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Modeling, nonlinear dynamical analysis of a novel power system with random wind power and it's control

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A B S T R A C T

The stability problem of power networks becomes increasingly important since the rapid development and broad application of wind energy technology. We continue to lack a well-established mathematical model to describe and characterize power systems associated with wind power in essence of random properties. Here, we present a novel model to solve this significant problem by incorporating the nonlinear dynamical theory and the fluctuation nature of wind energy. The model produces some interesting dynamical phenomena, e.g., routes to chaos. To eliminate the chaotic behavior which is disadvantageous to the stability and normal functioning of the whole system, we offer a fuzzy control approach to drive the system with uncertain parameters from chaotic states to steady states. The control method is validated by both numerical simulations and theoretical analysis. Our theory and control scheme can be expected to be potentially applicable in a variety of power systems with wind sources.

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1. Introduction

Wind power sources have been increasingly brought into the conventional power system recently [1–6]. At present, the generation capability of wind power sources relies on the conditions of natural environment, such as wind speed. Their grid-connection introduces significant stochastic fluctuation of generation which could be potentially spatial dependent. The stochastically variable wind sources on power system stability have significant impact on the dynamics of power systems, operational characteristics and stability of the whole power system, which has been given much attention [7–10]. Some effort has been dedicated to the small signal stability of power system with wind turbine generators. For example, Gautam et al. [11] developed an approach to analyze the impact of increased penetration of DFIG-based wind turbines on transient and small signal stability of a large power system. Bu et al. [12] proposed a method of probabilistic analysis to investigate the impact of stochastic uncertainty of grid-connected wind generation on power system small-signal stability. Other contributions to dynamic stability are major in frequency-domain approach [13]. Similarly, Kumar and Gokulakrishnan [14] studied the impact of FACTS controllers on the stability of power systems connected with wind energy conversion system. In particular, some papers mainly focus on voltage stability [15,16], angle stability [17,18], and thermal stability [19]. In addition, some publications are about transient stability [20,21], steady-state stability [22]. Despite existent contributions to the dynamic behaviors of wind turbines [23–26], there are few literature addressing the issue of the stability of the power system with random wind power based on nonlinear dynamics theory.

The control problem of nonlinear systems with uncertain parameters has been a well-established area [27–29]. Aghababa M. and Aghababa H. [30] investigated the problem of finite-time chaos synchronization between two different uncertain chaotic systems with unknown parameters and input nonlinearities. A study of sliding mode control of uncertain dynamical systems with time delay was presented by Song and Sun [31]. Sakthivel et al. [32] offered a robust H-infinity control design approach for a class of uncertain discrete-time stochastic neural networks with time-varying delays. In particular, due to the theoretical value and practical significance, fuzzy control has been employed in controlling nonlinear dynamics [33–35]. Yet, to the best of our knowledge relatively little attention has been given to implementing fuzzy control to power system associated with random wind energy [36].

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Regarding the lacking of mathematical approach for power systems with wind sources in essence of random properties, we model a power system consisting of a wind power generator and a normal generator. The dynamic characters of the system are studied in detail by the aid of nonlinear dynamical theory. Some interesting phenomena are observed, such as the routes to chaos. In order to eliminate chaos, an adaptive fuzzy control is offered to drive the system with uncertain parameters to a steady state.

The rest of the article is organized as follows. A new mathematical model of a typical power system with random wind energy is presented in Sec. 2. Sec. 3 studies the nonlinear dynamical behaviors in detail. An adaptive fuzzy control is proposed in Sec. 4. Moreover, the numerical simulations are in agreement with theory analysis. The conclusion is drawn in Sec. 5.

2. System model

The simple power system with random wind power is illustrated in Fig. 1 which can be viewed as a generalized case.

Here, 1 is the equivalent generator of electrical power system, 2 is equivalent wind generator of electrical power system, 3 and 4 are equivalent main transformers, 5 is load, 6 are circuit breakers and 7 is tie line of the power systems.

Rotor equations for the wind turbine model is

$$\alpha = \frac{\mathrm{d}w}{\mathrm{d}t} = \frac{\mathrm{d}^2\delta}{\mathrm{d}t^2}, \tag{1}$$

where α is the angular acceleration of wind turbine rotor, w is generator angular velocity and δ is the angle. Thus, we can get

$$J\alpha = M_{\mathrm{m}} - M_{\mathrm{e}} - M_{\mathrm{D}} \tag{2}$$

where J is the inertia moment of generators rotor including prime mover and generator rotor, M_{m} is mechanical torque which acts on the spindle of generator, M_{e} is braking electromagnetism torque of machines and M_{D} is damping torque.

