Research Article

Adaptive Sliding Mode Control Based on Equivalence Principle and Its Application to Chaos Control in a Seven-Dimensional Power System

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Received 12 November 2019; Revised 17 December 2019; Accepted 30 December 2019; Published 1 February 2020

Academic Editor: Mauro Gaggero

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The main purpose of the paper is to control chaotic oscillation in a complex seven-dimensional power system model. Firstly, in view that there are many assumptions in the design process of existing adaptive controllers, an adaptive sliding mode control scheme is proposed for the controlled system based on equivalence principle by combining fixed-time control and adaptive control with sliding mode control. The prominent advantage of the proposed adaptive sliding mode control scheme lies in that its design process breaks through many existing assumption conditions. Then, chaotic oscillation behavior of a seven-dimensional power system is analyzed by using bifurcation and phase diagrams, and the proposed strategy is adopted to control chaotic oscillation in the power system. Finally, the effectiveness and robustness of the designed adaptive sliding mode chaos controllers are verified by simulation.

1. Introduction

Power system, one of the high-dimensional and strongly coupled nonlinear systems, often exhibits complex nonlinear dynamic behaviors. Chaotic oscillation is an important phenomenon that has attracted considerable attention in recent years [1–3]. Results show that parameter variations, energy disturbance, and time delay can induce chaos in the power system [4–6]. Since chaotic oscillation affects its stability and may cause voltage collapse and other unacceptable accidents [7, 8], then how to effectively control chaos in the power system has become a common problem to be considered both theoretically and practically.

In recent years, various nonlinear control strategies have been applied to chaos control in power systems, such as feedback control [9], passive control [10], time-delay feedback control [9], quasi-sliding mode control based on relay characteristic function [11], variable speed synergetic control [12], and adaptive fixed-time fast terminal sliding mode control [13]. However, all aforementioned methods are

aimed at a simple two-dimensional power system model. Some scholars have also designed chaos controllers for a classical four-dimensional power system model. At present, the main control methods proposed for the model include finite-time feedback control [14], finite-time integral sliding mode control [15], finite-time passive control [16], chattering-free time scale separation sliding mode control [17], fixed-time integral sliding mode control [18], feedback linearization based sliding mode control [19], discrete time sliding mode control [20], fractional order sliding mode control [21], fast fixed-time nonsingular terminal sliding mode control [22], and fixed-time dynamic surface high-order sliding mode control [23]. However, it is worth noting that most of these controllers are abstract control inputs without considering realizability of the controller and there are also too many control inputs (see [14–21]), which make the proposed control methods impractical.

Actually, due to the complexity of the power system model itself, studying chaos control in a more complex model has more important research value. Among many

existing power system dynamic models, the seven-dimensional power system is the most complex model of all known power system models. Bifurcation and chaos phenomena in the model are analyzed in detail in [24]. Subsequently, several adverse effects of chaos on power system stability are studied based on the model in [25, 26]. Corresponding to analysis of the model, controlling its chaos still remains an important research topic. However, there is still scarce literature reporting chaos control in such a complex model.

Among many nonlinear control methods, sliding mode control has attracted many scholars' attention because of its simplicity, reliability, and effectiveness. However, the designed control inputs depend on system functions according to the conventional sliding mode control method. In order to simplify the control input, adaptive sliding mode control can be designed to make its control inputs easy to be realized in engineering. However, as long as designing an adaptive controller, many assumptions will be introduced in the controller design process. The most common assumptions are the Lipschitz assumption and the bounded state variables assumption [27–32]. Specifically, the famous Lipschitz assumption is often introduced into the adaptive controllers designed in [27–30], and it actually limits the applicability of designed controllers. In addition, it is always impossible to verify the validity of the assumption condition for complex system models. However, the adaptive controller in [31, 32] introduces assumption that state variables of a controlled system are bounded. Although the assumption is valid for chaotic systems, the application scope of the designed controller is always limited as long as it is introduced. More importantly, it is difficult to apply these control methods to control complex systems such as the seven-dimensional power system due to the introduction of these assumptions. In addition, adaptive sliding mode controllers designed in [33, 34] will behave chattering.

To solve the above problems comprehensively, an adaptive sliding mode control scheme is proposed to control chaos in the seven-dimensional power system. First, in order to ensure that the designed adaptive sliding mode controller has better control effect, a fixed-time sliding mode controller is designed for a controlled system. Based on equivalence principle of control effect, an adaptive sliding mode control scheme is proposed. The unique advantage of the adaptive sliding mode control is that no assumptions are introduced in the controller design process. Then, the proposed control scheme is used to control chaotic oscillation in a seven-dimensional power system. Simulation results verify its effectiveness and robustness.

