Electrical Power and Energy Systems 41 (2012) 27–33

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

Probabilistic load flow for voltage assessment in radial systems with wind power

W.C. Briceno Vicente *, R. Caire, N. Hadjsaid

Grenoble Electrical Engineering Laboratory, G2ELAB, Domaine Universitaire, BP 46, 38402 Saint Martin d'Heres Cedex, France

ARTICLE INFO

Article history:
Received 28 July 2011
Received in revised form 2 February 2012
Accepted 5 February 2012
Available online 20 March 2012

Keywords:
Distribution functions
Distributed power generation
Load flow
Monte-Carlo simulation
Power distribution
Power generation

ABSTRACT

Exploitation of renewable energy sources in power networks, especially wind energy, is considered an alternative for power generation as a non-polluting source with a low environmental impact and low operational cost. Hence, renewable energy has motivated the increment of penetration of Distributed Generation (DG) in distribution networks and the development of methodologies to evaluate their effects in the electrical system, which is characterized by uncertainties at all levels (generation, network and load). In this paper, a new analytical approach is explored to formulate and solve the Probabilistic Load Flow (PLF), which shows the voltage profile of a network including uncertainties of power injections and consumption. This approach is based on the linearization of load flow (LF) equations for Radial Distribution Systems (RDSs) using the probabilistic arithmetical laws. The solution is compared to Monte-Carlo Simulation (MCS), which is the most common simulation used to solve the PLF problem.

1. Introduction

At the present time, wind power is one of the fastest developing renewable energy resource in the world. The supplied power takes advantage of wind energy, which happens to be highly unpredictable (as a result of the changeable nature of weather conditions). The increase of wind power penetration has motivated the need to develop widely applicable methods to evaluate their impact in power systems. The biggest challenge is the uncertainty associated to wind power and the way to take it into account in assessment approaches.

Moreover, power systems involve different types of loads, which vary with time, as customer power requirements are not constant. Despite advances in forecasting methods, load variations continue to be characterized by a range of uncertainties. In order to deal with these load uncertainties in LF problem, many PLF methods have been proposed in the literature [5,7,10]. These methods are mainly emphasized on the transmission system, as before the event of DG, generation was principally included into the high voltage level of power system. Presently, there are few documents aiming for PLF solutions for distribution system [24,5].

Classical LF is the basis for the static analysis of any power system, as it is used for planning, operation and performance assessment. Classical LF is based on a deterministic load flow (DLF) that assumes that power injections, power consumptions, network parameters and topology are specified and do not change during the computation [24].

It is noteworthy that PLF requires state variable inputs to be modeled by a probabilistic density function (PDF), given that wind speed and load are modeled as Random Variables (RVs) due to their random behavior. PLF results allow a wide analysis of all the possible states of power system's state variables and their probability of occurrence, instead of a unique state obtained from DLF that uses deterministic values.

A first proposal of PLF was made in the 1970s [5], and has been further developed and applied for power systems under normal operation, short-term, and long-term planning [7]. PLF can be solved numerically, e.g. MCS method; analytically, e.g. convolution method, or even with a combination of both [10,13,16]. Another similar technique of stochastic load flow (SLF) developed in [4] assumes that system state variables can be modeled as normal distributions, which simplifies calculus complexity.

Presently, PLF is suitable to cope with issues associated with modern power systems, such as distribution systems integrated with a large amount of DG. PLF techniques are mainly based on the linearization of LF equations, network outages and interdependence among nodal power injections. Nevertheless, uncertainty of power production, non-Gaussian PDF and the clear dependence among variables originated methods such as: cumulants and Cornish–Fisher expansion in [23], and Gram–Charlie series in [22]. Those methods make use of the properties of statical moments and series expansions.

Other way to deal with uncertainties is using possibilistic load flow in [14] is based on fuzzy numbers. The uncertainty of input parameters is modeled as fuzzy distributions according to

* Corresponding author.
E-mail addresses: wendy.briceno-vicente@g2elab.grenoble-inp.fr (W.C. Briceno Vicente), raphael.caire@g2elab.grenoble-inp.fr (R. Caire), nouredine.hadjsaid@g2elab.grenoble-inp.fr (N. Hadjsaid).

0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijepes.2012.02.014

Nomenclature

CDF	cumulative distribution function
DLF	deterministic load flow
LF	load flow
MCS	Monte-Carlo Simulation
PEM	point estimated method
PDF	probabilistic density function
RDS	radial distribution system
RV	random variable
WT	wind turbine

membership functions of each parameter. Mathematical operations used in load flow must be adapted to fuzzy arithmetic laws. It is possible to relate possibilistic to probabilistic results.

