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Influence of Wind Power Integration on Power System Transient Stability Based on Stochastic Theory

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Abstract

Wind power has certain uncertainty and affects the transient stability of power system. The concept of standard Wiener process and Gaussian white noise is introduced. The Ito stochastic differential equation is given. Based on stochastic differential equation theory, different types of wind turbines are established. Consider the grid-connected model of wind speed fluctuations and establish a dynamic model of the power system considering wind power uncertainty. By means of the theory and numerical integration method of stochastic differential equations, it is applied to the stochastic model of power system to analyze the influence of wind power uncertainty on the electromechanical transient process of power system. Simulations are carried out in combination with simulation examples. The simulation results show that adding damping to the system can reduce the negative impact of wind power uncertainty.

Keywords: wind power uncertainty, transient stability, numerical analysis, damping, simulation

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INTRODUCTION

Wind energy is a clean and stable new energy source. It has also become one of the fastest growing energy sources in the world in recent years. It provides a stable power supply for economic growth and can effectively alleviate air pollution, water pollution and global warming (Chi et al. 2007, Li 2010, Li et al. 2008, Liu et al. 2013, Qiao and Lu 2009). However, the rapid development of wind power has brought great challenges to energy security and environmental safety. The uncertainty of wind energy is a shortcoming that we can't ignore. It is mainly reflected in the spatial and temporal distribution of wind direction, wind speed and other factors. The uncertainty in wind power conversion and the uncertainty outside the wind power system. Therefore, how to analyze the transient stability of power systems with dynamic random excitation is of great significance to the dynamic safety of power systems (Ju et al. 2013, Luo 2013, Ortega-Vazquez and Kirschen 2009, Ruisheng 2006, Zhou et al. 2014).The basic methods of transient stability analysis can be divided into two categories: numerical solutions and direct methods (Ai et al. 2016, Huang et al. 2009, Lei et al. 2011, Mashhour and Moghaddas-Tafreshi 2011, Xue et al. 2014). The direct method is faster because the calculation of the limit parameters is faster, the transient process of the scanning system is rough, and the model is too simple. The advantage of the numerical method is that the system model is exquisite, the calculation results are accurate, and the time response of various variables in the system can be provided. In this paper, numerical simulation is used to analyze the transient stability of power systems. Wind power uncertainty will deteriorate the transient stability of the system to a certain extent, and will cause low-frequency oscillations that cannot be eliminated for a long time, which will bring continuous problems to the stability of the power system. Consider adding damping in the system to reduce the negative impact of wind power uncertainty (State Grid Corporation of China, 2010, Wang and Yu 2010, Ye et al. 2012, Zhang et al. 2013, Zhao et al. 2013).

POWER SYSTEM DYNAMIC MODEL

In order to randomly model the influence of wind speed, the Wiener process with statistical characteristics and the stochastic differential equation describing stochastic process are introduced when describing the mechanical power input by the fan. In order to analyze the transient stability of wind power access to the power system, it is necessary to solve the random power system.

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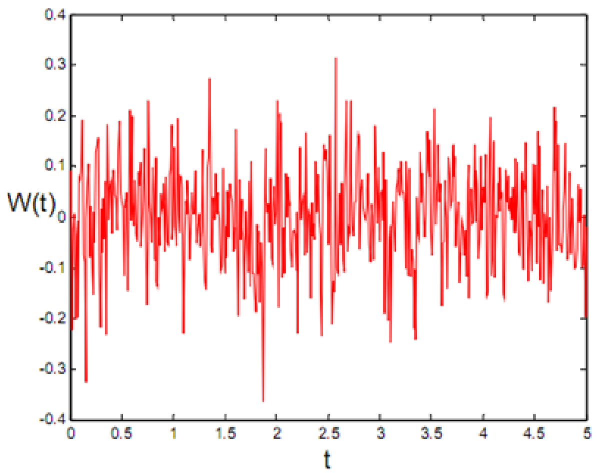

Fig. 1. Gaussian white noise

Standard Wiener Process and Gaussian White Noise

The stochastic process can be classified according to the parameter space, the state space is continuous and discrete, or can be classified according to the probability structure of the stochastic process. The Wiener process and Gaussian white noise are two types of stochastic processes.

Definition 1: Assume that $\{W(t), -\infty < t + \infty\}$ is in a random process while satisfying the following conditions.

