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Probabilistic load flow incorporating correlation between time-varying electricity demand and renewable power generation

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ABSTRACT

The time-varying demand and stochastic power generation from renewable distributed generating resources necessitate an exhaustive assessment of distribution feeder parameters for the purpose of long-term planning. This paper proposes a novel formulation of probabilistic load flow for distribution feeders with high penetration of renewable distributed generation. The dependency between the load demand of different consumer classes and generation from different types of renewable resources is addressed in this study. In order to capture the coincidental variations of demand and generation, associated time series data for the same time instances are used. A transformation matrix based probabilistic load flow is formulated using the method of cumulants. Moreover, Pearson distribution functions are used to estimate the probability distribution of the line flows. The proposed load flow method is tested on a practical distribution feeder with high penetration of solar photovoltaic and wind energy conversion systems. The results demonstrate the aptitude of the proposed method for conducting probabilistic load flow studies with dependent non-Gaussian distribution of load and generation.

1. Introduction

The increased concerns about clean energy generation and effective utilisation of distributed resources are accelerating the growth of renewable distributed generation (DG) into distribution networks. The growing trend of renewable DG requires the consideration of bidirectional power flow in a typical distribution feeder. Uncertainty associated with power injection from renewable resources and time varying load demands introduce abrupt variations in the power flows throughout the feeder. Probabilistic load flow (PLF) can be used to determine the amount of certainty in various network parameters obtained using sequential power flow solutions. Despite of uncertainties associated with variations in demand and generation, certain level of dependency exists between these quantities [1]. In order to evaluate the network parameters, both the uncertainty and the dependency among the varying quantities should be considered. A PLF solution, that can address the variations in the network parameters such as line flows, can aid in distribution feeder planning and operation with renewable DG units.

PLF is first proposed by Borkowska in 1974 [2]. In Ref. [3], convolution of the probability density functions (PDFs) of nodal powers is applied in DC load flow to compute the PDF of line flows for the network. Fast Fourier Transformation technique is used for computing the convolution between the density functions. In Ref. [4], point estimation method is used for PLF solution. For this method, $2m$ load flow calculations are required to solve the PLF with m number of uncertainties of the network components. It has been reported in Ref. [5] that the point estimation method is computationally complex for multivariate distribution of the nodal power injections. PLF solution for a distribution feeder is presented in Ref. [6] using Monte Carlo Simulation (MCS) based technique. Cumulants method is proposed in Ref. [7] to compute the reliability index of the electricity network and Laguerre series is used to estimate the PDF of load and generation. A comparative study on the performance of the series estimation with different numbers of cumulants is also presented in Ref. [7]. In Ref. [8], the method of moments is used for PLF calculation involving transmission network congestion. The Gram–Charlier series expansion is used to estimate the probability distribution of the line flows. In Ref. [5], Cornish–Fisher expansion series is used to estimate the probability distribution of line flows using short term forecasting data. Combined point estimation and cumulants method are used to evaluate the moments and cumulants of the line flows.

The determination of state variables for an electricity network with renewable resources demands for the consideration of stochastic generation patterns in the PLF formulation. In Ref. [6], the

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PLF is developed for a distribution feeder with solar photovoltaic (PV) based generation. In Refs. [9,10], wind generation is considered in the PLF to estimate the line flows of the transmission network.

The dependency between the demand and the renewable power generation must be considered in the PLF solution. In Ref. [11], linear dependency among the demands at different nodes is considered in the PLF. Linear dependency between the active and reactive power is also considered in this MCS based PLF solution. In Ref. [5], the correlation among the generation levels of different wind farms is considered in the PLF formulation. The correlation among the load demands at different nodes is also considered separately in this study. In Ref. [12], the correlation among the power outputs of different photovoltaic DG units in a distribution feeder is considered for PLF solution. It is noted that the correlation between generation and the demand is not considered in the studies reported in Refs. [5,9,12].

Dependent random number generation presented in Refs. [5,12] is developed based on the generation of the multivariate normal random numbers with a given correlation coefficient matrix. Afterwards, the multivariate normal random numbers are transformed into uniformly distributed random numbers and followed by the transformation to the actual distributed random numbers of the desired distribution. As a result, the individual random variables generated using this process show the respective distributions for their marginal distributions. However, the dependency among the multivariate random numbers remains same as the normal multivariate random numbers. An impact of this consequence can be found in the third cross central moments of the random numbers. Since the third order cross central moments of the multivariate normally distributed random numbers are zero, the third order cross central moments of the random variables generated using the procedures described in Refs. [5,12] are found to be zero. In real case, the dependency among the random variables may not follow the normal distribution [13].