The main contributions of this paper are as follows: (1) Compared with other adaptive sliding mode control methods, the proposed adaptive sliding mode controller based on the equivalence principle does not introduce any assumptions, and the designed control inputs does not include system functions, which make the designed control inputs to be directly applied to such complex dynamic system as the seven-dimensional power system model. (2) Compared with other power system chaos control methods, different from the existing methods which only control a simple two-dimensional and four-dimensional chaotic

power system, this paper directly control the most complex seven-dimensional chaotic power system, and the designed controller is more universal. (3) Compared with many control methods which only design abstract control inputs, this paper introduces an active energy storage device and static var compensation device commonly used in power system and designs control inputs for two devices, which make the proposed control method to have certain engineering guidance.

The rest of the paper is organized as follows. The design process of the proposed adaptive sliding mode controller is given in Section 2. In Section 3, the proposed adaptive sliding mode control scheme is used to control chaotic oscillation in the seven-dimensional power system. In Section 4, the effectiveness of proposed adaptive sliding mode control method is verified by simulation. The conclusion is finally drawn in Section 5.

2. Adaptive Sliding Mode Control

2.1. Mathematical Basis

Definition 1 (see [35]). Consider a differential equation system:

$$\begin{aligned}\dot{x} &= f(x), \\ x(0) &= x_0,\end{aligned}\tag{1}$$

where $x \in R$ and $f(x)$ denotes any nonlinear function.

Let the time required for the state variable of system (1) to stabilize to the origin be $T(x_0)$; if for $\forall x_0 \in R$, $\exists T_{\max} > 0$, such that $\lim_{x_0 \rightarrow \infty} [T(x_0)] \leq T_{\max}$ holds, then the state variable of system (1) is said to be stable in a fixed time.

Lemma 1 (see [35]). Consider a continuous positive definite function V ; let it satisfy differential inequality as follows:

$$\dot{V} \leq -(\alpha V^p + \beta V^q)^k, \quad V(0) = V_0,\tag{2}$$

where $\alpha > 0$, $\beta > 0$, $p > 0$, $q > 0$, and $k > 0$, and parameters p , q , and k satisfy $pk < 1$ and $qk > 1$.

Let the time required for state variable V of system (2) converging to the origin be $T(V_0)$; then, V will converge to the origin in a fixed time upper bounded by a constant, that is, $\lim_{V_0 \rightarrow \infty} [T(V_0)] \leq T_{\max}(V)$, and

$$T_{\max}(V) = \frac{1}{\alpha^k(1-pk)} + \frac{1}{\beta^k(qk-1)}.\tag{3}$$

Lemma 2. Consider a differential equation system:

$$\dot{y} = -\gamma(\alpha_1|y|^{m_1/n_1} + \beta_1|y|^{m_2/n_2})^{m_3/n_3} \cdot \text{sign}(y),\tag{4}$$

where $\alpha_1 > 0$, $\beta_1 > 0$, and m_1 , n_1 , m_2 , n_2 , m_3 , and n_3 satisfy $(m_1/n_1) \cdot (m_3/n_3) < 1$ and $(m_2/n_2) \cdot (m_3/n_3) > 1$, γ is a constant coefficient, and $\gamma > 0$.

Let the time required for the state variables of system (4) converging to the origin be $T(y_0)$; then, state variable y will converge to the origin in a fixed time upper bounded by a constant $T_{\max}(y)$, that is, $\lim_{y_0 \rightarrow \infty} [T(y_0)] \leq T_{\max}(y)$, and

$$T_{\max(y)} = \frac{1}{\gamma \cdot \alpha_1^{m_3/n_3} [1 - (m_1/n_1)(m_3/n_3)]} + \frac{1}{\gamma \cdot \beta_1^{m_3/n_3} [(m_2/n_2)(m_3/n_3) - 1]}. \quad (5)$$

Proof. Construct a Lyapunov function $W = |y|$; then, its derivative with respect to time is

$$\begin{aligned} \dot{W} &= \dot{y} \cdot \text{sign}(y) = -\gamma(\alpha_1 |y|^{m_1/n_1} + \beta_1 |y|^{m_2/n_2})^{m_3/n_3} \\ &= -\gamma(\alpha_1 W^{m_1/n_1} + \beta_1 W^{m_2/n_2})^{m_3/n_3} \\ &= -(\gamma^{n_3/m_3})^{m_3/n_3} (\alpha_1 W^{m_1/n_1} + \beta_1 W^{m_2/n_2})^{m_3/n_3} \\ &= -(\gamma^{n_3/m_3} \cdot \alpha_1 W^{m_1/n_1} + \gamma^{n_3/m_3} \cdot \beta_1 W^{m_2/n_2})^{m_3/n_3}. \end{aligned} \quad (6)$$

Let the time required for the state variable W converging to the origin be $T(W_0)$; from Lemma 1, we can obtain that $\lim_{W_0 \rightarrow \infty} [T(W_0)] \leq T_{\max(W)}$ and

$$\begin{aligned} T_{\max(W)} &= \frac{1}{(\gamma^{n_3/m_3} \cdot \alpha_1)^{m_3/n_3} (1 - m_1 m_3 / n_1 n_3)} \\ &\quad + \frac{1}{(\gamma^{n_3/m_3} \cdot \beta_1)^{m_3/n_3} (m_2 m_3 / n_2 n_3 - 1)} = T_{\max(y)}. \end{aligned} \quad (7)$$