(1) $W(0) = 0$ And the probability is 1;

(2) $\{W(t), -\infty < t < +\infty\}$ is a homogeneous independent incremental process;

(3) For $\forall t < s$, there is an increment of $W(s) - W(t) \square \sqrt{s-t}N(0.1)$, and $N(0.1)$ is a standard normal distribution.

Then $\{W(t), -\infty < t < +\infty\}$ is called the standard Wiener process.

Definition 2: If $\{W(t), -\infty < t < +\infty\}$ is the Wiener process in Definition 1.1, then the formal derivative $\frac{dW(t)}{dt}$ of $W(t)$ is Gaussian white noise, usually denoted as $\{W(t), t > 0\}$.

Since the formal derivative of the Wiener process has a Gaussian white noise pattern, Gaussian white noise can be generated by means of the Wiener process, as shown in **Fig. 1**.

Stochastic Differential Equation

Study the uncertainty, complexity, and unknown factors that exist objectively in the system. The stochastic differential equation used:

$$d\boldsymbol{X}(t) = \boldsymbol{f}(\boldsymbol{X}(t), t)dt + \boldsymbol{g}(\boldsymbol{X}(t), t)d\boldsymbol{W}(t)$$

$$(t \in T, X(t_0) = X_0)$$

Where $\boldsymbol{W}(t)$ is the standard m-dimensional Wiener process of $W_i(t), i = 1,2, \dots, m$, $\boldsymbol{f}(\boldsymbol{X}(t), t)$ and $\boldsymbol{f}(\boldsymbol{X}(t), t)$ become the drift coefficient and the diffusi $f(X(t), t)$ on coefficient, respectively.

Ito Stochastic Differential Equation

Ito calculus takes its name from the Japanese mathematician Ito Kiyoshi, extending the concept of calculus to a stochastic process, such as the Brownian motion (Wiener process), which can be analyzed using Ito calculus. The central concept of Ito's calculus is Ito's integral, which extends the traditional Riemann-Steel Jess integral into a stochastic process. The stochastic process is a random variable on the one hand and a non-differentiable function. With Ito integration, a stochastic process (integrated function) can be integrated into another stochastic process (integral variable). The integral variable will generally be a Brownian motion. The scalar form of Ito's points is as follows:

Let be a second-order moment process, $W(t)$ be a Wiener process, and split on [a,b].

$$a = t_0 < t_1 < \cdots < t_n = b$$

And set $\Delta_n = \max_{1 \le k \le n}\{t_k - t_{k-1}\}$, for the sum

$$I_n = \sum_{k=1}^{n} f(X(t_{k-1}), t_{k-1})[W(t_k) - W(t_{k-1})]$$

due to

$$\|f(X(t_k), t_k)[W(t_{k+1}) - W(t_k)]\|_2 = \|f(X(t_k), t_k)\|_2 \cdot \|[W(t_k) - W(t_{k-1})]\|_2 < \infty$$

, If the mean square limit $\lim_{\Delta t_n \to 0} I_n$exists, the limit is called $f(X(t), t)$ for Ito integral on $W(t)$, recorded as

$\lim_{n \to \infty, \Delta n \to 0} I_n = \int_a^b f(X(t), t)dW(t)$ theorem If $f(X(t), t)$ is a mean square continuous second-order moment process, and for any $s_1', s_2' \le t_{k-1} < t_k$ and $s_1, s_2 \le t_{k-1}$, $[f(X(s_1')), f(X(s_2')), W(s_2) - W(s_1)]$ and $[W(t_k) - W(t_{k-1})]$ are independent of each other, $f(X(t), t)$ exists and unique with respect to $W(t)$'s Ito integral.

If the form derivative of $W(t)$ is $[B(t), t \in T]$, then $B(t)$ is white noise. According to the definition and rule of Ito calculus, the differential form of stochastic differential equation can be written as Ito stochastic differential equation:

$$\begin{cases} d\boldsymbol{X}(t) = \boldsymbol{f}(\boldsymbol{X}(t), t)dt + \boldsymbol{g}(\boldsymbol{X}(t), t)d\boldsymbol{W}(t) \\ \boldsymbol{X}(t_0) = \boldsymbol{X}_0 \end{cases}$$

The form of the integral can be recorded as:

$$\begin{cases} \boldsymbol{X}(t) = \boldsymbol{X}(t_0) + \int_{t_0}^{t} \boldsymbol{f}(\boldsymbol{X}(t), s)ds + \int_{t_0}^{t} \boldsymbol{g}(\boldsymbol{X}(s), s)d\boldsymbol{W}(s) \\ \boldsymbol{X}(t_0) = \boldsymbol{X}_0 \end{cases}$$

Among them, $\boldsymbol{X}_0$ and $d\boldsymbol{W}(t)$ increment, $t \in T$ are independent of each other.

