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Adaptive robust control of chaotic oscillations in power system with excitation limits*

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With system parameters falling into a certain area, power system with excitation limits experiences complicated chaotic oscillations which threaten the secure and stable operation of power system. In this paper, to control these unwanted chaotic oscillations, a straightforward adaptive chaos controller based on Lyapunov asymptotical stability theory is designed. Since the presented controller does not need to change the controlled system structure and not to use any information of system except the system state variables, the designed controller is simple and desirable. Simulation results show that the proposed control law is very effective. This work is helpful to maintain the power system's security operation.

Keywords: chaos control, power system, adaptive control, Lyapunov asymptotical stability
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1. Introduction

Large-scale electrical network interconnection is an inevitable trend of the modern power system development, with which the electric generation and electric transmission become more and more highly-efficient and economical, while the complication of operation in power system has been increased and the security and stability of power system is facing an unprecedented challenge. In the past few decades around the world, some of the major power systems have suffered losing stabilization even collapse events occur in succession.[1−3] Recent investigations have shown that the chaotic oscillations in power system are the important causes of those destabilization and breakdowns.[4−8] Thus, it is indispensable to study the method of controlling or suppressing chaotic oscillations in power system. There have been many control methods of chaos in the field of theoretical researches so far.[9−12] Nevertheless, to the best of our knowledge, analytical investigation into controlling chaos in power system is infrequent. In our previous work,[13] we have controlled chaotic oscillations in a simple power system which is modelled by second-order heteronomous differential equations. However, there is an important shortcoming in this work because the effects of excitation limits are not taken into account. Actually, excitation limits are fundamental elements in the real model of power system. It has been shown that with system parameters falling into a certain area, power system considering excitation limits experiences chaotic oscillations which appear aperiodic, random, sudden or intermittent morbid electromechanic oscillations.[7,8] So, to control chaotic oscillations in power system with excitation limits is a significant task.

Adaptive stabilization of nonlinear systems containing unknown parameters has attracted many researchers' attention recently, see, for instance, the works by Li and Han,[14] and Qi.[15] The primary advantage of adaptive control is that it can carry into execution without the requirement that the ranges of the uncertainties and the disturbances should be known in advance. Considering that there are undeterministic parameters and noise interference in the real power system with excitation limits, we construct an adaptive controller in this paper. On the basis of Lyapunov asymptotically stability theory, we prove that the designed controller can control chaotic power system to the unstable fixed point. Since the presented controller is simple and straightforward, the designed controller will be more applicable to the practical use. Simulation results show that the proposed controller is very effective and robust against both the uncertainty in system parameters and external noise interference.

2. Power system model

A power system model with excitation limits under consideration in this paper is shown in Fig.1.

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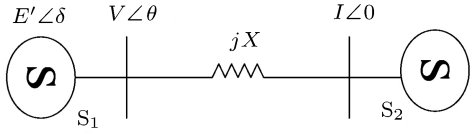


Fig.1. A power system model with excitation limits.

In this figure, $V\angle\theta$ is voltage magnitude and angle of the load bus terminal, $I\angle 0$, which is chosen as reference, is voltage magnitude and angle of the infinite bus terminal. Resistance X represents the transmission lines. The dimensionless power system model which consists of generator swing equations and excitation system equations is given by[7,8]

$$\dot{\delta} = 2\pi f_0 \omega,$$
$$M\dot{\omega} = -D\omega + P_{\mathrm{T}} - \frac{E'}{x'_{\mathrm{d}} + x}\sin\delta,$$
$$T'_{\mathrm{d0}}\dot{E}' = -\frac{x_{\mathrm{d}} + x}{x'_{\mathrm{d}} + x}E' + \frac{x_{\mathrm{d}} - x'_{\mathrm{d}}}{x'_{\mathrm{d}} + x}\cos\delta + E_{\mathrm{fd}},$$
$$T_{\mathrm{A}}\dot{E}_{\mathrm{fdr}} = -K_{\mathrm{A}}(V - V_{\mathrm{ref}}) - (E_{\mathrm{fdr}} - E_{\mathrm{fd0}}), \qquad (1)$$

where δ, ω, E' are state variables of generator swing equations, which denote the machine angle, the relative angular velocity between the generator S_1 and generator S_2, and the voltage magnitude behind the transient reactance respectively. The excitation system for the generator is represented by a single time constant high gain automatic voltage regulator (AVR) and the limiter as shown in Fig.2, where E_{fdr}, which is state variable of excitation system equation, indicates the input signal of wind-up limiter which limits the field excitation voltage E_{fd} to be strictly between the values $E_{\mathrm{fd_{min}}}$ and $E_{\mathrm{fd_{max}}}$, say,

$$E_{\mathrm{fd}} = \begin{cases} E_{\mathrm{fd_{max}}} & \text{if} \quad E_{\mathrm{fdr}} > E_{\mathrm{fd_{max}}}, \\ E_{\mathrm{fdr}} & \text{if} \quad E_{\mathrm{fd_{min}}} \le E_{\mathrm{fdr}} \le E_{\mathrm{fd_{max}}}, \\ E_{\mathrm{fd_{min}}} & \text{if} \quad E_{\mathrm{fdr}} < E_{\mathrm{fd_{max}}}. \end{cases}$$

