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Adaptive control method for chaotic power systems based on finite-time stability theory and passivity-based control approach

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ABSTRACT

Chaotic oscillation in a power system is considered the main cause of power blackouts in large-scale interconnected power grids. The chaotic oscillation mechanisms and the control methods for chaos oscillation of power systems need to be analyzed. This paper thus proposed an adaptive control method for chaotic power systems using finite-time stability theory and passivity-based control approach. The adaptive feedback controller is first constructed using the finite-time stability theory and the passive theory to make the chaotic power system equivalent to a closed-loop passive system. We then proved that the passive power system can stabilize the equilibrium points. We also extensively studied fourth-order power system. Results show that the controller based on the finite-time theory and the passivity-based control approach can effectively stabilize the chaotic behavior within finite time. The control strategy was also found to be robust to the different power system states.

1. Introduction

Power systems are usually large-scale, geographically distributed, and with hundreds to thousands of generators operating in parallel and synchronously. These power systems may vary in size and structure from one to another. Power systems involve numerous control features, such as relay protection and automatic devices and the control of Facilities Administration Control and Time Schedule (FACTS) devices. Therefore, the general structural model of local equipment should be built first, and the local models should then be connected to build a full power system model. The power system is thus a typical strong coupling, highly nonlinear, and multivariable dynamic system with rich nonlinear dynamic behavior. A power system is generally expressed by a highly nonlinear dynamic system of equations which includes system parameters. The inevitable trend of power system development is the establishment of large-scale power grid interconnection. Large-scale power grid interconnection has brought great convenience for the production and consumption of electricity. This innovation also stabilizes power systems. The power system exhibits irregular, sudden, or paroxysmal electromechanical oscillations when the periodic load disturbance reaches a certain amplitude [1-3]. These oscillations are chaotic oscillations. Chaotic behavior is considered a complex phenomenon of nonlinear systems that can push the power system to instability [4]. These oscillations are difficult to control or suppress by using conventional linear controllers. Analyzing the chaotic oscillation mechanism of power systems and examining the control methods for chaotic oscillation are therefore necessary.

The chaotic oscillation of power systems is considered the cause of voltage collapse and instability. Several techniques and strategies have been proposed in the past decades that can be used to study the chaos mechanism of power systems. Song [5] examined the chaotic behavior of two power systems by building a system of homoclinic orbit functions. Yorke [6] studied the transformer model and found that the saturation of the core will cause resonance and bifurcation and chaotic operating behavior of voltage. Chiang [7] used numerical methods to investigate the chaos and bifurcation of three-bus power system. O'Neill-Carrillo [8] proved that the electric arc furnace load has chaotic operating characteristics. Jia and Yu [9] have analyzed and simulated the chaos of the doubling cycle bifurcation and torus bifurcation of the power system since 2000. They also analyzed the relationship between the chaos and patterns of the power system. Wei [10] first studied the erosion effect of Gaussian white noise on the stability of power systems. He set the noise threshold which can make the system operate stably. Li [11] used mean square criterion to determine the necessary conditions for chaotic motion and discussed the influence of bounded noise and damping power index on chaotic motion. Ma [12] studied the bifurcation behavior of a time-delay power system and analyzed the bifurcation and chaos caused by different

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factors. A power system which is in the chaotic state of operation not only produces overvoltage but also causes over-current. These conditions will cause various effects, including insulation flashover, lightning protection, equipment damage, and severe power outage, which will significantly affect the safe operation of the entire system.

The stability of a power grid is an essential element that measures its reliability. Schafer developed a control method by using a direct and decentralized frequency price coupling to achieve a reliable dynamic demand response [13]. Fang et al. presented a control strategy which has two control algorithms, namely, one for grid-connected operations and the other for intentional-islanding operations [14]. Pedro proposed a flexible active power control based on a rapid current controller and a reconfigurable reference current selector [15]. Various control strategies are applied to power systems to ensure a reliable power supply and avoid power outage [16]. Chaos is considered a complex phenomenon in nonlinear systems that can push the power system toward instability. Chaotic power systems are more complex because they require more effective control methods to ensure the reliability of power systems. Enhancing the stability of the system operation and improving the power quality by analyzing and controlling the chaotic dynamic behavior of the power system are necessary.