In the above formula, we believe that the first integral is the mean square Riemann integral, and the second integral is the Ito integral.

Based on the actual engineering background of the power system, the random non-homogeneous term is caused by the access of new energy sources, such as the randomness of injection power such as wind power generation.

Power System Dynamic Model of Wind Power Uncertainty

Analysis of the stability of a power system containing wind power requires consideration of the randomness of wind speed and the resulting mechanical torque uncertainty. The fan model can be processed into a stochastic differential equation and used as a special generator to access the power system, which can form an electromechanical transient process model of the power system considering wind power uncertainty, such as:

$$\begin{aligned} d\boldsymbol{x}(t) &= \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{y}, t)dt + \boldsymbol{g}(\boldsymbol{x}(t), t)d\boldsymbol{W}(t) \\ \boldsymbol{0} &= \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{y}) \end{aligned} \tag{1}$$

Establish two common wind turbine models in the current power system:

(1) Conventional asynchronous fan model

$$\begin{aligned} \frac{dE'}{dt} &= -\frac{1}{T_0'}[E' - j(X_0 - X')I_s] - j\omega_s s E' \\ \frac{ds}{dt} &= \frac{1}{T_j(1-s)}(P_e - P_m) \\ U &= E' - (R_s - jX')I_s \\ P_e &= R_e\{E' I_s^*\} \end{aligned} \tag{2}$$

Among them, δ is the power angle, $\omega_s = 100\pi$ rad/s, s is the slip, T_j is the inertia constant, P_e is the electromagnetic power, and $P_m = P_{m,0} + \Delta P_h$ is the mechanical power, considering random fluctuation. U is the stator voltage, determined by the system, and I_s is the stator current, which establishes a connection to the power network.

(2) Direct-drive permanent magnet generators are connected to the grid by using two back-to-back full-power voltage source inverters (VSCs). If the dynamic characteristics of power electronics are not considered, the fans can be regarded as PV nodes according to different control modes. Or PQ nodes have no direct impact on system frequency. For considering the effects of random fluctuations in wind speed, the output of wind turbine nodes can be modeled as a stochastic process.

$$P_i = P_0 + \Delta P_h \tag{3}$$

For an asynchronous fan, the equation after connecting (2) to the power network is a stochastic differential algebraic equation of equation (1) as a power system model including an asynchronous fan; for a direct-drive wind turbine, it can be considered as a power network. A load with stochastic characteristics establishes a power system model of the form (1). For these power system models, Ito integral can be used to solve and analyze its electromechanical transient process.

POWER SYSTEM STABILITY CONCEPT AND SOLUTION METHOD

The transient process that occurs after a large disturbance in the power system may have two different outcomes: one is that the transient process is gradually attenuated, and the relative motion between the generators of the system gradually disappears, causing the system to transition to a new steady state operation. In this case, the generators are still running synchronously under this operating condition. For this outcome, we say that the power system is transiently stable. Another outcome is the strong oscillation of the power and voltage of the system during the transient process, so that some generators and loads cannot continue to operate. For this outcome, we say that the power system is transiently unstable. The basic methods of transient stability analysis can be divided into two categories: numerical solutions and direct methods. Because the system model described by the numerical method is exquisite and the calculation result is accurate, the numerical method is adopted in this paper. When numerical solution is used to calculate transient stability, differential equations and algebraic equations must be solved simultaneously in each integral step. This needs to be extended on the basis of the numerical integration method for solving differential equations in general. The main solution is to solve the problem law. The general process of numerical solution can be represented by the block diagram shown in **Fig. 2**.