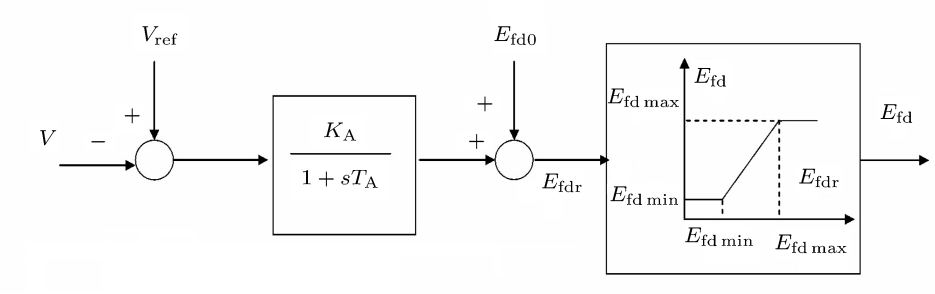


Fig.2. The simplified excitation model consisting of AVR and limiter.

The voltage V in Eq.(1) is described as:

$$V = \frac{1}{x + x'_{\mathrm{d}}}\sqrt{[(x'_{\mathrm{d}} + xE'\cos\delta)^2 + (xE'\sin\delta)^2]}\,.$$

All of the systemic parameter values taken in our studies are practical. In a realistic power system model, the mechanical power input P_{T} and the damping factor D are unknown, which can be modelled as operating parameters. The investigations in Refs.[7, 8] have shown that with parameters P_{T} and D falling into a certain area, power system (1) experiences complex nonlinear dynamical behaviours, such as bifurcation, chaotic oscillations, etc. After Ref.[7], we use the following parametric values:

$$P_{\mathrm{T}} = 1.30, \quad D = 110$$

in this paper, with which the power system displays chaos. The typical chaotic attractor in power system with excitation limits is shown in Fig.3.

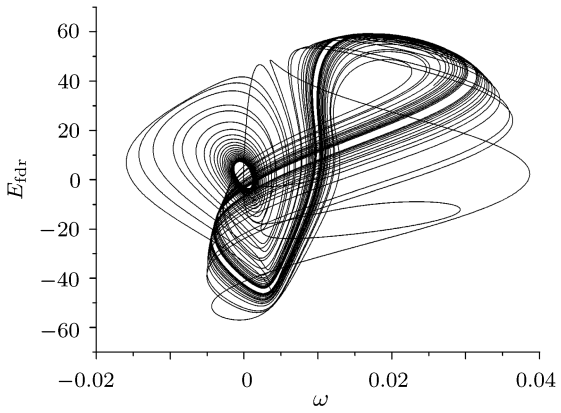


Fig.3. Typical multiple chaotic attractor in power system with system operating parameters $P_{\mathrm{T}} = 1.30$, $D = 110$.

Chaotic oscillations not only can extremely destroy the stabilization of the power system but also cannot be suppressed or controlled by adding the tra-

ditional excitation controller.[3] Therefore, how to control chaotic oscillations in power system with excitation limits is a significant job.

3. Adaptive control of chaotic oscillations in power system with excitation limits

3.1. Adaptive control law design

Consider the controlled chaotic system:

$$\dot{x}(t) = Ax(t) + f(x) + u(t)\,, \tag{2}$$

where, the state variable $x \in \Re^n$, the control input $u \in \Re^m$, f is nonlinear vector field and A is an unknown constant system matrix. Without loss of generality, we suppose that the vector field f has at least one equilibrium point.

Assumption 1 The nonlinear function $f(x)$ of the system (2) satisfies Lipschitz condition, i.e.,

$$\|f(x_1) - f(x_2)\| \leq L\|x_1 - x_2\|,$$

L refers to the Lipschitz constant.