The proof is completed. $\square$

2.2. Controller Design. Consider a controlled nonlinear system as follows:

$$\dot{x}_i = f_i(x, t) + g_i(x) \cdot u_i, \quad (8)$$

where $x = [x_1, x_2, \dots, x_N]^T \in R^N$ represents state vector and $x_i \in x$, $i = 1, 2, \dots, N$; $f_i(x, t) \in R$ denotes nonlinear function of x and t ; $g_i(x) \in R$ represents control input gain, and $g_i(x) \neq 0$; u_i represents control input.

Let the control objective of system (8) be a constant value x_{id} ; then, control error can be written as $e_i = x_i - x_{id}$, and one can get from system (8) that its error dynamics is

$$\dot{e}_i = \dot{x}_i - \dot{x}_{id} = \dot{x}_i = f_i(x, t) + g_i(x) \cdot u_i. \quad (9)$$

In order to ensure better control effect of the designed controller, a fixed-time control input which can make the state variable e_i converge precisely to zero is designed for controlled system (9).

For the error system (9), an integral fixed-time sliding surface is designed as

$$s_i = e_i + \gamma_i \int_0^t \left[(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2})^{m_3/n_3} \cdot \text{sign}(e_i) \right] dt, \quad (10)$$

where $\gamma_i > 0$, $\alpha_1 > 0$, and $\beta_1 > 0$.

To make system state reach the sliding surface $s_i = 0$ in a fixed time, let

$$\begin{aligned} \dot{s}_i &= \dot{e}_i + \gamma_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \\ &= f_i(x, t) + g_i(x) u_i + \gamma_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \\ &\quad \cdot \text{sign}(e_i) \\ &= -\varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i), \end{aligned} \quad (11)$$

where $\varepsilon_i > 0$, $\alpha_2 > 0$, and $\beta_2 > 0$.

According to Lemma 2, if the control input u_i is designed according to equation (11), the designed control input can make the system state reach the sliding surface $s_i = 0$ in a fixed time; then, $\dot{s}_i = 0$, namely, $\dot{e}_i = -\gamma_i (\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2})^{m_3/n_3} \text{sign}(e_i)$; this shows that when the system state reaches the sliding surface, the error e_i will also converge to zero in a fixed time, thus completing the control of system (8).

From equation (11), the expression of controller $u_{i(\text{ref})} = u_i$ can be solved as follows:

$$\begin{aligned} u_{i(\text{ref})} &= -\frac{1}{g_i(x)} \left[f_i(x, t) + \gamma_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \right. \\ &\quad \left. \cdot \text{sign}(e_i) + \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i) \right]. \end{aligned} \quad (12)$$

To design an adaptive sliding mode control input for system (8), control input in (12) can be used as a reference and design real control input $u_{i(\text{real})} = u_i$ for system (8) as

$$\begin{aligned} u_{i(\text{real})} &= -\frac{1}{g_i(x)} \left[\hat{\gamma}_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \text{sign}(e_i) \right. \\ &\quad \left. + \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i) \right], \end{aligned} \quad (13)$$

where $\hat{\gamma}_i$ denotes the adaptive parameters.

The design principle of adaptive law for adaptive parameter $\hat{\gamma}_i$ is to make real input $u_{i(\text{real})}$ and reference input $u_{i(\text{ref})}$ equivalent to each other after adaptive parameter $\hat{\gamma}_i$ converges to a constant value $\hat{\gamma}_i^*$, that is, to make $u_{i(\text{real})}$ and $u_{i(\text{ref})}$ satisfy the equality constraint:

$$\begin{aligned} u_{i(\text{real})}^* &= -\frac{1}{g_i(x)} \left[\hat{\gamma}_i^* \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \right. \\ &\quad \left. + \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i) \right] = u_{i(\text{ref})}, \end{aligned} \quad (14)$$

where $\hat{\gamma}_i^*$ represents the constant value after adjustment of adaptive parameter $\hat{\gamma}_i$.

