Electric Power Systems Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Identification and improvement of probabilistic voltage instability modes of power system with wind power integration

Xiaoyan Bian[a], Yan Geng[a,*], Fangqi Yuan[b], Kwok L. Lo[c], Yang Fu[a]

[a] Department of Electrical Engineering, Shanghai University of Electric Power, Shanghai, People's Republic of China
[b] Changxing Electric Power Supply Company, Huzhou, Zhejiang, People's Republic of China
[c] Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow, Scotland, UK

ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form 24 May 2016
Accepted 13 June 2016
Available online xxx

Keywords:
Doubly-fed induction generator (DFIG)
Voltage stability correlation ratio
Voltage instability mode coefficient
Static VAR compensator (SVC)
Probabilistic voltage stability

ABSTRACT

A probabilistic-based approach is presented to identify and improve small-disturbance voltage stability of power systems incorporating a wind farm, taking into consideration the stochastic uncertainty of system loads, output of wind turbine generators and synchronous generators. The whole system model is based on plug-in modeling technology (PMT) with detailed representation of doubly-fed induction generator (DFIG) dynamic model. The probabilistic distribution of state-matrix eigenvalues is obtained for analyzing the small-disturbance stability of power systems. Voltage stability correlation ratio and voltage instability mode coefficient are proposed for identifying voltage modes and improving voltage stability. The proposed approach is tested on a three-machine system and a nine-machine system. The simulation results show that the approach can quantify the well-known observation that wind farm integration may increase the voltage instability of the power system. The stochastic variations can induce a higher probability of system instability when compared with the one that does not have wind generation. Besides, with wider eigenvalues distributing after the wind generation installation, it makes more difficult for stability improvement. In this paper, static VAR compensator (SVC) is installed at the weakest point which is determined by the voltage instability mode coefficient to improve the system probabilistic voltage stability. The final results validate the efficiency and feasibility of the proposed approach.

1. Introduction

With the rapid development of wind power, impacts of large-scale wind power generation on power system stability have received more and more attention [1–3]. The intermittency of wind power output increases the uncertainty of the system, and with an increased risk of system dynamic instability, especially the voltage stability. The traditional analysis of small-disturbance voltage stability is usually based on one operating condition. When system operating condition changes, especially when wind farm output varies with the natural speed of wind, the obtained results based on one operating state are not reliable any longer. Consequently this leads to the application of probabilistic methods to study the small-disturbance voltage stability.

When considering uncertainties, previous studies [4–8] are usually focused on probabilistic rotor angle stability. A few researchers [9–12] apply probabilistic methods to study voltage stability. In [9,10], an approach based on static voltage stability analysis method with load flow calculation is proposed, but without considering the dynamic feature of system. In [11,12], the state-matrix eigenvalue analysis method is employed to study the small-disturbance voltage stability, incorporating participation factor for identifying the critical converter bus of the system, and the work illustrates the effectiveness of the dynamic analysis approach.

Until recently, a few researchers apply the probabilistic methods to dynamic analysis of voltage stability [11,12]. One of the difficulties of this approach is the heavy mathematical demand of probability theory. Another difficulty is the identification of the voltage instability modes from the state-matrix eigenvalue analysis, especially with wind power integration. Currently, for identifying voltage instability modes [13,14], system state variables are divided into two groups: the former one is strongly related to voltage stability, and the latter one is strongly related to rotor angle stability. For mixed-generation power system with wind power integration, some additional state variables related to voltage modes are introduced, consequently the above simple method is not applicable any more. A novel approach is proposed in this study for identifying and improving voltage instability modes. In

* Corresponding author. Tel.: +86 18817892309.
E-mail address: gfx19891025@163.com (Y. Geng).

http://dx.doi.org/10.1016/j.epsr.2016.06.026

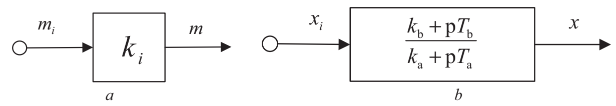

Fig. 1. Two types of elementary transfer block in PMT. (a) Zero-order block. (b) First-order block.

this paper, the voltage correlation matrix is built and based on it, voltage stability correlation ratio is obtained to determine the instability types of unstable modes, and the voltage instability mode coefficient is proposed to identify the weak points of voltage instability in a system.

Based on former work [4,5,8,15], the probabilistic approach is presented in this paper to study and improve the small-disturbance voltage stability, considering the uncertainties of system loads, the output of wind turbine generators and synchronous generators. This paper is organized as follows. In Section 2, Plug-in Modeling Technology (PMT) [16,17] is applied to build the whole system model with wind power integration, and by which the state matrix can be formed conveniently. In Section 3, the mean, variance and higher-order probabilistic numerical characteristics of nodal voltages can be obtained based on probabilistic power flow calculation, and the Gram-Charlier expansion-based method is employed to derive the probability density function (PDF) of system critical eigenvalues. In Section 4, voltage stability correlation ratio is derived based on the voltage correlation matrix, and the voltage instability mode coefficient is proposed to identify the system weak points. In Section 5, an example of three-machine twelve-bus power system with one grid-connected wind power source is presented. The operational data of loads and generators are obtained from daily operation curves, and wind farm operational curves are obtained from an actual wind farm recorded data. The probabilistic eigenvalues of system critical modes are obtained, and voltage instability modes and the weak points of voltage instability are identified by the proposed method. Finally, the static VAR compensator (SVC) is installed to improve the system probabilistic voltage stability. To validate the applicability of the proposed method, a larger and more complex power system with nine machines is employed to give a more strenuous test to the proposed approach, illustrated in Section 6. Some conclusions are provided in Section 7.