We propose an adaptive chaos control law u in the following

$$u = \hat{\mu}(x - x_0)\,, \quad \dot{\hat{\mu}} = -k\|x - x_0\|^2, \tag{3}$$

where, $\hat{\mu}$ is adaptive scalar, $\dot{\hat{\mu}}$ is adaptive algorithm, k is an arbitrary positive scalar, which can adjust the performance of adaptation algorithm, x_0 is the unstable equilibrium point of chaotic system. Without loss of generality, we choose x_0 as the control target.

Now, a theorem is introduced as follows, which is essential for the main result in this paper.

Theorem 1 If the assumption 1 is satisfied, the control law (3) will asymptotically stabilize chaotic system (2) at the equilibrium points.

Proof Supposing the assumption 1 is satisfied, we find that there consequentially exists a scalar μ such that all the eigenvalues of matrix $Q = A + LI + \mu I$, are negative,[16] where I is identity matrix. Let $\Delta x = x - x_0$, choosing a Lyapunov function $W = (1/2)\Delta x^{\mathrm{T}}\Delta x + (1/k)(\mu - \hat{\mu})^2$, and taking the time derivative of W along the trajectories of system (2), one can obtain that

$$\begin{aligned}\dot{W} &= \Delta x^{\mathrm{T}}(A + \mu I)\Delta x + 2\Delta x^{\mathrm{T}} f(\Delta x) \\ &\quad - (\mu - \hat{\mu})\Delta x^{\mathrm{T}}\Delta x - \frac{1}{k}(\mu - \hat{\mu})\dot{\hat{\mu}} \\ &\leq \Delta x^{\mathrm{T}}(A + \mu I + LI)\Delta x - (\mu - \hat{\mu})\Big(\Delta x^{\mathrm{T}}\Delta x + \frac{1}{k}\dot{\hat{\mu}}\Big) \\ &= \Delta x^{\mathrm{T}} Q \Delta x - (\mu - \hat{\mu})\Big(\Delta x^{\mathrm{T}}\Delta x + \frac{1}{k}\dot{\hat{\mu}}\Big)\,. \end{aligned} \tag{4}$$

Substituting Eq.(3) into Eq.(4), we obtain $\dot{W} \leq \Delta x^{\mathrm{T}} Q \Delta x$. Since the eigenvalues of matrix Q are negative, we have $\dot{W} \leq 0$. Thus, the chaotic system (2) is asymptotically stabilized at the equilibrium points x_0.

Remark The condition in assumption 1 is crucial, but very loose, for example, the condition holds as long as $\partial f(x_i)/\partial x_j (i, j = 1, 2, \cdots, n)$ are bounded. Since the chaotic attractor in nonlinear system is bounded, chaotic system can easily satisfy Lipschitz condition, leastwise content local Lipschitz condition.[17] Thus, chaotic power system satisfies assumption 1, in other words, the proposed control law is applicable for controlling chaotic oscillations in power system with excitation limits.

3.2. Application of adaptive robust controller to controlling chaotic oscillations in power system

With the knowledge above, we carry out controlling chaos in power system in this subsection. As we know that in conventional power system design, a stabilizing input called the power system stabilizer (PSS) signal is usually added to the voltage reference V_{ref}, we add directly the adaptive controller u to the voltage reference V_{ref} in Eq.(1) such that the quondam system structure avoid is transformed. Then the controlled Eq.(1) is changed to

$$\begin{aligned}&\dot{\delta} = 2\pi f_0 \omega, \\ &M\dot{\omega} = -D\omega + P_{\mathrm{T}} - \frac{E'}{x'_{\mathrm{d}} + x}\sin\delta, \\ &T'_{\mathrm{d0}}\dot{E}' = -\frac{x_{\mathrm{d}} + x}{x'_{\mathrm{d}} + x}E' + \frac{x_{\mathrm{d}} - x'_{\mathrm{d}}}{x'_{\mathrm{d}} + x}\cos\delta + E_{\mathrm{fd}}, \\ &T_{\mathrm{A}}\dot{E}_{\mathrm{fdr}} = -K_{\mathrm{A}}(V - (V_{\mathrm{ref}} + u)) - (E_{\mathrm{fdr}} - E_{\mathrm{fd0}}), \\ &u = \hat{\mu}(E_{\mathrm{fdr}} - E_{\mathrm{fdr0}}), \\ &\dot{\hat{\mu}} = -k\|E_{\mathrm{fdr}} - E_{\mathrm{fdr0}}\|^2, \end{aligned} \tag{5}$$

where E_{fdr0} is the unstable equilibrium point of state variable E_{fdr}. Once the E_{fdr} is asymptotically stabilized at the unstable equipoise point, the output signal of excitation limiter E_{fd} is stabilized, and then chaotic oscillations in power system are controlled. Since the presented control law is simple and straightforward,

the controller is desirable in practice. The control effectiveness is shown by numerical simulation as follows.

