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Security risk assessment using fast probabilistic power flow considering static power-frequency characteristics of power systems

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ABSTRACT

Large scale blackouts in the world have aroused the study of security risk assessment (SRA) urgently. SRA difficulties brought about by uncertainties can be solved by probabilistic power flow (PPF). Conventional methods usually focus on the probabilistic density function (PDF) and the cumulative distribution function (CDF) of node voltages and branch flows only. A SRA scheme of power system using fast PPF is proposed in this paper. The scheme took static power-frequency characteristics (SPFCs) into account, and fast decoupled power flow (FDPF) was used to solve PPF. Besides node voltage and branch flows, the scheme can obtain the PDF and CDF of frequency. The computing speed of the proposed scheme considering wind power multi-scenarios is enhanced compared to conventional method. SRA indices are introduced to evaluate the power system quantitatively. The examples on the IEEE RTS-24 system demonstrate the feasibility, rapidity and validity of the proposed scheme.

1. Introduction

Recent blackouts occurred around the world [1,2] have caused extensively serious social consequences and economic losses. With the gradually expanding of the power grid scale, and the increasingly complex of the operating conditions, it calls for the power grid to operate more stably and safely. With the shortage of primary energy, and environment pollution brought about by thermal power, the electricity industry worldwide is turning increasingly to clean and renewable energy to generate electricity. Wind power, due to its mature technology and relatively low cost, is the fastest growing and most widely utilized renewable energy in power system at present. However, the fluctuation and uncertainty of wind power both give rise to the increase in the uncertainty of the power system operation, posing greater challenges to the safe and stable operation. Besides, load forecasting error and changes in operating conditions are also factors of uncertainty. Therefore, it is of great importance and need to build a fast and accurate power system SRA tool to do online evaluations [3].

PPF is a statistical method which can take the uncertainties into account. By considering stochastic factors such as load variation and generator force outage, PPF provides an overall operating feature of the power system, which helps to discover potential risk and weakness of the operating conditions.

Analytical method and simulation method are main schemes for modeling and solving PPF. Monte Carlo simulation is one of the most straightforward methods to solve the PPF problem [4,5], however, it usually takes thousands of simulations to gain meaningful and accurate results, and the such long computing time consuming could not meet the requirement of real time online analysis. By applying linearization method and convolution calculation, analytical method can obtain the PDF and CDF of desired variables. Conventional recursive convolution calculation part is of large computational complexity, so some researchers have made improvement to reduce the computational burden. The combined cumulants and Gram–Charlier expansion method use the properties of statical moments and series expansion, which can significantly reduce the storage and computing time [6–8].

Ref. [9] establishes a procedure for calculating the load flow PDF of a power system taking into account the presence of wind power generation by means of DC power flow model, and it can only present the probabilistic descriptions of active power and angles of voltage vector. Ref. [10] considers the branch outages to simulate the changes of network structure, to analysis the static security risk of the power system. However, it requires repeatedly forming the sensitivity matrix to calculate the PPF of every contingency, because each run of the PPF needs recalculating the Jacobian matrix, which takes too much computational cost. FDPF linearization model can solve the problems above effectively. No doubt the FDPF model can provide the complete results of high accuracy. The principal point is that the triangular factorization of the

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admittance matrix remaining constant, which can be stored before the loop to avoid recalculation in the iterations as well as PPF calculation of every contingency.

Whereas frequency is one of the most significant indices of the power system to judge power quality, current PPF techniques only concern the probabilistic distribution of node voltages and branch flows, rarely about frequency [4–13]. The result of frequency can be obtained by power flow calculation when consider the effect of SPFCs of the power system. Thus, besides node voltages and branch flows, calculating the probabilistic distribution of frequency can presenting an integrated and comprehensive assessment of the power system, and figuring out the overall possible risks and weaknesses.

Due to the fluctuation and intermittence of wind power, the wind power output forecasting accuracy is far from adequate. Refs. [14,15] build Markov chain models of wind speed, to determine the most likely scenarios and the probability of each scenario via the wind speed state of the previous moment. Building wind power multi-scenario model and using complete probability method, can reasonably solve the linearization model inapplicable issue when the wind power fluctuates in a large scale.

The paper is structured as follows. In Section 2, an improved FDPF model and algorithm considering SPFCs is presented. Based on the wind power multi-scenarios, PPF combines cumulants and Gram–Charlier expansion method to obtain the PDF and the CDF of node voltages, branch flows as well as frequency is presented in Section 3. Section 4 outlines the SRA indices. Example results are shown in Section 5. A discussion about secondary frequency regulation and conclusion are summarized in Sections 6 and 7 respectively.

2. FDPF modeling considering SPFCs

2.1. SPFCs of the power system

When the active power balance of rated frequency (f_N) is destroyed, generators equipped with governor will regulate the outputs automatically, to maintain the power balance of the system. Primary frequency regulation characteristic of generator in steady-state can be presented by the equation below [16].

$$P_{Gi} = -K_{Gi}(f - f_{0i}) \quad \text{for } i = 1, 2, \ldots, g \tag{1}$$

where P_{Gi} is the active power output of the i-th generator, K_{Gi} is the SPFC coefficient of the i-th generator, f_{0i} is the no-load frequency, and g is the number of generators.

