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Multi-linear Monte Carlo simulation method for probabilistic load flow of distribution systems with wind and photovoltaic generation systems

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ABSTRACT

In this paper, a probabilistic method is proposed to analyze the steady-state operating conditions of an active electrical distribution system with Wind (WD) and Photovoltaic (PV) generation plants. This method takes into account the uncertainties of power load demands and power production from renewable generation systems and combines Monte Carlo simulation techniques and multi-linearized power flow equations. The power flow equations include models of wind turbine and PV generation units and multi-linearization is accomplished by applying a criterion based on the total active power of the system. The method properly extends a probabilistic method proposed in the relevant literature for traditional passive electrical distribution systems to the field of an active electrical distribution system with WD and PV generation units. Numerical applications are presented and discussed with reference to a 17-bus test distribution system characterized by WD and PV systems connected at different busbars. The results obtained with the proposed algorithm are compared with the results obtained using a Monte Carlo simulation algorithm that included non-linear power flow equations.

1. Introduction

Economic, technological, and environmental incentives are changing our approach to developing and using electricity generation and transmission/distribution systems. In this context, centralized generating facilities are giving way to smaller, more distributed generation, due in part to the loss of traditional economies of scale [1].

In particular, the characteristics of electrical distribution systems have been modified significantly due to the presence of more and more photovoltaic (PV) and wind (WD) generation units. However, these renewable resources pose many challenges for grids and their operators. Distribution systems, in fact, have been designed traditionally with the assumption of a passive network, but networks have become active, thereby generating several new technical considerations that must be addressed involving steady-state and transient issues. This paper is focused on the steady-state issues.

The problems of understanding and quantifying the technical impacts that a significant penetration of PV and WD generation units may have on the steady-state operation of a distribution system have been addressed extensively in the relevant literature [2–5], and several publications have paid extensive attention to the analysis of load flow at the power frequency of these systems.

In performing the analysis of the load flow of an active network, one should take into account that unavoidable uncertainties affect the input data of operating conditions. Traditional cases of uncertainties are the time variations of load demands and network configurations. Now, WD and PV generation units are introducing new and significant causes of uncertainties due to the random nature of wind speed and solar radiation, both of which depend on the weather. In such a case, probabilistic approaches are mandatory.

The importance of the probabilistic approaches is based on the fact that long- and medium-term system planning and the short-term operation (i.e., one day ahead operation) of electrical distribution systems are affected significantly by the uncertainties

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associated with generating electricity using wind and solar energy. Thus, as the market penetration of WD and PV plants increases, the uncertainties associated with the operation and management of power systems also will increase. This indicates a need for adequate probabilistic tools for long-term and daily operation of power systems that may provide important advantages as a less expensive network in power planning and better management of congestion in power operating systems.

In addition, problems in distribution systems with WD and PV farms, such as undervoltages and overvoltages, are well known. Due to the risk of incurring damage to the system's components, it is especially important to avoid the overvoltages that can occur in the case of low loads and high wind/solar energy production. Using deterministic load flow analyses to ascertain such conditions can be inadequate, because these analyses should be conducted for some specific load or wind/solar energy production conditions, neither of which is always easy to identify [6]. Thus, correctly assessing the wind and PV generators in distribution systems requires the use of probabilistic load flow [6,7].

Several approaches have been presented in the relevant literature focused on probabilistic load flows that included WD and PV generators [6,8–23]. The main approaches were:

- non-linear Monte Carlo simulation;
- linear Monte Carlo simulation;
- convolution-based approach;
- Markov-based approach;
- Universal Generating Function-based approach;
- Bayesian-based approach;
- Special Distributions-based approach; and
- hybrid approaches.