When the real control input of system (9) is designed as in (13) and taking constraint (14) into account, then system (9) can be rewritten as

$$\begin{aligned}
\dot{e}_i &= f_i(x, t) - \left[\hat{\gamma}_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \right. \\
&\quad \left. + \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i) \right] \\
&= f_i(x, t) - \left[\hat{\gamma}_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \right. \\
&\quad \left. + \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i) \right] + g_i(x) u_{i(\text{ref})} \\
&\quad - g_i(x) u_{i(\text{real})}^*.
\end{aligned} \tag{15}$$

By substituting (12) and (14) into (15), we can obtain

$$\begin{aligned}
\dot{e}_i &= (\hat{\gamma}_i^* - \hat{\gamma}_i - \gamma_i) \left[\left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \right] \\
&\quad - \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i).
\end{aligned} \tag{16}$$

To design the adaptive law for adaptive parameter $\hat{\gamma}_i$, a Lyapunov function is constructed as

$$V_1 = \sum_{i=1}^N \left[\frac{1}{2} s_i^2 + \frac{1}{2} (\hat{\gamma}_i - \hat{\gamma}_i^*)^2 \right]. \tag{17}$$

Then, its derivative with respect to time is

$$\begin{aligned}
\dot{V}_1 &= \sum_{i=1}^N [s_i \dot{s}_i + (\hat{\gamma}_i - \hat{\gamma}_i^*) \dot{\hat{\gamma}}_i] \\
&= \sum_{i=1}^N \left\{ s_i \left[\dot{e}_i + \gamma_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \right] \right. \\
&\quad \left. + (\hat{\gamma}_i - \hat{\gamma}_i^*) \dot{\hat{\gamma}}_i \right\}.
\end{aligned} \tag{18}$$

By substituting (16) into (18), one can obtain

$$\begin{aligned}
\dot{V}_1 &= \sum_{i=1}^N [s_i \dot{s}_i + (\hat{\gamma}_i - \hat{\gamma}_i^*) \dot{\hat{\gamma}}_i] \\
&= \sum_{i=1}^N \left[s_i \cdot (\hat{\gamma}_i^* - \hat{\gamma}_i - \gamma_i) \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \right. \\
&\quad \cdot \text{sign}(e_i) - \sum_{i=1}^N \left[s_i \cdot \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \right. \\
&\quad \cdot \text{sign}(s_i) + \sum_{i=1}^N \left[s_i \cdot \gamma_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \right. \\
&\quad \cdot \text{sign}(e_i) + (\hat{\gamma}_i - \hat{\gamma}_i^*) \dot{\hat{\gamma}}_i \left. \right].
\end{aligned} \tag{19}$$

Design the adaptive law as

$$\dot{\hat{\gamma}}_i = \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \cdot s_i. \tag{20}$$

Then, we can know that

$$\dot{V}_1 = \sum_{i=1}^N \left[-\varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot |s_i| \right] \leq 0. \tag{21}$$

It means from $\dot{V}_1 \leq 0$ that the system state finally reaches the sliding surface $s_i = 0$, and the adaptive parameter $\hat{\gamma}_i$ converges to a constant $\hat{\gamma}_i^*$; then, the error variable e_i converges to zero, thus completing control of system (8).

The above controller design process shows that as long as control input of system (8) is finally designed as an adaptive sliding mode controller (22), then system (8) will be controlled to the objective:

$$\begin{cases} u_{i(\text{real})} = -\left(\frac{1}{g_i(x)} \right) \cdot \left[\hat{\gamma}_i \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) + \varepsilon_i \left(\alpha_2 |s_i|^{m_1/n_1} + \beta_2 |s_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_i) \right], \\ \dot{\hat{\gamma}}_i = \left(\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(e_i) \cdot s_i, \end{cases} \tag{22}$$

where $s_i = e_i + \gamma_i \int_0^t (\alpha_1 |e_i|^{m_1/n_1} + \beta_1 |e_i|^{m_2/n_2})^{m_3/n_3} \text{sign}(e_i) dt$.

Remark 1. Problems studied in [27–30] can be summed up as designing an adaptive controller for controlled system (8). However, these methods introduce Lipschitz assumption in the design process and can only control the state variable to the corresponding equilibrium point, because their stability proof processes need to satisfy $f_i(x_0) = 0$, where $f_i(x_0)$ denotes the controlled system function and x_0 represents the control objective. While it is worth noticing that the proposed controller design process does not introduce any assumptions and any constant objective can be realized for controlled system (8) by the designed controller.

Remark 2. Problems studied in [31, 32] can also be attributed to designing an adaptive controller for controlled system (8). However, these methods introduce assumption that state variable x_i of controlled system (8) is bounded in the controller design process, i.e., the assumption that $|x_i| \leq M$, where M is a constant.

Remark 3. Adaptive sliding mode controllers designed in [33, 34] behave obvious chattering, which makes it difficult to apply in practice. However, the proposed control inputs are continuous and there is no chattering phenomenon.

Remark 4. If disturbances and uncertainties are not considered, problems studied in [36–38] can be reduced to designing sliding mode controllers for controlled systems (8), while their control inputs include system function $f_i(x, t)$. Since it is often difficult to obtain the exact system model in practical, then these controller design methods greatly reduce their practicability. However, the proposed controller does not contain $f_i(x, t)$, and it can be applied to control complex systems such as seven-dimensional power system.