2. System modeling based on PMT

2.1. Plug-in modeling technology (PMT)

The Plug-in Modeling Technology (PMT) is suitable for modeling standard power system components, and an entire system is exclusively represented by two types of blocks and five types of parameters [16,17] as shown in Fig. 1, where m_i and m are the input and output vectors for the zero-order block in Fig. 1a, respectively, x_i and x are the input and output vectors for the first-order block in Fig. 1b, respectively.

The relationship between two types of blocks can be described by a connecting matrix $\boldsymbol{L}$ as (1),

$$\begin{bmatrix} \boldsymbol{X_i} \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{L}_1 & \boldsymbol{L}_2 \\ \boldsymbol{L}_3 & \boldsymbol{L}_4 \end{bmatrix} \begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{M} \end{bmatrix} \tag{1}$$

where $\boldsymbol{L}_1$–$\boldsymbol{L}_4$ are the submatrices.

In this paper, the model of multi-machine system with DFIG-based wind farm is formed by PMT which is very versatile as shown in Fig. 2. Any component modeled as a module with four pins of voltage and current can be conveniently plugged into the network module. Since the machine model, including synchronous generator and DFIG (with five pins), is described in its own d–q frame, and a transformation adapter (5-pin to 4-pin) between these two frame is required. Block models of control equipments, such as excitation system, governor system and PSS, can be amalgamated easily to the machine [16,17]. Other control devices, such as static VAR compensator (SVC), a shunt device of flexible alternative current transmission systems, can be easily plugged into the network as shown in Fig. 2, where ΔI_{RJi} and ΔV_{RJi} ($i = 1, \ldots, N$) represent the input and output variables connected to the network, respectively, $\boldsymbol{Y}_1$ and $\boldsymbol{Y}_2$ are the nodal admittance matrices of electricity network 1 and 2, respectively, m denotes the number of synchronous

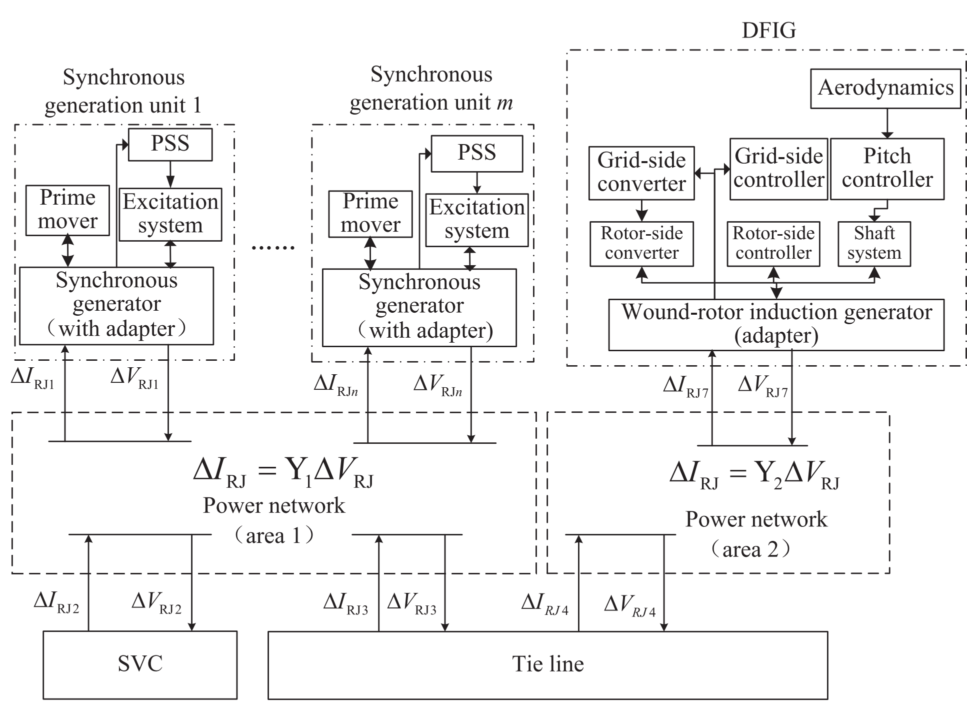

Fig. 2. Schematic diagram of the power system based on PMT.

Please cite this article in press as: X. Bian, et al., Identification and improvement of probabilistic voltage instability modes of power system with wind power integration, Electr. Power Syst. Res. (2016), http://dx.doi.org/10.1016/j.epsr.2016.06.026