4. Numerical simulation results

In this section, some simulation results for the controlled system (5) are presented. The systematic parameters take the same values as those in Section 2. Power system is displaying chaotic oscillations before the controller u is carried out and the unstable equilibrium point of power system is $x_0 = (1.0409, 0, 1.3559, 1.9229)^{\mathrm{T}}$.[7] So, one can obtain $E_{\mathrm{fdr0}} = 1.9229$. In order to eliminate the effect of the initial values, controller u is put into effect at $t = 30$ s. Figure 4 shows the results of control when the control parameter is set as $k = 5$. From Fig.4 one can find that the system states can be regulated to the unstable equilibrium point x_0, in other words, chaotic oscillations in power system are controlled. The speed of dynamic response can be further increased (or reduced) by tuning the control parameter k.

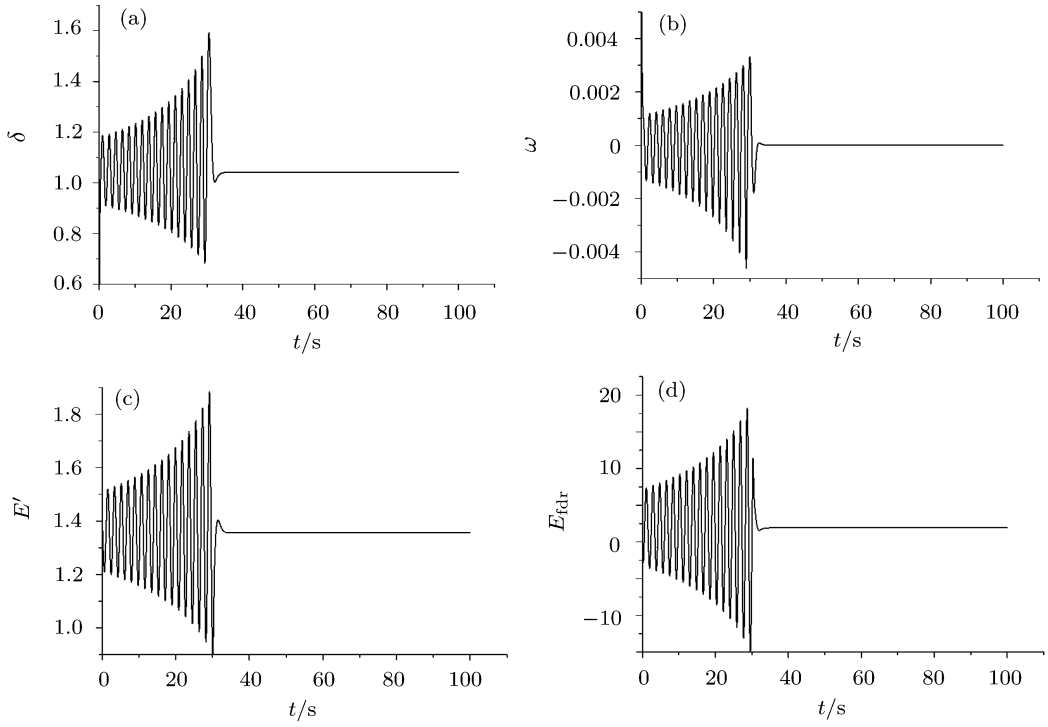


Fig.4. Control chaotic oscillations in power system to unstable equilibrium point $x_0 = (1.0409, 0, 1.3559, 1.9229)^{\mathrm{T}}$ with $k = 5$ while utilizing the controller at $t = 30$ s. (a) The dynamic response curves of δ; (b) The dynamic response curves of ω; (c) The dynamic response curves of E'; (d) The dynamic response curves of E_{fdr}.

5. Robustness analysis of the controller

The robustness of the controller against uncertainty in system parameters and external noise interference is discussed in this section, which is a general issue in practical applications.

Firstly, we validate the robustness of the designed controller against the uncertainty in system parameters through investigating numerical simulation results with taking variational values of unknown parameters. For example, we change undeterministic parametric values from $P_{\mathrm{T}} = 1.30$, $D = 110$ to $P_{\mathrm{T}} = 1.40$, $D = 120$ and keep all of the other parametric values unchanged. Chaotic oscillations in power system occur. The unaltered controller u is put into effect at $t = 30$ s. The control result is shown in Fig.5, where only the result of E' is shown in order to economize the length of paper. From Fig.5, we can see that the chaotic oscillations is stabilized at the control target x_0. A large amount of number simulation shows that no matter how mutative the operating parameters are, chaotic power system can asymptotically stabilize at equilibrium point, which indicates

that the designed controller can avoid the influence of undeterministic parameters.