3. Adaptive Sliding Mode Control for Chaotic Oscillation in Power Systems

3.1. System Model and Its Chaotic Oscillation. The seven-dimensional power system model is a most complex one among many power system models, and its dynamics can be described as [24–26]

$$\begin{cases} \dot{\delta}_m = \omega_B s_m, \\ \dot{s}_m = \frac{-ds_m + P_m - P_g}{2H}, \\ \dot{E}'_q = \frac{-E'_q + (x_d - x'_d)I_d + E_{fd}}{T_{d0}}, \\ \dot{E}'_d = \frac{-E'_d - (x_q - x'_q)I_q}{T_{q0}}, \\ \dot{E}_{fd} = \frac{-E_{fd} + K_A(V_{ref} - V_t)}{T_A}, \\ \dot{\delta}_L = \frac{Q - Q_{ld} - Q_0 - q_2 V_L - (q_3 - B_c)V_L^2}{q_1}, \\ \dot{V}_L = \frac{P - P_{ld} - P_0 - p_1 \cdot f(\cdot)/q_1 - p_3 V_L}{p_2}, \end{cases} \quad (23)$$

where δ_m and s_m represent generator angle and generator slip, respectively; E'_q and E'_d represent transient potential of damper winding on q-axis and d-axis, respectively; E_{fd} denotes the excitation potential; δ_L and V_L represent voltage phase angle and amplitude of the load bus, respectively; and $f(\cdot) = Q - Q_{ld} - Q_0 - q_2 V_L - (q_3 - B_c)V_L^2$.

Parameter coupling relationships and parameter values of system (23) are shown in the Appendix. The initial values of the power system are selected as follows: $\delta_m(0) = 1.3331$, $s_m(0) = 0$, $E'_q(0) = 1.332678$, $E'_d(0) = -0.3283$, $E_{fd}(0) = 4.198$, $\delta_L(0) = 0.2396$, and $V_L(0) = 0.93$. Among many system parameters, P_m is an important bifurcation parameter to find the parameter condition for chaotic oscillation. Under the parameters given in the Appendix, and when the variation range of P_m is $P_m \in [1.34, 1.363]$, the maximum method can be used to draw the bifurcation diagram of system state δ_m varying with parameter P_m as shown in Figure 1.

From the bifurcation diagram, it can be concluded that when $P_m \in [1.34, 1.3552]$, the system is under periodic motion

state. When $P_m \in [1.3552, 1.3605]$, typical period doubling bifurcations occur in the system. And in the interval $P_m \in [1.3605, 1.363]$, the whole system enters into chaotic state completely, and chaotic oscillation occurs in the power system. In order to obtain the phase diagram of chaotic oscillation, let $P_m = 1.363$, then the system phase diagram can be obtained as shown in Figure 2. System state behaves as a strange attractor on phase diagram, and the time responses of state variables must behave as aperiodic waveforms, which are not allowed in the stable operation of the power system. Therefore, the chaos controller must be designed for chaotic power systems.

3.2. Controller Design for Chaos in Power System. The seven-dimensional power system is a typical three-bus power system. The three buses include generator bus, load bus, and infinite bus. To control chaotic oscillation and restore the whole system from chaotic oscillation to stable operation, it is necessary to restore the whole system to re-synchronization and control the load bus voltage to its rated value. In this way, the chaos control problem in power systems comes down to the control of active power and reactive power of the whole system. In order to make the designed controllers have a certain engineering practical value, we connect the active energy storage device on the generator bus and static var compensation device on the load bus and introduce dynamic models of two devices [39–41]; then, the controlled power system model can be given by combining dynamics of these devices with power system model as

$$\begin{cases} \dot{\delta}_m = \omega_B s_m, \\ \dot{s}_m = \frac{-ds_m + P_m - P_g - P_{es}}{2H}, \\ \dot{P}_{es} = -\frac{1}{T_{es}}P_{es} + \frac{K_{es}}{T_{es}}u_{es}, \\ \dot{E}'_q = \frac{-E'_q + (x_d - x'_d)I_d + E_{fd}}{T_{d0}}, \\ \dot{E}'_d = \frac{-E'_d - (x_q - x'_q)I_q}{T_{q0}}, \\ \dot{E}_{fd} = \frac{-E_{fd} + K_A(V_{ref} - V_t)}{T_A}, \\ \dot{\delta}_L = \frac{Q - Q_{ld} - Q_0 - Q_{svc} - q_2 V_L - (q_3 - B_c)V_L^2}{q_1}, \\ \dot{V}_L = \frac{P - P_{ld} - P_0 - p_1 \cdot f_1(\cdot)/q_1 - p_3 V_L}{p_2}, \\ \dot{B}_{eq} = -\frac{1}{T_{svc}}B_{eq} + \frac{K_{svc}}{T_{svc}}u_{svc}, \end{cases} \quad (24)$$

where P_{es} represents the active power absorbed by energy storage device; T_{es} , K_{es} , and u_{es} represent the time constant,

FIGURE 1: Bifurcation diagram of system state δ_m varying with P_m .

control input gain, and control input of the energy storage device, respectively; B_{eq} and T_{svc} represent the equivalent admittance and time constant of static var compensator; K_{svc} and u_{svc} represent the control input gain and control input of static var compensator; $Q_{svc} = B_{eq} V_L^2$, which represents the reactive power supplied by static var compensator to load bus; and $f_1(\cdot) = Q - Q_{ld} - Q_0 - Q_{svc} - q_2 V_L - (q_3 - B_c) V_L^2$.

