Electrical Power and Energy Systems 95 (2018) 96–107

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Probabilistic voltage stability assessment of distribution networks with wind generation using combined cumulants and maximum entropy method

Meghdad Tourandaz Kenari *, Mohammad Sadegh Sepasian, Mehrdad Setayesh Nazar

Department of Electrical Engineering, Shahid Beheshti University, A.C., Tehran, Iran

A R T I C L E   I N F O

Article history:
Received 24 July 2016
Received in revised form 29 June 2017
Accepted 6 August 2017

Keywords:
Cumulant
Probabilistic load flow
Radial distribution network
Voltage dependent load
Voltage stability
Wind power

A B S T R A C T

From the voltage stability viewpoint, a proper probabilistic analysis of the active distribution networks is essential for distribution system operator to identify and rank the weak buses of system. This paper introduces a probabilistic voltage stability index (VSI) to study the local stability of radial distribution networks including wind generation uncertainty. This index can identify the most sensitive bus to the voltage collapse. The proposed model combines the cumulants with the maximum entropy technique based on a backward/forward sweep technique. The suggested method evaluates not only the voltage magnitude, but also the voltage stability condition of each node in a probabilistic manner. Furthermore, the uncertainties of distributed generation and load demand are taken into account by this index. The proposed methodology is applied to IEEE 33-bus and 69-bus distribution test systems, and the results are interpreted. Four scenarios are studied to assess the impacts of substation voltage changes and different probability density functions of load on the distribution functions of voltage and VSI. Moreover, the effects of voltage dependent load model on the probabilistic VSI are studied. The results of different case studies have demonstrated that the proposed approach is fast and accurate.

1. Introduction

Nowadays, the distribution systems are operated close to their thermal and stability limits, due to the economic and environmental constraints. In the active distribution networks (ADNs), various uncertainties are imposed by the integration of renewable energy resources and new stochastic loads, such as electric vehicles. In such conditions, the evaluation of voltage stability has attracted more attention than ever before. Simultaneously, the importance of probabilistic analysis tools in ADNs has been increased. Therefore, a suitable voltage stability index (VSI) can obtain more accurate insight into the system stability margins.

Some researchers have paid attention to the static voltage stability studies in the distribution systems [1]. The impact of integrating wind-driven squirrel cage induction generator-based distributed generator (DG) on the static voltage stability of radial distribution network (RDN) has been studied in [2]. Ref. [3] has solved the problem of static voltage stability optimization in a distribution system with DG using continuation power flow (CPF). Moreover, in [4], a continuation method is employed to study the voltage stability of distribution system. The CPF allows the determination of the maximum loading point of distribution systems. However, the computational burden of CPF is high because of the update of Jacobian matrix for predictor and corrector steps [5]. Furthermore, because of high R/X ratio in distribution systems, the Jacobian matrix in such systems will be ill-conditioned close to the maximum loading point [5]. Therefore, the CPF methods based on the Newton–Raphson (NR) technique are mostly unstable for distribution systems. In [5], a method is presented to assess the voltage stability of RDNs based on the secant predictor. Gubina and Strmcnik [6] have proposed an approach for the voltage stability assessment in radial networks. Nevertheless, the proposed model is valid only at the operating point [7].

The researchers have proposed various static VSIs to identify the critical buses and lines of distribution systems. Steady-state VSIs can be classified into two types [8]: local indices and system indices. The system indices estimate the voltage stability margin of system. The system load margin indices are generally proposed based on the optimization methods or CPF. On the other hand, the local indices measure the stability margin of each bus or branch, and thereby the system critical bus or branch can be identified. Paper [9] has proposed different local branch-based indices.

---

* Corresponding author.
E-mail addresses: m_tourandaz@sbu.ac.ir (M. Tourandaz Kenari), m_sepasian@sbu.ac.ir (M.S. Sepasian), m_setayesh@sbu.ac.ir (M. Setayesh Nazar).

http://dx.doi.org/10.1016/j.ijepes.2017.08.011
0142-0615/

However, they have some errors in the theoretical derivations [10]. Chakravorty and Das [7] have proposed a VSI for all nodes of RDNs. In this method, the node with minimum value of VSI is the most sensitive node to the voltage collapse. In [11], a VSI is proposed for finding the most sensitive node to the voltage collapse in RDN. The study is based on the catastrophe theory.

Although several studies have focused on the deterministic analysis of voltage stability in distribution networks, very few works have considered the uncertainty of loads and DGs using probabilistic approaches. Accordingly, the main contribution of this paper lies in introducing a probabilistic VSI to identify the critical buses of distribution network taking into account the uncertainties associated with the load demand and wind power. Furthermore, a cumulant-based method is developed for probabilistic assessment of voltage, based on the backward/forward sweep (BFS) technique. Moreover, the impacts of gamma distribution (GD) for load demand, voltage dependent model for load, and voltage of slack bus on the proposed VSI have been studied.