From Eqs. (1) and (2), one has

$$J\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = M_{\mathrm{m}} - M_{\mathrm{e}} - M_{\mathrm{D}} \tag{3}$$

In industrial practices, inertia moment of generator rotor J can be represented by H customarily. Thus, Eq. (3) is rewritten as

$$\frac{H}{2\pi f_0}\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = M_{\mathrm{m}} - M_{\mathrm{e}} - M_{\mathrm{D}} \tag{4}$$

where H and t are in seconds for the unit; fundamental frequency is 50 Hz $f_0 = 50$ Hz, δ is in radian for the unit, M_{m}, M_{e} and M_{D} are expressed as per unit values (M_{m}, M_{e}, M_{D}).

Taking industrial practices into consideration, torque M can be replaced by power P, which is given by

$$M = \frac{P}{w}. \tag{5}$$

One has

$$H\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = P_{\mathrm{m}} - P_{\mathrm{e}} - P_{\mathrm{D}}, \tag{6}$$

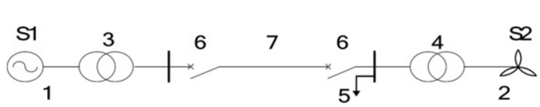

Fig. 1. Simple interconnected power system with random wind power system.

where mechanical power P_{m}, electromagnetic power P_{e} and damping power P_{D} are expressed as per unit values (P_{m}, P_{e}, P_{D}). Their base values are in kV A for the unit.

Actually, damping power P_{D} is approximated as

$$P_{\mathrm{D}} = \frac{D}{2\pi f_0}\frac{\mathrm{d}\delta}{\mathrm{d}t} \tag{7}$$

where D is generator damping coefficients, which is a constant.

Considering P_{e} is proportional to $\sin\delta$ and time base value is $T_{\mathrm{B}} = 1/2\pi f_0$, Eq. (6) can be simplified as

$$\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = \frac{1}{H}P_{\mathrm{m}} - \frac{1}{H}P_{\mathrm{e}}\sin\delta(t) - \frac{D}{H}w(t) \tag{8}$$

The electrical power system with random wind energy is described as

$$\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = \frac{1}{H}P_{\mathrm{m}} - \frac{1}{H}P_{\mathrm{e}}\sin\delta(t) - \frac{D}{H}w(t) + \frac{1}{H}P_{\mathrm{s}}\cos\beta t \tag{9}$$

where P_{s} and β are parameters of the random wind energy, they represent its amplitude and frequency, respectively. Here, one sets $d_1 < P_{\mathrm{s}} < d_2$.

From Eqs. (1) and (9), the state equations of the electrical power system with random wind energy could be obtained as follows

$$\begin{cases} \dot{\delta}(t) = w(t) \\ \dot{w}(t) = \frac{1}{H}P_{\mathrm{m}} - \frac{1}{H}P_{\mathrm{e}}\sin\delta(t) - \frac{D}{H}w(t) + \frac{1}{H}P_{\mathrm{s}}\cos\beta t \\ y(t) = \delta(t) - \delta_0(t) \end{cases} \tag{10}$$

where P_{m} is mechanical power and P_{e} is electromagnetic power of the wind power system, $\delta(t)$ and $w(t)$ are system state variables, $y(t)$ is output variable of the system.

For that system 1 in Fig. 1 is similar to system 2 in Fig. 1, P_{s} in system 1 in Fig. 1 represents the amplitude of the random wind generator.

If one denotes $\alpha = P_{\mathrm{e}}/H$, $\gamma = D/H$, $\rho = P_{\mathrm{m}}/H$, and $F = P_{\mathrm{s}}/H$, Eq. (10) can be rewritten as

$$\begin{cases} \dot{\delta}(t) = w(t) \\ \dot{w}(t) = \rho - \alpha\sin\delta(t) - \gamma w(t) + F\cos\beta t \end{cases} \tag{11}$$

where F is a random quantity, which is $d_1/H < F < d_2/H$.

3. Nonlinear dynamical analysis

When the power system operates in rated conditions, a random energy disturbance, such as the fluctuation of the random energy frequency or the random energy amplitude, will affect the stability of the system. Subsequently, the system will enter a new operating state. Because of the nonlinearity of every part, there will be a complex transient process. This paper only focuses on the nonlinear dynamical behaviors along with the fluctuation of the amplitude of the power system. This is because of the fact that the method of analyzing nonlinear dynamical behaviors in different random energy interferences is approximately same. Therefore, here we only study the differential adjustment of P_{s}.

3.1. Bifurcation map

The Bifurcation map is used to analyze the dynamical characteristics of the nonlinear system as the system parameter varies. Bifurcation is the main route to chaos from a stable state.

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