From different studies reported in the literature on the PLF solution using the method of moments, it is observed that the procedures involved in PLF solution can be divided into four steps, as shown in Fig. 1, namely uncertainty modelling of the random variables, generation of the moments and cumulants of the random variables, computation of the cumulants of the dependent random variables, and estimation of the probability distribution of the dependent random variables. In many PLF studies, the Taylor series approximation is used for estimating the probability distribution of the dependent random variables. With the series expansion methods such as Gram–Charlier series, Edgeworth series and Cornish–Fisher series, normal density function is used as the base function. Although these series expansions show satisfactory performance for the Gaussian or near-Gaussian distributions, non-Gaussian distributions cannot be accurately estimated using these series expansions [14]. Since, the load demand typically follows Gaussian distribution; series approximation can be suitable for PLF solution of the electric network with low penetration of renewable energy resources. The probability distributions of the generated power from different types of renewable DG systems are usually non-Gaussian. The non-Gaussian components dominate the probability distributions of the line flows when the renewable DG penetration is high. For this reason, new methodology is required for obtaining PLF solution of a distribution feeder with high penetration of the renewable DG units. The load demand in the distribution feeder and the power from renewable DG systems may be affected by weather conditions, seasonal variations and human activities. It is envisaged that there could be a dependency between the time varying load demand and stochastic generation from renewable DG systems, which needs to be accounted while obtaining a PLF solution.

Analytical methods for probabilistic analysis of power systems are widely used since those are less computationally intensive with acceptable accuracy and can provide greater insight on the influencing attributes related to the power system operation. On the other hand, Monte Carlo simulations (MCS) techniques are preferred for complex system analysis where it is difficult to model the large number of variables. Sequential MCS technique uses transition probabilities between the component states to sample the chronological order of random variables. Hence, sequential MCS technique can include the correlation between random variables and considered as a standard methodology for benchmarking results obtained from analytical methods. Non-sequential MCS technique uses random sampling from the probability distributions of the variables and it exhibits fast convergence characteristics and simplicity compared to time sequential MCS technique [15]. However, non-sequential MCS technique requires additional computational efforts to establish correlation between random variables. Also, it is to be noted that the non-sequential MCS technique demands for high computation time and lacks accuracy in estimating PDF and cumulative distribution function (CDF) of the network parameters as compared to the proposed method.

Load duration method (LDM), linear regression method and non-linear regression method are used for non-sequential MCS in Ref. [16] to incorporate the correlation between demand and solar photovoltaic (PV) generation. Latin hypercube sampling technique has been applied for random sampling of non-sequential MCS technique in Ref. [17] to account the correlation between demand and wind generation. In Ref. [18], data clustering technique, aggregated Markov model, LDM and pseudo-chronological method are used in non-sequential MCS technique to incorporate the dependency between demand, generation outage and scheduled maintenance for reliability study of power systems. A detailed comparison between these methods and with sequential MCS technique is also presented in Ref. [18].

This paper proposes a new methodology to solve PLF for a distribution feeder with high penetration of renewable DG units. The dependency between the load demands of different consumer classes and generation from different types of renewable resources is also addressed in this study. In order to capture the coincidental variations, time series data of the demand and generation for the same time instance are used to evaluate cross moments and cumulants. The sufficiently long length of the time series data has been considered to include the seasonal variations in the demand and generation. A transformation matrix based probabilistic load flow is formulated and used for obtaining a PLF solution. Pearson distribution functions are used to estimate the probability distribution of the line flows. The proposed method is tested on a practical distribution feeder with high penetration of renewable DG units.

The paper is organised as follows. In Section 2, the uncertainty modelling of demand and generation, and transformation matrix

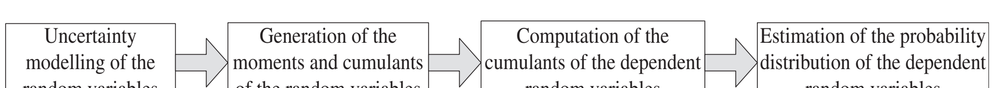

Fig. 1. Steps involved in PLF based on method of moments.