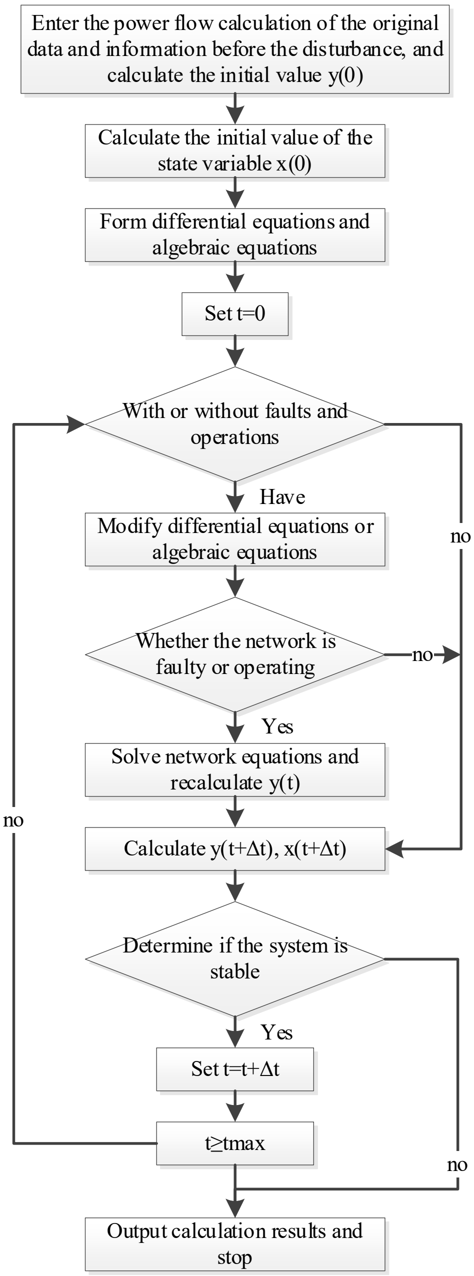

Fig. 2. Basic flow chart of transient stability analysis

INFLUENCE OF WIND POWER UNCERTAINTY ON POWER SYSTEM TRANSIENT STABILITY

Single Machine Infinity System with Wind Farm

Considering the impact of wind power uncertainty on the static stability of the power system, the fan model is used in a single-machine infinity system. The wind farm composed of a plurality of wind turbines with a single synchronous generator and a plurality of wind turbines with a wind farm as shown in **Fig. 3** is connected to a conventional bus after being separately boosted, and the wind turbine is a direct drive wind turbine. It is considered as a PQ node and randomly injects power into the system.

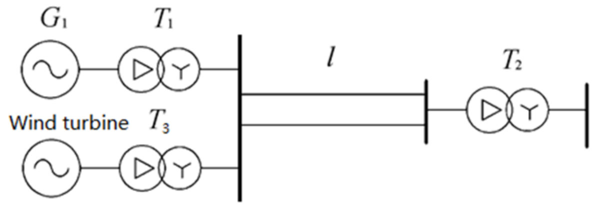

Fig. 3. Single-machine infinity system with wind farm

The power of the wind farm is the same as that of the conventional unit when the uncertainty is not considered. The initial operating point is $P_0 = 1.0$, $Q_0 = 0.2$, and the dynamic fan is regarded as the dynamic load access system, the equivalent load $Z = -1 - j0.2$, and the boosting total reactance $x_{T1} = 0.138$, double loop total reactance x_1=0.243, step-down variable total reactance x_{T2}=0.122, generator transient reactance x'_d=0.295, inertia time constant T_j=8.18 s, damping coefficient D=1.0, initial operating point is P_0=1.0, $Q_0 = 0.2$, electromotive force $E' = 1.41$, power angle $\delta_0 = 34.46°$. The above parameters (except δ_0) are standard values, the reference power S_B=220 MVA, and the reference voltage U_B=209 kV.

For the sake of realization, it is assumed that the generator transient electromotive force E' remains unchanged, and the excitation voltage variation and the role of the rotor damper winding are not considered. The motor infinity system description equation is:

$$\begin{cases} \dfrac{d\delta}{dt} = \omega_s(\omega - 1) \\ \dfrac{d\omega}{dt} = \dfrac{1}{T_J}(P_m - P_e - D(\omega - 1)) \\ \dot{I}_s = (\dot{E}' - \dot{U})/Z_\Sigma \\ P_e = Re\{\dot{E}\hat{I}_s\} \end{cases}$$

The above model is solved using the numerical solution of stochastic differential equations. Here we consider the Euler method (EM) and the fourth-order Runge-Kutta method. Take 0.1 s as the step size, first set the damping D to 0, and the calculation result is shown in **Fig. 4**.