To achieve the control objective for system (24), its output is determined as follows: $y_1 = \delta_m$ and $y_2 = V_L$. Then, sliding mode functions are designed as

$$\begin{cases} \sigma_1 = \left(\frac{d}{dt} + \lambda_1 \right)^2 \delta_m, & \lambda_1 > 0, \\ \sigma_2 = \left(\frac{d}{dt} + \lambda_2 \right) (V_L - 1), & \lambda_2 > 0. \end{cases} \quad (25)$$

FIGURE 2: Phase diagram of the seven-dimensional chaotic power system.

It can be concluded from (25) that the derivative of sliding mode function σ_1 with respect to time is

$$\dot{\sigma}_1 = \ddot{\delta}_m + 2\lambda_1 \dot{\delta}_m + \lambda_1^2 \delta_m = f_{es} + g_{es} u_{es}, \quad (26)$$

where

$$\begin{cases} f_{es} = \frac{\omega_B}{2H} \left(-d\dot{s}_m - \dot{P}_g + \frac{1}{T_{es}} P_{es} \right) + 2\lambda_1 \dot{\delta}_m + \lambda_1^2 \delta_m, & g_{es} = -\frac{\omega_B K_{es}}{2H \cdot T_{es}}. \end{cases} \quad (27)$$

It can also be concluded from (25) that the derivative of sliding mode function σ_2 with respect to time is

$$\dot{\sigma}_2 = \ddot{V}_L + \lambda_2 \dot{V}_L = f_{svc} + g_{svc} u_{svc}, \quad (28)$$

where

$$\begin{cases} f_{svc} = \frac{\dot{P} - p_1 [\dot{Q} + B_{eq} V_L^2 / T_{svc} - B_{eq} \cdot 2V_L \dot{V}_L - q_2 \dot{V}_L - (q_3 - B_c) 2V_L \dot{V}_L] / q_1 - p_3 \dot{V}_L}{p_2} + \lambda_2 \dot{V}_L, \\ g_{svc} = \frac{p_1 K_{svc} V_L^2}{q_1 p_2 T_{svc}}. \end{cases} \quad (29)$$

The system composed of (26) and (28) is expressed as follows:

$$\begin{cases} \dot{\sigma}_1 = f_{es} + g_{es} u_{es}, \\ \dot{\sigma}_2 = f_{svc} + g_{svc} u_{svc}. \end{cases} \quad (30)$$

In this way, the chaos control problem of complex seven-dimensional power system is finally transformed into the control problem of two first-order systems with sliding mode functions σ_1 and σ_2 as state variables given as in (30).

And control objective is to make σ_1 and σ_2 converge to 0, that is, the state of controlled system (24) reaches sliding surfaces $\sigma_1 = \{\delta_m \mid \sigma_1(\delta_m) = 0\}$ and $\sigma_2 = \{V_L \mid \sigma_2(V_L) = 0\}$. Once the system state of the power system model reaches sliding surfaces, the control objective can be achieved from (25).

According to the proposed adaptive sliding mode control scheme, adaptive sliding mode controllers designed for system (30) (i.e., system (24)) can be expressed as follows:

FIGURE 3: Time responses of sliding mode functions.

FIGURE 4: Adjustment curves of adaptive parameters.

$$\left\{ \begin{array}{l} u_{es} = -\frac{1}{g_{es}} \left[\hat{\gamma}_1 \left(\alpha_1 |\sigma_1|^{m_1/n_1} + \beta_1 |\sigma_1|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(\sigma_1) + \varepsilon_1 \left(\alpha_2 |s_1|^{m_1/n_1} + \beta_2 |s_1|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_1) \right], \\ \dot{\hat{\gamma}}_1 = \left(\alpha_1 |\sigma_1|^{m_1/n_1} + \beta_1 |\sigma_1|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(\sigma_1) \cdot s_1, \\ u_{svc} = -\frac{1}{g_{svc}} \left[\hat{\gamma}_2 \left(\alpha_1 |\sigma_2|^{m_1/n_1} + \beta_1 |\sigma_2|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(\sigma_2) + \varepsilon_2 \left(\alpha_2 |s_2|^{m_1/n_1} + \beta_2 |s_2|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(s_2) \right], \\ \dot{\hat{\gamma}}_2 = \left(\alpha_1 |\sigma_2|^{m_1/n_1} + \beta_1 |\sigma_2|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(\sigma_2) \cdot s_2, \end{array} \right. \quad (31)$$

where

$$\left\{ \begin{array}{l} s_1 = \sigma_1 + \gamma_1 \int_0^t \left[\left(\alpha_1 |\sigma_1|^{m_1/n_1} + \beta_1 |\sigma_1|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(\sigma_1) \right] dt, \\ s_2 = \sigma_2 + \gamma_2 \int_0^t \left[\left(\alpha_1 |\sigma_2|^{m_1/n_1} + \beta_1 |\sigma_2|^{m_2/n_2} \right)^{m_3/n_3} \cdot \text{sign}(\sigma_2) \right] dt, \end{array} \right. \quad \gamma_1 > 0, \gamma_2 > 0, \varepsilon_1 > 0, \varepsilon_2 > 0. \quad (32)$$

