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Improvement on probabilistic small-signal stability of power system with large-scale wind farm integration

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ABSTRACT

This paper studies probabilistic small-signal stability of power systems with wind farm integration, considering the stochastic uncertainty of system operating conditions. The distribution function of the real-part of system eigenvalue is computed by the method of probabilistic eigenvalue analysis. For improving probabilistic small-signal stability, PSS is adopted. A method for optimizing PSS based on participation factor and center frequency method is proposed. In order to evaluate the above proposed methods, the procedure is applied to a test system. The simulation results show that the stochastic variation of wind generation can induce a higher probability of system instability when compared with one that has no wind generation. With eigenvalues distributing in a wider range, it becomes difficult for PSS tuning. By applying the proposed optimized PSSs approach, probabilistic stability of system can be significantly improved.

Introduction

With the rapid development of wind power in China, impacts of large scale wind power penetration on power system stability have been paid more and more attention [1–4]. The random fluctuations of wind power output increase the uncertainty of the system, which will produce adverse effect on the system dynamic stability, especially the small-signal stability. It is meaningful to analyze power system small-signal stability with probabilistic methods considering the effects of uncertainty of wind power farm output and stochastic change of load. There are two kinds of methods to analyze small-signal probabilistic stability of power system with wind power penetration: one is based on the Monte Carlo simulation by which a large number of deterministic samples are generated by Monte Carlo sampling to calculate the probability of stability. This method is employed in [5,6]. Although the Monte Carlo simulation has accurate results, it is a time-demanding method because it requires computation of a large number of deterministic samples. The other one is the numerical analysis method. The probabilistic characteristics of eigenvalues are obtained by a formula to determine the probability of stability which is used only in Refs. [7,8]. The method requires complex formula derivation, but only one step of calculation to obtain the probabilistic distribution of system eigenvalues. In [7,8], Gram–Charlier series and system eigenvalue sensitivity are applied to study the impact of wind power fluctuations on the small-signal probability stability of the system, and is used to verify the correctness of numerical analysis method. But the wind generation model established in [7,8] is a simple one, and only the output variation of wind farm is considered as system uncertainties. It is verified in [8] that the integration of wind farm would cause system probabilistic small-signal instability, but in their study, no measures are proposed to improve system probabilistic stability.

Based on the former studies [9–14], a probabilistic small-signal stability method is proposed in this paper by considering the stochastic variation of wind farm output, the fluctuation of load and the synchronous generator output. The complete DFIG transient model [15–17] is adopted. The probabilistic small-signal stability of power system with wind power integration is analyzed by numerical analysis method, and power system stabilizer (PSS) on synchronous generators is applied to improve the stability probability. The previous study on PSS [18,19] shows that the coordinated PSS can enhance the network damping. The PSS in this previous work is designed without considering the uncertainties of random wind power, generating and loading conditions. It may lose damping performance and fail to stabilize the system when operating condition changes. In order to adapt the PSS parameters in multi-operating conditions of power system, this

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paper presents an approach based on participation factors and center frequency method for PSS parameters tuning and coordination.

The paper is organized as follows. In 'PMT modeling technique', the Plug-in Modeling Technology (PMT) [20] is introduced to build the complete system model. In 'Probabilistic distribution of power system eigenvalues in multi-operating conditions', the expression of the probability distribution of system eigenvalues is obtained by the Gram–Charlier expansion method. In 'PSS parameter adjustment/setting based on the center frequency method', the center frequency method based on participation factors is proposed for adjusting the parameters of PSS for improving probabilistic small-signal stability. In 'Case study', an example of 4-machine 2-area power system with grid-connected wind power source is given. The proposed approach is applied to analyze and improve the probabilistic stability. The results of probabilistic stability analysis on the test system demonstrate that the small-signal stability of power system is indeed affected by the stochastic variation of grid-connected wind generation and can be improved by the proposed installation of PSS.

PMT modeling technique

PMT is adopted in this paper to construct state matrix of power system when analyzing small-signal stability of electric power system [9,12,20]. The whole model of the system is shown in Fig. 1.

In Fig. 1, each system component is modeled as a module with 4 pins of voltage and current, which can be conveniently plugged into the network module.

The models of synchronous generator units in [21,22], which contain the complete six-order generator model, including the excitation system and the prime mover model, are used to represent the general power plants in this paper. Complete transient models [15–17] of the Doubly Fed Induction Generator (DFIG), which is widely used in wind farm, are adopted. The whole model [15–17] of the doubly fed induction generator including wind turbine, two-mass shaft system, rotor-side converter and grid-side converter and their control system, and pitch angle control system for reflecting the effect of wind farm on power system are all included.

Probabilistic distribution of power system eigenvalues in multi-operating conditions

The eigenvalues of the state matrix $\boldsymbol{A}$ are used to determine the stability of the power system with respect to small disturbances. The eigenvalues are determined by the operating state given by each set of generation and load. Hence it should be noted that, as the operating state varies with respect to generation and load changes, the eigenvalues also vary.

Under multi-operating conditions, with loads and output of wind turbine generator and synchronous generators regarded as random variables which may possess any type of distribution, probabilistic methods are applied to load flow calculation and eigenvalue computation. The method based on Gram–Charlier expansion with a hybrid algorithm using moments and cumulates is employed to obtain the Probabilistic Density Function (PDF) of system critical eigenvalues.