Active loads of the power system will change with frequency variation in steady-state operating. The SPFC of active load in steady-state can be expressed as:

$$P_{Di} = P_{DNi} + K_{Di}(f - f_N) \tag{2}$$

where P_{Di} and P_{DNi} are active power of the i-th bus with frequency of f and f_N respectively, K_{Di} is the SPFC coefficient of load on the i-th bus.

This paper is mainly focus on the steady-state of the power system, whereas the secondary frequency regulation is strongly linked to the temporal evolution of the system, which will not be discussed in this paper [17] (see Fig. 1).

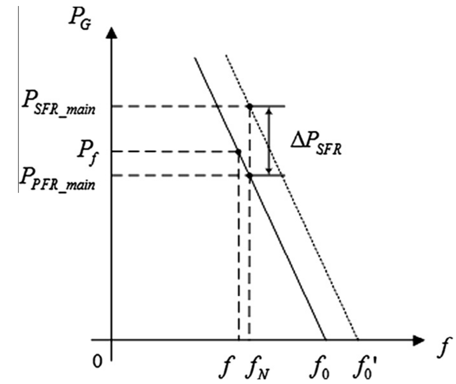

Fig. 1. Secondary frequency regulation process.

2.2. FDPF modeling considering SPFCs

For a power system of n buses including m PV buses, the node power equations can be presented as follows.

$$\begin{cases} P_i = V_i \sum_{j \in i} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ Q_i = V_i \sum_{j \in i} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{cases} \quad \text{for } i = 1, 2, \ldots, n \tag{3}$$

For all the buses,

$$\Delta P_i = P_{Gi} - P_{Di} - P_i = 0 \tag{4}$$

For PQ buses,

$$\Delta Q_i = Q_{Gi} - Q_{Di} - Q_i = 0 \tag{5}$$

where, P_{Gi} and P_{Di} can be calculated from Eqs. (1) and (2), Q_{Gi} is the reactive power output of the generator on the i-th bus, and Q_{Di} is reactive power load on the i-th bus.

Frequency, the added unknown variable, is primarily impacted by P but rarely by Q, for the reason that frequency is determined by generator speed that affected by P mostly. In consideration of these physical properties, assuming the n-th bus as the slack bus, the correction equations of FDPF algorithm can be written as:

$$\begin{bmatrix} \mathbf{\Delta P/V} \\ \Delta P_n/V_n \\ \mathbf{\Delta Q/V} \end{bmatrix} = -\begin{bmatrix} \mathbf{B}' & \mathbf{C} & \\ \mathbf{B}'_\mathbf{n} & C_n & \\ & & \mathbf{B}'' \end{bmatrix} \begin{bmatrix} \boldsymbol{\Delta\theta} \\ \Delta f \\ \mathbf{\Delta V} \end{bmatrix} \tag{6}$$

where $\mathbf{\Delta P}$, $\mathbf{\Delta Q}$, $\boldsymbol{\Delta\theta}$, $\mathbf{\Delta V}$, $\mathbf{V}$, $\mathbf{B}'$ and $\mathbf{B}''$ are the same as the significations in original FDPF algorithm. ΔP_n and V_n are the active power correction and voltage of the slack bus respectively. $\mathbf{B}'_\mathbf{n}$ is the imaginary part of mutual admittance between slack bus and the other buses. Substituting,

$$C_i = \frac{\partial \Delta P_i}{\partial f} = \begin{cases} -K_{Gi} - K_{Di} & \text{for generator buses} \\ -K_{Di} & \text{for load buses} \end{cases} \quad i = 1, 2, \ldots, n-1 \tag{7}$$

$$C_n = \frac{\partial \Delta P_n}{\partial f} = -K_{Gn} - K_{Dn} \tag{8}$$

Block solving (6),

$$\mathbf{V}^{-1}\mathbf{\Delta P} = -\mathbf{B}'\boldsymbol{\Delta\theta} - \mathbf{C}\Delta f \tag{9}$$

$$V_n^{-1}\Delta P_n = \mathbf{B}'_\mathbf{n}\mathbf{B}'^{-1}\mathbf{V}^{-1}\mathbf{\Delta P} - \left(V_n^{-1}C_n - \mathbf{B}'_\mathbf{n}\mathbf{B}'^{-1}\mathbf{C}\right)\Delta f \tag{10}$$

Rearranging from Eqs. (9) and (10),

$$\boldsymbol{\Delta\theta} = -\mathbf{B}'^{-1}\mathbf{V}^{-1}\mathbf{\Delta P} - \mathbf{B}'^{-1}\mathbf{C}\Delta f \tag{11}$$

$$\Delta f = -\frac{V_n^{-1}\Delta P_n - \mathbf{B}'_\mathbf{n}\mathbf{B}'^{-1}\mathbf{V}^{-1}\mathbf{\Delta P}}{V_n^{-1}C_n - \mathbf{B}'_\mathbf{n}\mathbf{B}'^{-1}\mathbf{C}} \tag{12}$$

Eqs. (11) and (12) are critical steps of solving the proposed model. $\mathbf{B}'$ remains invariably in the iterations, thus triangular factorization can be used to solve the correction equations, in order to reduce the amount of computation.