Chaos control of power systems has received considerable attention from researchers. Min [17] studied a single-machine infinite nonlinear dynamic system by bifurcation and Lyapunov exponent. A novel adaptive anti-synergetic membrane controller is designed to enable the power system to operate on a stable orbit. Borah [18] studied the chaotic dynamics of fractional PMSG and designed a novel predictive control method in the sense of fractional order. In addition, the mathematical model of D-PMSG is established [19]. The chaotic behavior and limit cycle phenomena in a certain working condition or certain parameter ranges were proven. The adaptive controller is designed on the basis of Lyapunov stability theory. Yang [20] established the mathematical model of permanent magnet synchronous generators and designed the chaos control law considering the system disturbance. Jia [21] developed a hybrid control strategy based on state feedback and parameter perturbation for chaos voltage-controlled Buck converter. Wei and Luo [22] designed a nonlinear controller based on the finite-time stability theory and Lyapunov stability theory to control the chaotic oscillation of BLDCM system and verified the accuracy and effectiveness of the control strategy. All of these control methods however are intended for chaotic motor, chaotic converter, or chaotic second-order equivalent power systems. To the best of our knowledge, high-dimensional chaotic power system has not been investigated.

In the finite-time control method, as the name suggests, the complex dynamical system with finite-time means achieves stability within a finite time. This method is useful in several practical engineering fields. Mohammad et al. introduced an adaptive control scheme for chaos suppression of non-autonomous chaotic rotational machine systems with fully unknown parameters in finite time [23]. Gao et al. proposed a zero error system algorithm based on automatic control theory and finite-time control principle [24]. Wang et al. used a nonlinear controller to control chaos in a BLDCM system based on the finite-time stability theory and the Lyapunov stability theory [25]. Several finite-time synchronization methods have been proposed in [26–28].

This study developed an adaptive control method for chaotic power systems using the finite-time stability theory and the passivity-based control approach. passivity-based control approach is considered an alternative tool for analyzing the stability of integer-order nonlinear systems [29]. The adaptive feedback controller is constructed using the passive theory and the finite-time stability theory to make the chaotic power system equivalent to a closed-loop passive system. We then proved that the controlled power system can stabilize the equilibrium points. The fourth-dimensional power system is used as the test system. The results show that the controller based on the finite-time stability theory and the passivity-based control approach can effectively stabilize the chaotic behavior. We concentrate on the chaos control problem of power systems and how to deal with the designing controller.

This paper proposed a control method based on the finite-time stability theory and the passivity-based control theory for fourth-dimensional chaotic power system. The key innovation of this article is that a chaotic power system adaptive finite-time passive controller is proposed. Adaptive control method, passive control method and finite -time control method have been used in electric power fields respectively. But The adaptive feedback controller is first constructed using the finite-time stability theory and the passive theory and used to control chaotic power system. This control method not only possesses the advantages of passive controller, but also can be realized in a finite time, which is designed simple and has actual engineering significance.

The details on the innovations of the proposed method are as follows:

(1) The passivity-based theory combines with finite-time theory is proposed. To the best of our knowledge, the control theory idea is the first proposed.
(2) For chaotic power systems, we proposed a new trial, which is not used before, combined adaptive control theory with the passivity-based theory and the finite-time stability theory to develop a novel adaptive control method.

The remainder of this paper is organized as follows. Section 2 will present the theoretical principle. Section 3 will describe the chaotic power system. Section 4 will discuss the design and verification of the adaptive control method for chaotic power systems. Section 5 concludes the paper.

2. Theoretical principle

Passivity is a concept related to the system's external input and output. Passivity is a special case of dissipation. The physical meaning of the dissipative inequality is to show that the energy increasing of the system from the initial time to the current moment is less than or equal to the sum of the energy externally injected. This indicates that the movement of the passive system is always accompanied with the loss of energy. Passive system is a dynamic system which considers the energy exchange between the system and the outside world. If the system is passive, it can keep the system internal stability. Therefore, for the unstable system with oscillation, the controller can be constructed according to the passive theory. The term passivity-based control was introduced in Ortega and Spong [30] to define a controller design methodology, which achieves stabilization by passivity theory. The corresponding closed-loop system will become passive to keep the internal stability. In this section, some important definitions and results related to passivity and passivity-based control of nonlinear systems are provided.

Consider the nonlinear system as follows:

$$\begin{aligned} \dot{x} &= f(X) + g(X)u \\ y &= h(X) \end{aligned} \tag{1}$$

where $X \in R^n$ is the state vector, $u \in R^m$ is the external input vector, and $y \in R^m$ is the output vector. f and g are assumed to be smooth vector fields and h is a smooth mapping.

Definition 1. The system (1) is said to be passive if there exists a positive constant λ such that for $\forall t \geq 0$, satisfying

$$\int_0^t \upsilon^T y(\tau) d\tau \geq \lambda \tag{2}$$