The rest of the paper is organized as follows: in Section 2, the computational procedure of solution technique using combined cumulants and maximum entropy (CCME) approach is introduced. Next, the linearization technique of load flow (LF) formulation is explained in Section 3. Section 4 introduces the proposed probabilistic VSI. The probabilistic model for solving the problem is presented in Section 5. Section 6 describes the probabilistic models of wind turbine (WT) and load. In Section 7, the method is applied to the IEEE 33-bus and 69-bus distribution systems in four scenarios, and the results are discussed. Finally, the conclusions are presented in Section 8.

2. Structure of proposed problem

In this section, a solution procedure is proposed for probabilistic assessment of voltage and VSI in RDNs as follows:

Step 1: Import all the required data, including the network parameters, the probability density functions (PDFs) of load and wind speed (WS).
Step 2: Derive the wind power density function using the Weibull PDF of WS and the active power curve of WT.
Step 3: Compute the cumulants of input random variables (RVs) using statistical properties.
Step 4: Calculate the expected values (EVs) of output RVs using the BFS load flow, considering the mean values of input RVs.
Step 5: From the cumulants of input variables, calculate the cumulants of voltages and VSIs.
Step 6: Obtain the cumulative distribution function (CDF) and PDF of output RVs, and determine the weak nodes of network.

3. Radial distribution load flow

Radial distribution networks are ill-conditioned because of some particular features such as high R/X ratio, unbalanced loads, radial structure, and distributed generation. These factors may cause the convergence problem in the LF solution when the conventional NR method is used. Therefore, various methods are proposed for solving LF in an RDN. These methods are briefed as follows: (1) BFS technique, including power summation methods [12], current summation methods [13], and admittance summation methods [14]; (2) Gauss implicit Z-matrix method [15]; (3) modified NR or Newton like method [16]; (4) compensation-based technique [17]; (5) direct-approach technique like the bus-injection to branch-current matrix (BIBC) and the branch-current to bus-voltage (BCBV) matrix method [18]; (6) loop impedance matrix method [19].

3.1. BFS method using power summation technique

In this paper, BFS algorithm using power summation technique is used for probabilistic load flow (PLF) solution. In the backward sweep, the equivalent power for each branch is obtained by the summation of downstream powers of every branch:

$$S_n = S_j + S_{loss_n} + \sum_{m\in M} S_m, \tag{1}$$

where S_n is the power of branch n, j denotes the ending bus of branch n, S_j represents the demanded power of the connected load at the node j, S_{loss_n} is the power loss of branch n, M denotes the set of branches which are connected to the node j, and S_m represents the power of branch m.

In the forward sweep, from the slack bus toward the ending bus, current of branch n, J_n, will be calculated:

$$J_n = \left(\frac{S_n}{V_i}\right)^*, \tag{2}$$

where V_i denotes the voltage of sending node of branch n. After that, the voltage of each node must be updated:

$$V_j = V_i - Z_n \times J_n, \tag{3}$$

where Z_n represents the series impedance of branch n. The power loss of each branch can be calculated by:

$$S_{loss_n} = (V_i - V_j) \times J_n^*. \tag{4}$$

By calculating all the real and reactive power errors, the maximum errors at the network branches in the kth iteration may be used as the convergence criterion as the following:

$$\begin{aligned} \Delta P_l^k &= \mathrm{Re}|S_l^k - S_l^{k-1}|, \quad l = 1,2,\ldots,L, \\ \Delta Q_l^k &= \mathrm{Im}|S_l^k - S_l^{k-1}|, \quad l = 1,2,\ldots,L, \end{aligned} \tag{5}$$

where L is the total number of branches. As an alternative, the maximum voltage magnitude mismatch can be used as the convergence criterion:

$$\Delta V_r^k = \left|\left|V_r^k\right| - \left|V_r^{k-1}\right|\right|, \quad r = 1,2,\ldots,R, \tag{6}$$

where R is the total number of nodes.

To incorporate the wind DG units in this LF model, a PQ node can be considered for DG. In this model, WT treats as a negative PQ load. Similarly, PV model can be considered for DG node [20,21].

3.2. Linear model of radial LF

In the PLF problem, the nodal active and reactive power injections are expressed by their PDFs. Therefore, in order to obtain the PDFs or CDFs of voltage, power loss, and line flow, the LF equations must be linearized around the expected operating values. These expected points are obtained by performing a deterministic load flow (DLF). To achieve the linearization model, the unknown variables are represented as linear equations of the nodal injections. After that, the cumulant-based technique is employed to calculate the probability distribution functions of outputs.

To illustrate the concept of the linearization technique, let Z be the multiplication of two independent RVs, X and Y. These RVs can be rewritten around their expected points (X_o and Y_o) as follows:

$$X = X_o + \Delta X, \tag{7}$$

$$Y = Y_o + \Delta Y, \tag{8}$$

where ΔX and ΔY are the deviations of X and Y about X_o and Y_o, respectively. Neglecting the second-order term, Z can be stated as Eq. (9):