It can be seen from **Fig. 4** that in an undamped system, the uncertainty of the wind power system causes the power angle of the fan to swing more and more until it is unstable, but the amplitude of the oscillation is small and needs to be gradually increased for a long time.

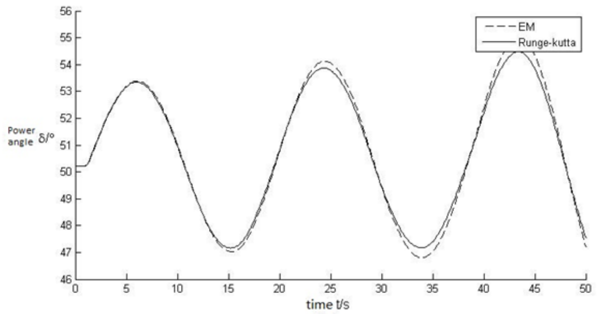

Fig. 4. Comparison of the results of the EM method and the fourth-order Runge-kutta method

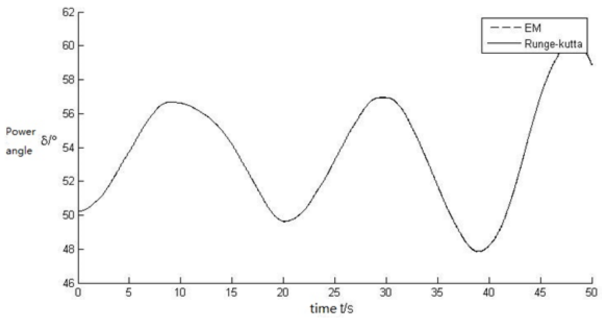

Fig. 5. Comparison of the results of the small step size of the EM method and the fourth-order Runge-kutta method

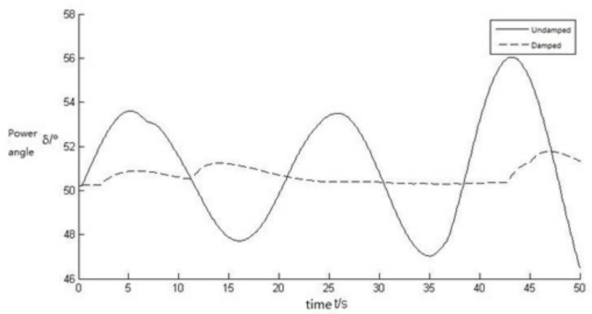

Fig. 6. Random static stabilization with and without damping

It can be seen from **Fig. 5** that the gap between the two algorithms is not large, but as time accumulates, the error becomes more and more obvious. For the sake of accuracy, the following analysis uses a numerical solution of the fourth-order Runge-kutta stochastic differential equation in 0.01 s step.

It can be seen from **Fig. 6** that the damping tendency can be well suppressed in the case of adding damping. At the same time, it can be found that because the Wiener process is a stochastic process, the numerical solution of the stochastic differential equation is solved by numerical solution, and the results obtained each time are different. Therefore, it is difficult to judge the stability problem of the system from one result, so

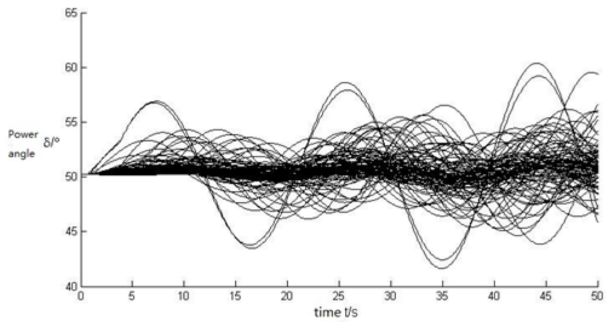

Fig. 7. Random static stability results for a solution of one hundred times

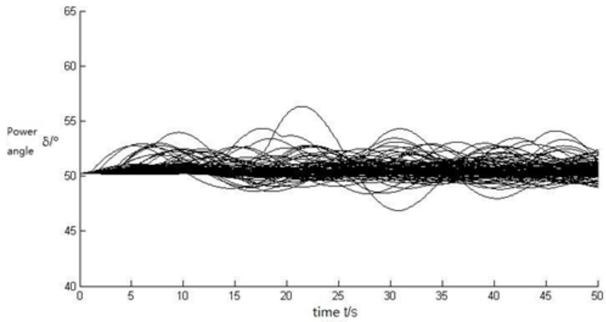

Fig. 8. Random static stability results obtained by solving the solution of one hundred times after damping

several repeated experiments are taken here to study the influence of uncertainty on the stability of the system.

