihong and X. H. Yu, "Terminal sliding mode control of MIMO linear systems," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 44, no. 11, pp. 1065–1070, 1997.

[31] N. Noroozi, B. Khaki, and A. Seifi, "Chaotic oscillations damping in power system by finite time control theory," *International Review of Electrical Engineering*, vol. 3, no. 6, pp. 1032–1038, 2008.

[32] N. Cai, W. Li, and Y. Jing, "Finite-time generalized synchronization of chaotic systems with different order," *Nonlinear Dynamics*, vol. 64, no. 4, pp. 385–393, 2011.

[33] B. Khaki, B. Ranjbar-Sahraei, N. Noroozi, and A. Seifi, "Interval type-2 fuzzy finite-time control approach for chaotic oscillation damping of power systems," *International Journal of Innovative Computing, Information and Control*, vol. 7, no. 12, pp. 6827–6835, 2011.

[34] X. Liu, W. Lu, and T. Chen, "Finite-time and fixed-time stability and synchronization," in *Proceedings of the 35th Chinese Control Conference, CCC 2016*, pp. 7985–7989, July 2016.

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

[36] 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.

[37] M. Liu, J. Wu, and Y.-z. Sun, "Fixed-time stability analysis of permanent magnet synchronous motors with novel adaptive control," *Mathematical Problems in Engineering*, vol. 2017, Article ID 4903963, 11 pages, 2017.

[38] 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 & Cybernetics Systems*, no. 99, pp. 1–10, 2017.

[39] J. Gao and Y. Cai, "Fixed-time control for spacecraft attitude tracking based on quaternion," *Acta Astronautica*, vol. 115, article no. 5463, pp. 303–313, 2015.

[40] J. Ni, L. Liu, C. Liu, X. Hu, and T. Shen, "Fixed-time dynamic surface high-order sliding mode control for chaotic oscillation in power system," *Nonlinear Dynamics*, vol. 86, no. 1, pp. 401–420, 2016.

[41] Y. Sun, X. Wu, L. Bai, Z. Wei, and G. Sun, "Finite-time synchronization control and parameter identification of uncertain permanent magnet synchronous motor," *Neurocomputing*, vol. 207, pp. 511–518, 2016.

[42] S. P. Bhat and D. S. Bernstein, "Finite-time stability of continuous autonomous systems," *SIAM Journal on Control and Optimization*, vol. 38, no. 3, pp. 751–766, 2000.

[43] J. Ni, L. Liu, C. Liu, X. Hu, and L. Cheng, "Fractional order fixed-time nonsingular terminal sliding mode control for chaotic oscillation in power system," in *Proceedings of the 36th Chinese Control Conference, CCC 2017*, pp. 493–498, July 2017.

[44] H. K. Khalil, *Nonlinear Systems*, Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 3rd edition, 2002.