Remark 5. If the controllers for system (30) is designed according to the conventional controller design method, then the control inputs must contain complex system function terms f_{es} and f_{svc} . However, since the adaptive sliding mode control input (31) is given for system (30), the terms f_{es} and f_{svc} will not appear in the control inputs.

4. Simulation

Example 1. First, the effectiveness of the proposed control method is verified. Control parameters are selected as follows: $K_{es} = 1$, $T_{es} = 1$, $K_{svc} = 1$, $T_{svc} = 1$, $\lambda_1 = 5$, $\lambda_2 = 5$, $\gamma_1 = 5$, $\gamma_2 = 5$, $\varepsilon_1 = 10$, $\varepsilon_2 = 10$, $\alpha_1 = 1$, $\beta_1 = 1$, $\alpha_2 = 1$, $\beta_2 = 1$, $m_1 = 7$, $n_1 = 5$, $m_2 = 7$, $n_2 = 3$, $m_3 = 3$, and $n_3 = 5$. It is worth noting that the random values of control

parameters here are only to demonstrate the effectiveness of the proposed control method. In engineering practice, these values can be artificially adjusted according to the actual operating conditions of the system. The initial values of the adaptive parameters are $\hat{\gamma}_1(0) = 0$ and $\hat{\gamma}_2(0) = 20$. After the designed two adaptive sliding mode controllers (31) are put into operation, the time response curves of sliding mode functions are shown in Figure 3. It is obvious that two sliding mode functions defined in (25) converge rapidly to 0, which indicates that the state of controlled seven-dimensional power system (24) reaches sliding mode surfaces.

In the whole control process, the adaptive parameters are shown in Figure 4, and the two adaptive parameters are gradually adjusted to constant values. Figures 5 and 6 present the state variables of controlled power system (24). Each state variable restores to a stable state, and chaotic oscillation in the seven-dimensional power system is effectively suppressed. The evolution process diagram of the states of the uncontrolled and controlled system in phase space is shown in Figure 7. It can be seen that the state of uncontrolled power system eventually evolves into a strange attractor over time, while the state of controlled system evolves from the original chaotic attractor into an equilibrium fixed point in phase space.

FIGURE 5: Time responses of controlled power system.

FIGURE 6: Active power absorbed by energy storage device and equivalent admittance of static var compensation device.

FIGURE 7: Continued.

FIGURE 7: System state evolution process of uncontrolled and controlled power system in phase space. (a) $\delta_m - s_m - E'_q$ space. (b) $s_m - E'_q - E'_d$ space. (c) $E'_q - E'_d - E_{fd}$ space. (d) $E'_d - E_{fd} - \delta_L$ space. (e) $E_{fd} - \delta_L - V_L$ space. (f) $V_L - s_m - \delta_m$ space.

FIGURE 8: Control inputs for the seven-dimensional power system.

FIGURE 9: Time responses of controlled seven-dimensional power system considering parameter variation and uncertainty.

FIGURE 10: Time responses of active power absorbed by the energy storage device and equivalent admittance of static var compensation device considering parameter variation and uncertainty.

through a specific evolution trajectory. The time responses of designed control inputs (31) are shown in Figure 8, and as it can be seen that control inputs are finally stable and smooth.

Example 2. Next, the robustness of proposed control method is verified. In system (23), parameter d represents the damping coefficient of the power system; P_m represents mechanical input power of the generator; Q_{ld} represents reactive power of the load; and P_{ld} represents active power of the load. Since these parameters play an important role in the operation of power system, they are considered to verify the robustness of designed controller. Then consider the variation and uncertainty of these parameters (only d is an uncertainty) as follows:

$$\begin{cases} d = 0.05 \cdot [1 + \sin(t)], \\ P_m = 1.363 - 0.3 \cdot \varepsilon(t - 3), \\ Q_{ld} = 0 + 0.2 \cdot \varepsilon(t - 4) - 0.1 \cdot \varepsilon(t - 6), \\ P_{ld} = 0 + 0.2 \cdot \varepsilon(t - 5) - 0.3 \cdot \varepsilon(t - 6), \end{cases} \quad (33)$$

where $\varepsilon(t)$ is a step function.

In this way, the time responses of state variables of the controlled power system (24) can be obtained as shown in Figures 9 and 10. The two figures show that the power system can still recover from the original chaotic oscillation state to the equilibrium state under the condition of parameter variation and uncertainty, which proves that the proposed control method is robust to parameter variation and uncertainty.