Repeating one hundred experiments although each experiment is different, the tendency to gradually lose stability can be seen. Consider adding damping $D = 1.0$, using the same ordinate range as the previous experiment, and doing another hundred experiments:

According to the results, it can be seen that the system instability trend is obviously suppressed, which means that under the appropriate damping, the single-machine infinite fan system is the same as the static stability decision of the conventional generator set. In $\frac{dP_e}{d\delta} > 0$, it can maintain static stability without Instability.

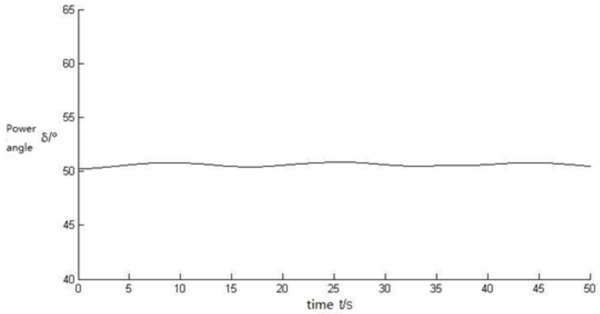

Fig. 9. Mean value of random static stability results obtained by solving the solution of one hundred times after damping

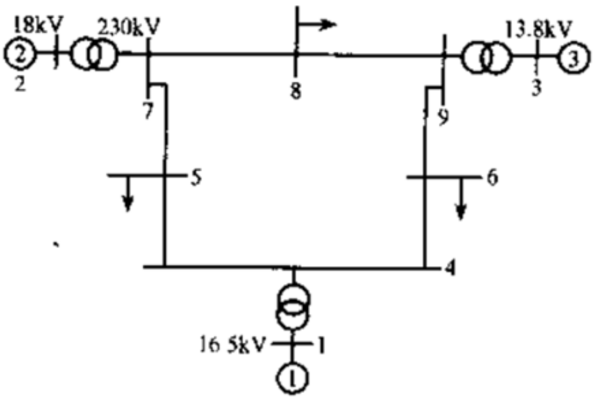

Fig. 10. Three-machine nine-node system

Three-Machine Nine-Node System

As shown in **Fig. 10**, the three-machine nine-node power system. The system has three generators, three loads and nine branches. The randomness of wind power generation is considered as the random excitation of the power system. A random disturbance term P_L is directly added to the right side of the generator rotor equation of motion.

$$\begin{aligned} \frac{d\delta}{dt} &= \omega_s(\omega - 1) \\ \frac{d\omega}{dt} &= \frac{1}{T_J}(P_m - P_e - P_L - D(\omega - 1)) \end{aligned} \quad (4)$$

Assume $P_L = \sigma B(t)$

$B(t)$ is a standard Gaussian process mean value 0, variance is 1); σ^2 is the equation of P_L. The generator rotor model is combined with the simple power system dynamic model to form a power system dynamic model that takes into account wind power uncertainty, and the following analysis is performed.

Firstly, the generator of node 1 is considered to be a random excitation of wind power, and the random static stability simulation is performed using the Runge-kutta method in steps of 0.001 s. The relative rocking angle

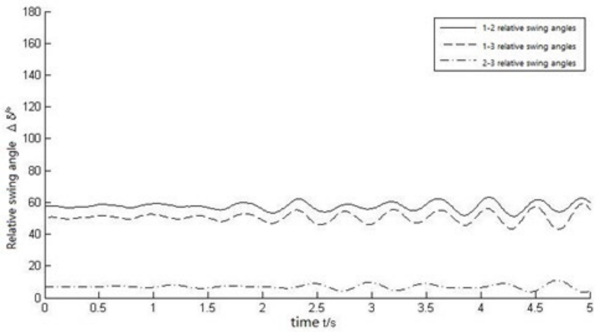

Fig. 11. Nine-node system takes into account the numerical solution of uncertainty

