Fuzzy-based Sliding Mode Control of Chaotic Oscillation in Power System

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Abstract. Power system will occur chaotic oscillation when it is exist periodic load disturbances. As for it, the simplified mathematical model of interconnected two-machine second-order power system is established based on the modelling and analysis of nonlinear system theory, and the dynamic behaviour of chaotic oscillation in power system is analysed. According to the sliding mode control and fuzzy control theory, the fuzzy-based sliding mode control is proposed, it is also analysed and proved theoretically. Simulations results show that the proposed method can suppress the chaotic oscillation in power system effectively. It not only reduce the convergence time, but also reduced the chattering of the system, and has strong robustness.

1. Introduction

The power system is a highly coupled nonlinear system with complex nonlinear dynamic behavior. In recent years, many large interconnected power system blackouts are caused by uncontrollable chaotic oscillation. When nonlinear dynamic phenomena such as bifurcation or chaotic oscillation appear in the system, the system will be unstable or even the interconnection system will be split, which will seriously endanger the safe operation of the system, lead to large-scale power failure, and cause huge losses to the national economy. Chaotic oscillation has seriously threatened the safe and stable operation of the power system [1-5]. Therefore, the study of the chaotic oscillation behavior and control in power systems is of great significance.

In order to suppress the chaotic oscillation in power system, it is usually divided into two aspects: controlling the behavior of the system to the desired orbit and suppressing the occurrence of chaotic oscillations. The typical method generally has the passive control method [6], the adaptive compensation control method [7], inverse system control method [8], least squares support vector machine control method [9], nonlinear feedback variable control method [10] and sliding mode control [11-12]. Among them, the sliding mode control method has the advantages of fast response, excellent transient characteristics and robustness to parameter changes and external disturbances, and it is widely used in power system chaos oscillation control. However, the control law of sliding mode control is discontinuous, which leads to the chattering problem of the control output. In order to eliminate the chattering phenomenon of sliding mode control, a chaotic oscillation controller which is affected by uncertain factors is designed by combing the fuzzy control and sliding mode control method, it can reduce the influence of switching control on sliding mode and eliminate and suppress the chattering phenomenon.
In this paper, a mathematical model of the interconnected two-machine power system is established, its nonlinear dynamic behavior is analysed, and the mechanism of chaotic oscillation is revealed. Combined with the sliding mode control and fuzzy control theory, a fuzzy sliding mode control method is proposed to suppress the chaotic oscillation in power system and realize its equilibrium control. Simulation results show that the control method can weaken the chattering and accelerate the convergence speed of the system, and can effectively suppress the chaotic oscillation in power system.

2. Mathematical Model
This paper takes the interconnected two-machine second-order power system model as the research object. By simplifying the accurate model of the system, the interconnected second-order power system model is shown in Figure 1. The interconnected second-order power system model consists of generator, substation, transmission and distribution line, and power load.

![Second-order power system schematic](image)

Figure 1. Second-order power system schematic

Its mathematical model can be written as follows:

\[
\begin{align*}
\frac{d\delta}{dt} &= \omega \\
\frac{d\omega}{dt} &= -\frac{1}{H} P_s \sin \delta - \frac{D}{H} \omega + \frac{1}{H} P_m + \frac{1}{H} P_c \cos \beta t 
\end{align*}
\]  

(1)

Where: let \( a = \frac{1}{H} P_s \), \( b = \frac{D}{H} \), \( c_1 = \frac{P_m}{H} \), \( F = \frac{P_c}{H} \), \( x_1 = \delta \), \( x_2 = \omega \), then formula (1) can be simplified to:

\[
\begin{align*}
\frac{dx_1}{dt} &= x_2 \\
\frac{dx_2}{dt} &= -ax_1 - bx_2 + c_1 + F \cos \beta t
\end{align*}
\]  

(2)

In the stable state, the phase diagram of system is a closed curvilinear trajectory under periodic motion, and when the chaotic phenomenon occurs, the phase diagram is a strange attractor diagram which is not closed. Through the curvilinear trajectory of the phase diagram of the system, chaos can be observed directly. Take the initial value of the system as \((\delta_0, \omega_0) = (0.43, 0.003)\), when \( a = 1 \), \( b = 0.02 \), \( c_1 = 0.2 \), \( \beta = 1 \), \( F = 0.2593 \), the relative electrical angle and the relative rotor angular velocity of the system oscillate continuously and irregularly. The time domain waveforms are shown in Figure 2. At this time, the interconnected system is in a chaotic oscillation state, and this oscillation will make the interconnected second-order power system lose its stability.
From the above simulation results, it can be seen that the relative electrical angle and relative angular velocity have sustained irregular oscillation under the condition of this parameter, and the phase diagram of system is a strange attractor trajectory which is no closed. At this time, the interconnected system is in a chaotic oscillation state, and it will destabilize the interconnected second-order power system.