5. Conclusion

Based on equivalence principle of control effect, an adaptive sliding mode control scheme is proposed for the controlled system. The unique advantage of the scheme is that no assumptions are introduced into the controller design process, and the designed controller has a wide range of applications. The proposed adaptive sliding mode controller scheme is used to control chaos in the seven-dimensional power system model, and the effectiveness and robustness of the designed controller are verified by simulation. In addition, the method proposed in the paper can be used to control other complex systems. Compared with controlling chaos in the two-dimensional and the four-dimensional power system models in

other literature studies, this paper completes the chaos control problem in a complex seven-dimensional power system model. Compared with controllers designed in many literature studies which belong to abstract control inputs, this paper introduces dynamic models of the energy storage device and static var compensation device to make the designed controller more practical in engineering.

Appendix

Parameter P_g in system (23) represents active power transmitted by the generator and its expression is

$$P_g = E'_q I_q + E'_d I_d + (x'_d - x'_q) I_d I_q, \quad (\text{A.1})$$

where

$$\begin{cases} I_d = \frac{[(\sin \phi - Y x'_q) \cdot (Y E'_q - a) + \cos \phi \cdot (Y E'_d - b)]}{A}, \\ I_q = \frac{[\cos \phi \cdot (Y E'_q - a) - (\sin \phi - Y x'_d) \cdot (Y E'_d - b)]}{A}, \\ A = [(\cos \phi)^2 + (\sin \phi - Y x'_q) \cdot (\sin \phi - Y x'_d)], \\ a = E_b Y_3 \cos(\delta + \phi - \phi_3) + Y_1 V_L \cos(\delta_L - \delta - \phi + \phi_1), \\ b = -E_b Y_3 \sin(\delta + \phi - \phi_3) + Y_1 V_L \sin(\delta_L - \delta - \phi + \phi_1), \\ Y = \sqrt{(Y_1 \cos \phi_1 + Y_3 \cos \phi_3)^2 + (Y_1 \sin \phi_1 + Y_3 \sin \phi_3)^2}, \\ \phi = \arctan \left[\frac{(Y_1 \sin \phi_1 + Y_3 \sin \phi_3)}{(Y_1 \cos \phi_1 + Y_3 \cos \phi_3)} \right]. \end{cases} \quad (\text{A.2})$$

Parameters P and Q in system (23) represent active power and reactive power transmitted to the load bus, respectively, and their expressions are as follows:

$$\begin{cases} P = V_t V_L Y_1 \cos(r_1) - V_L^2 Y_1 \cos(\phi_1) + E_b V_L Y_2 \cos(r_2) - V_L^2 Y_2 \cos(\phi_2), \\ Q = V_t V_L Y_1 \sin(r_1) + V_L^2 Y_1 \sin(\phi_1) + E_b V_L Y_2 \sin(r_2) + V_L^2 Y_2 \sin(\phi_2), \end{cases} \quad (\text{A.3})$$

where

$$\begin{cases} V_t = \sqrt{V_d^2 + V_q^2}, \\ V_d = E'_d - x'_q I_q, \\ V_q = E'_q + x'_d I_d, \\ r_1 = \delta_L - [\delta + \arctan(V_d/V_q)] - \phi_1, \\ r_2 = \delta_L - \phi_2. \end{cases} \quad (\text{A.4})$$

Constant values of the above system parameters are

$$\begin{aligned}
 Y_1 &= 4.9752, \\
 Y_2 &= 1.6584, \\
 Y_3 &= 0, \\
 \phi_1 &= -1.4711, \\
 \phi_2 &= -1.4711, \\
 \phi_3 &= -1.4711, \\
 E_b &= 1.0, \\
 x_d &= 1.79, \\
 x_q &= 1.71, \\
 x'_d &= 0.169, \\
 x'_q &= 0.23, \\
 T_{d0} &= 4.3, \\
 T_{q0} &= 0.85, \\
 H &= 2.894, \\
 \omega_B &= 377, \\
 d &= 0.05, \\
 P_0 &= 0.4, \\
 Q_0 &= 0.6, \\
 B_c &= 0.2, \\
 p_1 &= 0.24, \\
 q_1 &= -0.02, \\
 p_2 &= 1.7, \\
 q_2 &= -1.866, \\
 p_3 &= 0.2, \\
 q_3 &= 1.6, \\
 Q_{1d} &= 0, \\
 P_{1d} &= 0, \\
 K_A &= 200, \\
 T_A &= 0.05, \\
 V_{\text{ref}} &= 1.12.
 \end{aligned} \tag{A.5}$$

In these parameters, all values are in per unit values, except for angles, which are in degrees.

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest in preparing this article.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant no. 51877162) and the Science Fund for Creative Research Groups of the National Natural Science Foundation of China (Grant no. 51521065).

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