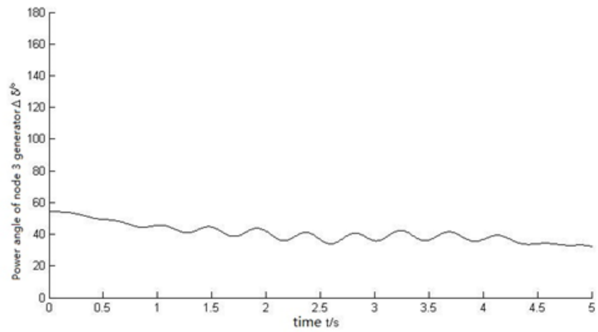

Fig. 12. Power angle curve of the No. 3 node generator in a nine-node system

between the power angles of the units is shown in **Fig. 11**. The power angle curve for a single generator is shown in **Fig. 11**.

Similar to the stand-alone infinity system, although the system's low-frequency oscillations are generated, the uncertainty of the fan is not significant in the stability of the system. If the simple process changes each generator model to equation (4) and doubles the random excitation, there is the case of **Fig. 12**.

It can be seen that the power system enters a continuous oscillation state, and it is necessary to reduce the oscillation amplitude by increasing the damping.

THE INFLUENCE OF WIND TURBINE UNCERTAINTY ON THE TRANSIENT STABILITY OF THE SYSTEM CONSIDERING FAULTS AND STOPS

Single Machine Infinity System with Wind Farm

For a single-machine infinity system containing wind power, at 5 s, a three-phase short-circuit fault occurs at the head end of one of the double-circuit lines, and then the faulty line is cut. Based on the parameters of the system, the following analysis of the transient stability of the system in this case.

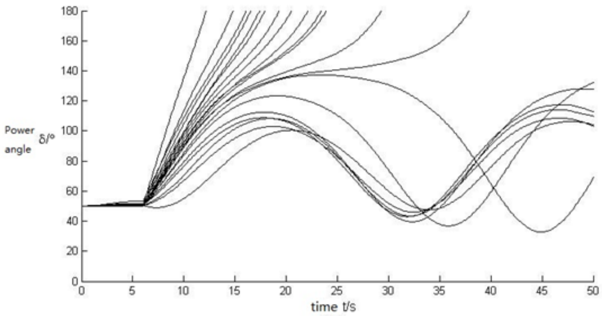

Fig. 13. 20 test results when $\sigma = 1$

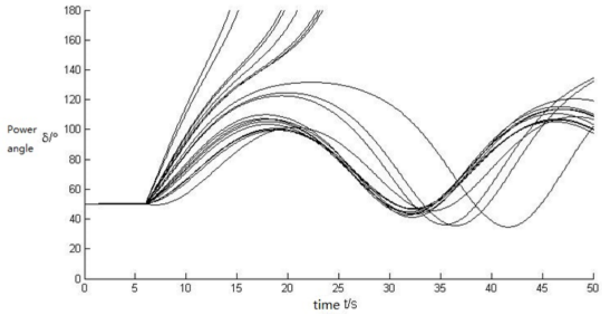

Fig. 14. 20 test results when $\sigma = 0.5$

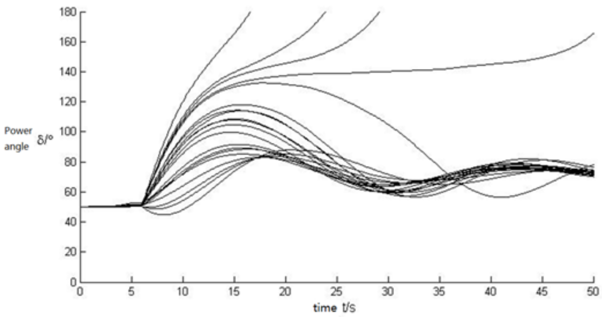

Fig. 15. 20 experimental results when $\sigma = 1$ is added after damping

Considering the uncertainty of wind power, taking $\sigma = 1$, using the small step EM algorithm to numerically simulate the fault occurrence and resection process, it can be found that the simulation results are different each time due to randomness. Therefore, statistics are performed.

As shown in **Fig. 13**, the fault is selected in 6.1 s, and 20 simulations are performed, in which the instability is 13 times and the stability is 7 times.

Taking $\sigma = 0.5$, the same test was carried out 20 times. The statistical instability was 8 times, and the system was stable for 12 times. Initial conclusions can be drawn: (1) wind power uncertainty will deteriorate the transient stability of the system; (2) different excitation strengths have different effects on transient stability, and the greater the excitation intensity, the greater the impact.