3. Organization of the Text

3.1. Design of equivalent controller

The chaotic oscillation model of the second-order power system is selected as the research object, and the power angle of the generator is taken as the control target, then the system is a single input single output radial nonlinear system:

\[
\begin{align*}
\frac{dx_1}{dt} &= x_2 \\
\frac{dx_2}{dt} &= f(x_1, x_2) + g(x_1, x_2, t)u + d(t) \\
y &= x_1
\end{align*}
\]

(3)

Where: \( f(x_1, x_2) = [-\alpha \sin x - \gamma x_2 + \rho] \), \( g(x_1, x_2, t) = 1 \), \( d(t) = F \cos \beta t \), among them, \( x \in \mathbb{R}^n, u \in \mathbb{R}, y \in \mathbb{R} \), disturbed term bounded: \( d(t) \leq F \).

Set the output tracking target of the system as \( x_d \), and the tracking error of the system is:

\[
e = x_d - x
\]

(4)

Then the switching function is:
\[ s(x,t) = ce + e \]  \hspace{1cm} (5)

Where:  \( c \) is a positive integer. It is known that when  \( s = 0 \), the system enters a stable dynamic system. The designed switching function can be derived as follows:

\[ s(x,t) = c e + e \]  \hspace{1cm} (6)

After sorting out:

\[ s(x,t) = c e + x_d - f(x_1,x_2) - g(x_1,x_2,t)u - d(t) \]  \hspace{1cm} (7)

Let  \( s(x,t) = 0 \), when ignoring the case of disturbance \( d(t) \), the equivalent control rate  \( u_{eq} \) is:

\[ u_{eq} = \frac{1}{g(x_1,x_2,t)} [c e + x_d - f(x_1,x_2)] \]  \hspace{1cm} (8)

### 3.2. Design of switching controller

In order to satisfy the sliding mode reaching condition  \( s(x,t) \cdot s(x,t) \leq -\eta \lvert s \rvert \), where  \( \eta > 0 \), the switching control must be used. In this paper, the constant velocity approach law is adopted, and the switching control law is:

\[ s = -\eta \text{sgn} s, \eta > 0 \]  \hspace{1cm} (9)

Where:  \( \eta \) is the approach velocity, when  \( s > 0 \),  \( s(t) = -t\eta \); when  \( s < 0 \),  \( s(t) = t\eta \); when  \( s(t) = 0 \), the time from the initial state to the switching surface is can be obtained:  \( t^* = s_0 / \eta \), where:  \( s_0 \) is the value of the switching function at the initial time  \( t = 0 \). Therefore, it is very important for the selection of  \( \eta \) and has a large effect on the approach velocity.

The switching controller is designed as follows:

\[ u_{sw} = \frac{1}{g(x_1,x_2,t)} \eta \text{sgn}(s) \]  \hspace{1cm} (10)

Where:  \( \eta > F \).

In order to overcome the effect of uncertain disturbance,  \( \eta \) is required to be larger than the disturbance amplitude  \( F \). The equivalent controller and the switching controller are combined to obtain the conventional sliding mode controller:

\[ u = u_{eq} + u_{sw} \]  \hspace{1cm} (11)

Under the action of the conventional sliding mode controller  (11), the switching surface  \( s = 0 \) is stable, that is  \( s \cdot s < 0 \). Take formula (11) into formula (5) and get:

\[ s \cdot s = s \cdot (-\eta \cdot \text{sgn}(s)) - s \cdot d(t) = -\eta \lvert s \rvert - sd(t) \]  \hspace{1cm} (12)
Since $\eta > 0$ and $d(t) \leq F$, it can get $s \dot{s} < 0$.