For probabilistic load flow computation, all nodal voltages ($\boldsymbol{V}$) and nodal injections ($\boldsymbol{Y}$) are regarded as random variables. In an N-node system, $\boldsymbol{Y}$ can be expressed as a quadratic function.

$$\boldsymbol{Y} = \boldsymbol{f}(\boldsymbol{V}) = \boldsymbol{g}(\boldsymbol{V}_1\boldsymbol{V}_1, \ldots, \boldsymbol{V}_i\boldsymbol{V}_j, \ldots, \boldsymbol{V}_{2N}\boldsymbol{V}_{2N}) \tag{1}$$

With expansion at expectation point $\overline{V}$ using Taylor series, these equations can be represented as in Eq. (2).

$$\boldsymbol{Y} = \boldsymbol{f}(\overline{\boldsymbol{V}}) + \boldsymbol{J}_{\overline{\boldsymbol{V}}}\Delta\boldsymbol{V} + \boldsymbol{f}(\Delta\boldsymbol{V}) \tag{2}$$

where $\boldsymbol{J}_{\overline{\boldsymbol{V}}}$ is the Jacobin matrix at the expectation point $\boldsymbol{J}_{\overline{\boldsymbol{V}}} = \frac{\partial \boldsymbol{f}(\boldsymbol{V})}{\partial \boldsymbol{V}}\Big|_{\boldsymbol{V}=\overline{\boldsymbol{V}}}$

With $\boldsymbol{Y} = \bar{\boldsymbol{Y}} + \Delta\boldsymbol{Y}$, the expected value of Y is expressed as in Eq. (3).

$$\overline{\boldsymbol{Y}} = \boldsymbol{f}(\overline{\boldsymbol{V}}) + \overline{\boldsymbol{f}(\Delta\boldsymbol{V})} \tag{3}$$

where $\overline{f(\Delta\boldsymbol{V})} = g(\boldsymbol{C}_{\boldsymbol{V}_1,\boldsymbol{V}_1}, \ldots, \boldsymbol{C}_{\boldsymbol{V}_i,\boldsymbol{V}_J}, \ldots, \boldsymbol{C}_{\boldsymbol{V}_{2N},\boldsymbol{V}_{2N}})$, $\boldsymbol{C}_{\boldsymbol{V}_i,V_J}$ can be obtained by Eq. (4)

$$\boldsymbol{C}_{\boldsymbol{V}} = \boldsymbol{J}_{\overline{\boldsymbol{V}}}^{-1}\Big\{\boldsymbol{C}_{\boldsymbol{Y}} - E\Big[\boldsymbol{J}_{\overline{\boldsymbol{V}}}\Delta\boldsymbol{V}\boldsymbol{f}^{\boldsymbol{T}}\Delta(\boldsymbol{V}) + \boldsymbol{f}(\Delta\boldsymbol{V})\Delta\boldsymbol{V}^{\boldsymbol{T}}\boldsymbol{J}_{\overline{\boldsymbol{V}}}^{\boldsymbol{T}} + \boldsymbol{f}(\Delta\boldsymbol{V})\boldsymbol{f}^{T}(\Delta\boldsymbol{V})\Big] + \overline{\boldsymbol{f}(\Delta\boldsymbol{V})\boldsymbol{f}^{\boldsymbol{T}}(\Delta\boldsymbol{V})}\Big\}\left(\boldsymbol{J}_{\overline{\boldsymbol{V}}}^{-1}\right)^{T} \tag{4}$$

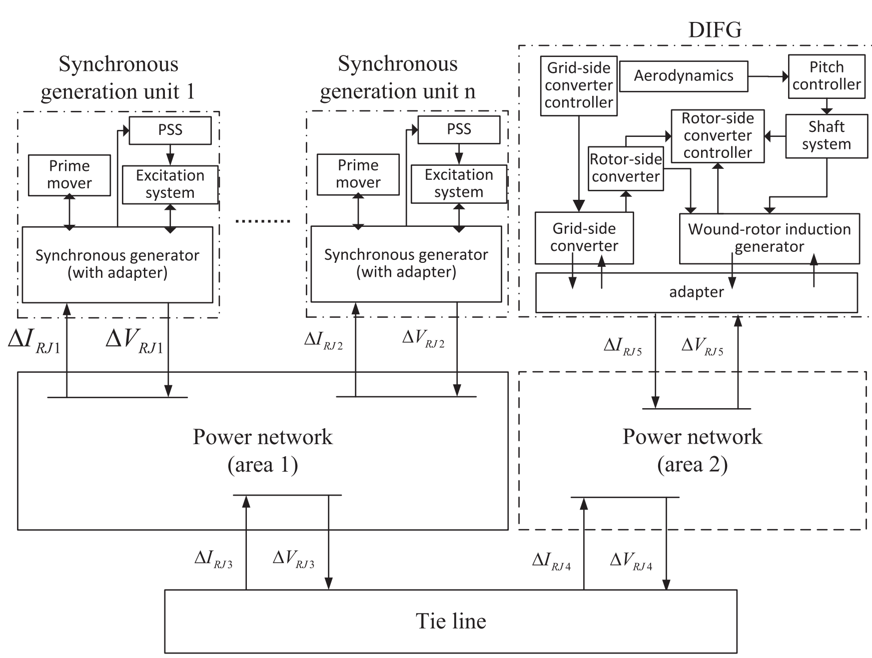

Fig. 1. The power system with DIFG in PMT.