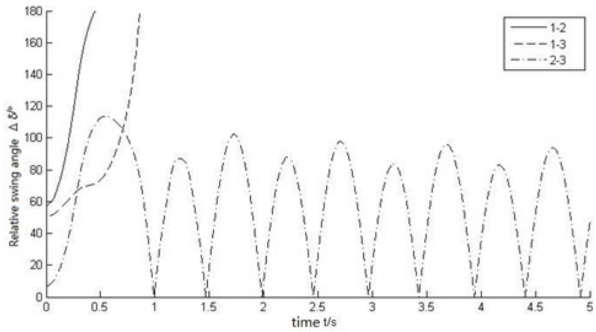

Fig. 16. One of the results of the 0.28 s clear fault

In order to reduce the influence of wind power uncertainty, in the case of $\sigma = 1$, consider adding $D = 1$ damping to the system and performing 20 experiments. The result is shown in **Fig. 15**, where the instability is 4 times and there are 16 times. Can keep the system stable. It shows that damping can reduce the negative impact of wind power uncertainty on the power system.

Three-Machine Nine-Node System

For the three-machine nine-node system, a three-phase short-circuit fault three-machine nine-node system occurs on the 5-7 line at 0 seconds, and the generator of the node 1 is replaced by a fan. If the uncertainty is not taken into account, the deterministic equation can be used. It is tested that the 0.28 s clear fault can ensure that the relative rocking angle between the generators does not exceed 180°; if the uncertainty is taken, there is a certain probability that the system will lose stability during the numerical solution time.

However, in the case of leaving a certain margin, such as 0.2 seconds to clear the fault, the test is one hundred times. Although the calculation result is different for considering the uncertainty, no instability is found within 5 s of the numerical solution. It can be stated that if the fault clearing time leaves a certain margin, the transient stability of the wind power system containing the wind power is guaranteed. However, the shock of the system will still cause damage to the power system, and fluctuations caused by uncertainty will aggravate this.

If damping is added, the low-frequency oscillations due to large disturbances will be effectively suppressed and gradually stabilized, but the improvement of the transient stability of the system is not obvious.

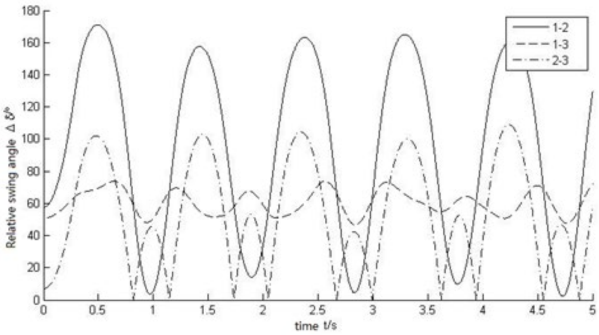

Fig. 17. The second result of the 0.28 s clear fault

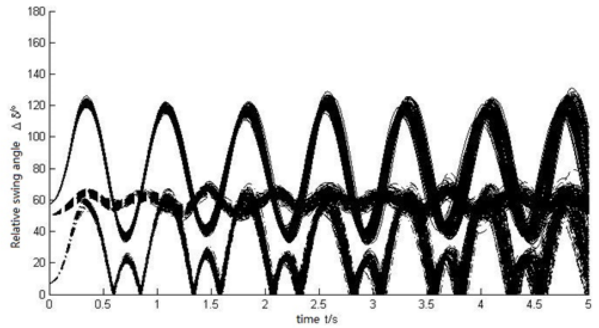

Fig. 18. 2 s clearing the fault value to solve a hundred results

CONCLUSION

Based on the proposed model and the numerical integration theory of stochastic differential equations, a case study is carried out to establish an infinite system that takes into account wind power uncertainty. The static stability is discussed in the example, and the conclusion is drawn:

1. Wind power uncertainty will deteriorate the transient stability of the system to a certain extent, and will cause low-frequency oscillations that cannot be eliminated for a long time.

2. Introduce the fan model into the power system model, and introduce the numerical calculation method of stochastic differential equations to simulate the electromechanical transient process of the power system considering wind power uncertainty, and discuss the stochastic transient stability of the power system.

3. After adding damping to the system, the negative impact of wind power uncertainty is weakened, which makes the system run more stable.

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