In this paper, a new radial distribution PLF method that takes into account load and wind generation variations is proposed. This approach is based on an analytic formulation of voltage drop, which is obtained from Fresnel triangle for RDS where loads are mainly of PQ type (constant active and reactive power). Voltage profile is deduced from the application of arithmetic operations among RV variables using convolution techniques. This method is applied on the IEEE 28-bus radial system [15] and the results are validated and compared to the MCS solution.

2. Probabilistic load flow

The PLF can be performed using either a numerical or an analytical approach [7]. A numerical approach, e.g. the MCS method, substitutes a chosen number of the system parameters and handles them as RVs in order to perform a deterministic analysis. An analytical approach analyzes a system and its inputs using the exact mathematical expressions of RVs, e.g. PDFs and obtains its results in terms of mathematical expressions.

2.1. Analytical approach

The basic idea of analytical approach is to apply the arithmetic of RVs. It models power system states variables as PDFs and solves LF problem using convolution techniques. However, the difficulties of solving PLF equations by the convolution of PDFs input variables are twofold [7,4,2]:

i. LF equations are non-linear.
ii. Input power variables at different buses are usually not completely independent or linear-correlated.

Therefore, some assumptions are usually made in order to easily perform PLF using an analytical approach, such as [3]:

i. Linearization of LF equations.
ii. Total independent or linear-correlated power variables.
iii. Normal distribution and discrete distribution are usually assumed for load and generation, respectively.
iv. Network configuration and parameters are constant.

The decision, whether to use the MCS method or the analytical method, is a trade-off between time consumption and accuracy.

2.2. Point estimation approach

Point-estimate method (PEM) is another analytical approach which uses RV statistical moments that are tuned in the PDFs and their cumulants. Thus, statistical moments are evaluated in nonlinear power LF equations, which requires less computations and derives the convolution equations involved in RV arithmetic. Hence, PEM could provide a detailed modeling of the relationship between LF solution variations and uncertain input parameters [20], and consequently accurate and efficient results. Then, results obtained by this method require to integer moments to reconstruct and find the PDFs of RVs. PEM has been used in unbalanced PLF studies with correlated and non-correlated RVs in [6].

2.3. Expansion series

According to PEM, it is possible to obtain the PDF, or CDF of a random variable, if its moments, or cumulants are known. One proposal of PEM develops RVs as Gram–Charlier series [23] and proposes the expansion of a normal $N(0,1)$ distribution in terms of Tchebycheff–Hermite polynomials, which allows cumulants calculus. Another proposal of PEM is by Cornish–Fisher expansion series [22] related to the Gram–Charlier series. It solves DC load flow obtaining the mean value (first moment) and calculates to fourth order moments and cumulant of RVs.

2.4. Monte-Carlo simulation

One of the numerical approaches for PLF analysis is the Monte-Carlo Simulation (MCS) method. The two main features about MCS is random number generation and random sampling [7]. This method uses the exact non-linear LF equations; hence results of PLF by this technique can be used as reference values for other PLF approaches [3]. In order to get a high degree of accuracy, the MCS method requires large amount of LF computations, which can be very time consuming, depending on the computational power. The MCS methods are unpractical for real-time simulations, but for short term analysis such as one day ahead, they are usually appropriate, depending on the size of the power system.

3. Load model

Load is highly dependent on human activities, and temporal factors such as time of the day, day of the week or season of the year. Consequently, load varies continually with a high degree of uncertainty. In probability theory, load uncertainty can be adjusted by PDFs, which fit its behavior.

Several RVs have been used to model electrical loads behavior, for instance: uniform PDF, Weibull PDF [11], normal PDF [19], log-normal PDF [19] and beta PDF [12,17].

3.1. Normal load

Power load consumption (P_L) is assumed as a normal $N(\mu,\sigma)$ distribution [3], characterized by mean value (μ) and standard deviation (σ) of the power consumed. Normal distribution is a symmetric function around mean value, hence it considers a maximal value of load, instead of considering the two daily load peaks. Thus, due to properties of normal distribution, variations of load around mean value have the highest probabilities of occurrence, such as: $N(\mu \pm \sigma) = 64.2\%$ and $N(\mu \pm 2*\sigma) = 95.4\%$.