3.3. Design of switching controller

Sliding mode variable structure control introduces the problem of buffeting. In order to reduce the chattering, fuzzy control is added to the strategy of sliding mode variable structure control. When the system is running on the switching surface, the equivalent control is used to ensure that it keeps on running on the sliding surface; when the system is running outside the sliding surface, the traditional sliding mode variable structure control, which combines the equivalent control and the switching control, can be used to eliminate the chattering caused by the excessive inertia., and the system can quickly reach the sliding surface. Then design the following fuzzy control rules.

If $s(t)$ is ZO then $u$ is $u_{eq}$ \hspace{1cm} (13)

If $s(t)$ is NZ then $u$ is $u_{eq} + u_{sw}$ \hspace{1cm} (14)

The fuzzy sets ZO and NZ represent "zero" and "non-zero" respectively. The fuzzy rule formula (13) indicates that when the switching function $s(t)$ is zero, the fuzzy controller is equivalent control $u_{eq}$, and the fuzzy rule formula (14) indicates that when the switching function $s(t)$ is non-zero, the fuzzy controller is equivalent control $u_{eq}$ and switching control $u_{sw}$.

Using the defuzzy method, the fuzzy controller is designed as:

$$u = \frac{\mu_{ZO}(s)u_{eq} + \mu_{NZ}(s)(u_{eq} + u_{sw})}{\mu_{ZO}(s) + \mu_{NZ}(s)} = u_{eq} + \mu_{NZ}(s)u_{sw}$$ \hspace{1cm} (15)

$$\mu_{ZO}(s) + \mu_{NZ}(s) = 1$$ \hspace{1cm} (16)

When $\mu_{NZ}(s) = 1$, then $u = u_{eq} + u_{sw}$. At this time, the control law is the traditional equivalent sliding mode control; when $\mu_{NZ}(s) \neq 1$, the chattering of the system is eliminated by the change of the membership function.

By analyzing the above derivation process, the fuzzy control system can make the system reach the sliding surface in a limited time under any initial conditions. In the whole control process, switching control $u_{sw}$ is used to overcome the interference of uncertain term and disturbance term $d(t)$, so as to make the system robust. When the system moves to the sliding mode surface, the switching control effect disappears and the equivalent control takes effect to make the system reach the equilibrium point along the trajectory of $S=0$. During the operation stage of the whole sliding mode, its dynamic characteristics only depend on the parameters of the switching function $u_{eq}$, and are independent of the parameter uncertainty and disturbance term of the system. Therefore, the chaotic power system has robustness in the whole control process.

4. Numerical simulation

In order to verify the control effect of the designed chaotic oscillation controller, the simulation research is carried out with MATLAB. When the system parameters are $\alpha = 1, \gamma = 0.02, \rho = 0.2, F = 0.2593$, the sliding mode variable structure controller $c = 25, \eta = 10 + F = 10.2593$, the tracking target
function is sinusoidal tracking $x_d = \sin 2\pi t$. The input membership function and output membership function of the fuzzy system are shown in Figure 3.

![Fuzzy membership function](image)

**Figure 3.** Fuzzy membership function.

After adding the fuzzy control, the tracking error of the fuzzy sliding mode controller is shown in Figure 4. As show in Figure 4.a, the tracking error $e = x_d - x_i$ is controlled around line $x = 0$ with small error, and the chattering of the system can be eliminated well.
The change curve of output and reference signal of the system under fuzzy sliding mode control is shown in Figure 4.b. From the above simulation results, it can be seen that the chaotic motion of the power system is suppressed under the action of the fuzzy sliding mode controller. And under the action of the fuzzy sliding mode controller, the system output $x_i$ can track the signal $x_d = \sin 2\pi \tau$, the tracking error control is better, and the chattering problem of the system is solved.

5. Conclusion
Under certain parameters, chaotic oscillation will occur in interconnected two-machine power system, and the dynamic characteristics of chaotic oscillation are analyzed by timing sequence diagram and phase diagram. In order to suppress the chaotic oscillation, a fuzzy sliding mode controller based on the
fuzzy control theory and sliding mode control theory is proposed. The controller can effectively suppress the chaotic oscillation in power system. The numerical simulation results show that the designed controller can not only weaken the chattering of the sliding mode control, but also accelerate the convergence time of the system, and has the advantages of fast response, good stability and strong robustness.

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