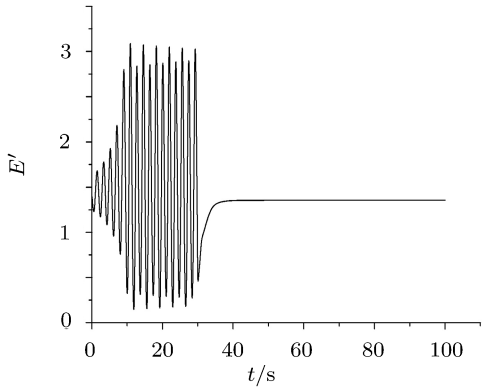


Fig.5. Chaotic power system can still be controlled to target when the undeterministic parametric values are changed to $P_{\rm T} = 1.40$, $D = 120$ and all of the other parametric values are maintained, where only the control result of E' is shown for saving the length of paper.

Secondly, to ascertain the robustness of the presented controller against external noise interference, we exert the additive random noise $n = 0.5 + 0.4\sin(2t)$ to the second equation of system (4). Suppose the control goal still is the fixed point x_0 and all parametric values are maintained. The result of control is shown in Fig.6, where it can be seen clearly that the output of control can track given goals, just the control accuracy may be reduced to some extent. Hence, the designed control law is certainly robust against external noise interference.

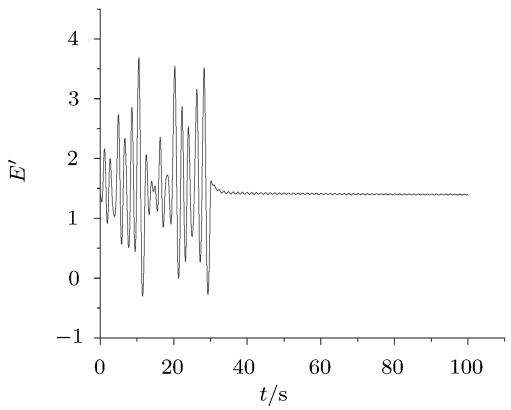


Fig.6. The control result of E' in presence of external arbitrary noise interference $n = 0.5 + 0.4\sin(2t)$.

6. Conclusions

In this paper, an adaptive control law based on Lyapunov asymptotically stabilizing theory is designed to control the chaotic oscillations in power system, which is a beneficial try that applies chaos control method to a special plant. Since the presented controller is simple and straight-forward, which does not need to change the controlled system structure and not to use any information of system except the system state variable $E_{\rm fdr}$, the designed controller will be more applicable to the practical use. Simulation results indicate that the proposed control law is very effective and robust against both the uncertainties in system parameters and external noise interference. The obtained result of this paper is valuable to maintain the power system's security operation.

References

[1] Yu Y N 1983 *Electric Power System Dynamics* (New York: Academic) p56
[2] Chiang H D, Liu C C and Varaiya P P 1993 *IEEE Trans. Power Syst.* **41** 407
[3] Carreras B A, Lynch V E and Dobson I 2002 *Chaos* **12** 985
[4] Rajesh G K and Padiyar K R 2001 *Int. J. Bifurc. Chaos* **11** 2509
[5] Ohta H and Ueda Y 2002 *Chaos, Solitons* and *Fractals* **14** 1227
[6] Jing Z J, Xu D S, Chang Y and Chen L N 2003 *Int. J. Electro. Power Energy Syst.* **21** 443
[7] Ji W and Venkatasubramanian V 1996 *Int. J. Electro. Power Energy Syst.* **18** 279
[8] Ji W and Venkatasubramanian V 1999 *IEEE Trans. Circ. Syst.*-I **46** 405
[9] Tong P Q 1995 *Acta Phys. Sin.* **44** 169 (in Chinese)
[10] Luo X S and Wang B H 2001 *Chin. Phys.* **10** 17
[11] Luo X S, Chen G R, Fang J Q, Zou Y L and Quan H J 2003 *Acta Phys. Sin.* **52** 790 (in Chinese)
[12] Zheng Y A 2006 *Chin. Phys.* **15** 2549
[13] Wei D Q and Luo X S 2007 *Chaos, Soliton* and *Fractals* **31** 665
[14] Li Z and Han C Z 2002 *Chin. Phys.* **11** 666
[15] Qi D L 2006 *Chin. Phys.* **15** 1715
[16] Hua C C and Guan X P 2004 *Chaos, Soliton* and *Fractals* **22** 55
[17] Wei R and Wang X Y 2004 *Acta Phys. Sin.* **53** 3298 (in Chinese)