The non-linear procedure consisted of solving the load flow equations several times, each time assuming as input data one set of input random variables generated according to their assigned probability density functions. The linear Monte Carlo simulation uses the Monte Carlo approach either for a non-linear equation system linearized around the expected value region or to the DC load-flow equations. The convolution approach requires that a linear form of the load flow equations be obtained first, and then the convolution process is applied. The Markov-based approach is based on the assumption that the input random variables, such as the wind speed, can be considered as a stochastic process modeled approximately by using the discrete Markov process (Markov's chains). The Universal Generating Function-based approach models the wind farms as multi-state systems, the probability distribution of which were determined by the Universal Generating Functions technique. In the Bayesian theory-based method, the Bayesian inference is used to predict the probability density function of the hourly active power generated by PV/Wind systems. The special distributions-based approach consists of approximating the probability density functions of the output random variables of interest with probability density functions for which analytical expressions are univocally determined once only some moments or cumulants of the pdfs to be approximated are known. Hybrid approaches properly combine the base-techniques. Numerical comparisons and a depth analysis of all methods were reported in Ref. [8].

Even though all the above probabilistic modeling approaches for load flow analysis of electrical distribution systems that include WD and PV generators have been proposed and discussed in the relevant literature [6,8–23], the approaches based on non-linear or linear Monte Carlo simulations seem particularly attractive and were among the most-extensively applied.

However, non-linear Monte Carlo simulations can require high computational efforts to obtain highly accurate results, whereas the linear Monte Carlo simulation requires reduced computational efforts. However, it can be affected by significant errors in the presence of high non-linearity, when the load probability density functions (pdfs) are multimodal (i.e., bimodal) and in presence of high correlations among the random input variables [24].

To overcome the inaccuracies of the linear Monte Carlo simulation while reducing the need for excessive computational efforts, a probabilistic load flow was proposed in Ref. [25] for passive balanced systems, combining Monte Carlo simulation techniques and multi-linearized power flow equations; the multi-linearization algorithm uses a criterion based on the total load of the system to determine different linearization points. The algorithm was used successfully in several test cases, and it allowed error reductions that were particularly significant in the tail regions (and, therefore, in the percentile evaluation) of the probability density functions of the variables of interest. In Ref. [26] the multi-linearization technique of [25] was extended to unbalanced passive distribution systems. In unbalanced systems, too, the multi-linearization allowed for the evaluation of the output random variable pdfs with an accuracy greater than that obtainable with a linear Monte Carlo simulation technique based on only one linearization point.

Motivated by the issues, problems, and requirements indicated above, the first aim of this research was to properly extend the application of the multi-linear approach of [25,26] to an active distribution system with PV and WD generation systems. This approach, in fact, seems to fit very well the active systems, since the steady-state modeling of PV and WD generation systems introduces additional degrees of non-linearity that can be significant in the load flow equations to be solved, and, in addition, a high correlation can exist among wind speeds in different farm locations as well as bimodal distributions (i.e., mixture distributions of two Weibull distributions or a Weibull distribution and a normal truncated distribution of wind speed) can be experimented [27]. Our consideration of bimodal distributions for the random input variables of a multi-linear probabilistic load flow of an active distribution system is viewed as an additional original contribution of this paper.

This paper is organized as follows. First, the description of the probabilistic load flow equations of an active distribution system with PV and WD generation systems is presented, and, then, the details of the multi-linear algorithm are described. Numerical applications also are reported and discussed with reference to a 17-bus test distribution system in which WD and PV systems are connected at different busbars. Our conclusions and suggestions for future work are given in the final section.

2. Probabilistic method for the analysis of a distribution system with PV and WD generation units

Let us refer to an active electrical distribution system characterized by the presence of wind farms and photovoltaic systems. When its structure and the parameters of its electrical components are known, the probabilistic load flow analysis of such a system requires first a probabilistic modeling of loads, wind, and PV generators and, then, an algorithm for solving the model of the entire electrical system.

In probabilistic studies, the load characteristics can be assumed to have a normal distribution, as well as binomial, discrete, or other correlated/uncorrelated distributions; the normal distribution models are the most frequently used. For example, with reference to probabilistic balanced power flows [28], reported an extensive list of references on this subject, and other references are reported in Ref. [29].

In the following subsections, first, we address the issue of the probabilistic models of PV and wind generation units and, then, a