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Probabilistic harmonic load flow using an improved kernel density estimator

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ABSTRACT

Harmonic distortion in power systems is a growing phenomenon that could lead to serious problems. Harmonic load flow (HLF) methods have been developed in order to predict and solve many of the problems caused by harmonics from a deterministic point of view. Probabilistic approaches for HLF calculation are necessary due to the existence of uncertainties in electrical power systems and random nature of harmonics. In this paper, a new method using an improved kernel density estimator for probabilistic harmonic load flow (PHLF) calculation is presented. Unlike many other methods, this one is immune to errors caused by simplified probabilistic techniques based on linearized models or any simplifying assumptions. Its implementation for any problem is easy and it can handle the correlated variables. The proposed method has been tested on the well-known IEEE 14-bus harmonic test system. The simulation results clearly show that it guarantees a reasonable execution time as well as an acceptable accuracy in obtaining the harmonic probability density functions (PDFs) of output random variables.

Introduction

There is a growing concern about harmonics in power systems, because they could lead to serious problems such as resonance problems, additional losses, malfunction of devices and system stability reduction. Many researches have been done on this issue [1–9]. Harmonic load flow (HLF) methods have been employed increasingly on a deterministic basis in power systems in order to predict and solve many of the problems caused by harmonics [10], but it should be noted that linear and nonlinear loads as well as the network configuration vary in a random and probabilistic way [11]. All these features make the harmonic distortion a phenomenon involving different kinds of uncertainties and as a consequence, probabilistic HLF (PHLF) calculation is necessary to deal with the uncertainties associated with the input data. In recent international standards such as IEC 1000-3-6 and EN 50160, there is an increasing interest in the probabilistic characterization, for example the probability/maximum daily and weekly values, of voltage and current harmonics. Thus, the knowledge of the whole harmonic PDF is required for standard application [12–14]. It should be noted that correlation exists between loads due mainly to common environment and social factors. Moreover, in the operation of a power system, a group of generators is controlled to meet the load area and it means that generation/generation and generation/load correlations also exist [15]. Therefore, the methods that are able to handle the correlated variables are of huge interest.

Several Methodologies based on the probability and possibility theories have been proposed in order to model the aforementioned uncertainties [16–21]. Monte Carlo Simulation (MCS) is widely employed in power system analyses to model the uncertainties. In this method, random number generators are used to assign specific probability distributions to certain parameters in order to reflect the probability density function (PDF) of the random variables. Then repeated simulations with the obtained random values are performed [20]. MCS is known as a system-dimension independent and accurate approach; however, its execution may be computationally intensive [22]. In order to reduce the computational efforts, the point estimate method (PEM) is applied to MCS in [23] by using the first statistical moments of input random variables such as mean, variance, skewness and kurtosis. Although PEM has some advantages, there are some limitations associated with it. The estimating points may be outside the region in which the random variable is defined especially when it has a relatively large standard deviation. Moreover, increasing the number of estimating points could result in calculating high-order moments of a random variable. A novel probabilistic PHLF method based on a fast PEM (FPEM) has been discussed in [24] in order to remove all these drawbacks. In [16], a methodology for HLF calculation based on the

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possibility theory has been proposed. In this approach, possibility distributions instead of probabilities have been used as the input to describe the uncertainties. In a developed model in [21], possibility non-interaction among the uncertain parameters was assumed (possibility non-interaction in possibility theory, is roughly speaking, a concept similar to probabilistic independence in probability theory). Such assumption is rather conservative and could lead to uncertainty overestimation. Therefore, an improved possibilistic HLF to overcome the foregoing drawback has been reported in [17]. One of the disadvantages of the possibilistic methods is that they do not have the ability to estimate PDFs of output random variables. In [25], an analytical Probabilistic harmonic load flow (PHLF) method has been presented. In this method, the network has been modelled using the bus impedance matrix at each harmonic order. It should be mentioned that for harmonic sources, the amplitude and the phase angle variations were also taken into account. Several classical approaches have been presented in [18] in order to approximate the true PDFs of the voltage and current harmonics. These approaches are as follows:

- Gram–Charlier's and Edgenworth's series approach
- Pearson's approach
- Johnson's approach

Summarizing the approaches, in the Edgenworth's and Gram–Charlier's approach the true PDF is approximated using a series of the derivative of the normal PDF. The biggest problem in this approach is related to the choice of the most appropriate number of the series terms to be employed. The Pearson's approach is based on a particular family of PDFs (called a system of distributions) used to approximate the true PDFs. The Johnson's approach is based on the choice of a proper transformation to convert a given PDF into another known form. This approach requires knowing only the first four moments of the PDF to be approximated [18]. Despite the computational efficiency of these analytical and approximate approaches, since they are based on HLF equations which are linearized around an expected value region, they do not have an acceptable accuracy [20].

In this paper, a new method using an improved kernel density estimator for the PHLF calculation in order to obtain the PDFs of output variables for each harmonic of interest is presented. The usefulness of nonparametric density estimators in statistical analyses and Monte Carlo computational methods has been proved [26]; here, the main intention is to utilize a kernel density estimator, as the most popular one, in the PHLF studies. Since the proposed method has utilized MCS in its implementation and overcome its main drawback, which is computational burden, it has several advantages which are outlined as follows:

- It applies MCS to the nonlinear HLF equations and there is no need to linearize the HLF equations or make any simplifying assumptions. Consequently, a good level of accuracy could be achieved.
- Unlike analytical methods, whose efficiency and computational effort depend on the system dimension, this method is independent of the system dimension and thus, its execution time for any problem is reasonable.
- Its implementation is easy, even for a complex system.
- It has the ability to handle the correlated variables.
- Since it uses a nonparametric density estimator to plot the PDFs of PHLF results, there is no need to make any assumptions about which density family the data is generated from.
- By using the proposed method, the whole PDF is obtained and it could lead to evaluating probability/maximum daily and weekly values with high accuracy. As mentioned before, such values are mandatory for standard application and thus, it can be considered as one of the practical usages of the method in utilities.

The paper is organized as follows: in Section 'Deterministic HLF formulation', the HLF formulation is briefly reviewed. Section 'Improved kernel density estimator' explains the improved kernel density estimator, as the employed nonparametric density estimator. Section 'Proposed PHLF' presents the proposed PHLF. Afterwards, the obtained results for the IEEE 14-bus harmonic test system are presented in Section 'Case study' and finally, conclusions are given in the last section.

Deterministic HLF formulation

The complete analytical form of HLF nonlinear equations, which is the basis of the PHLF, is reported in [27]. Here, the equations are briefly reviewed, for the sake of completeness. These equations can be expressed by the following equations [19]:

$$\begin{aligned} \left(P_L^1\right)^{SP} &= P_L^1(U^1,\phi^1) \\ \left(Q_L^1\right)^{SP} &= Q_L^1(U^1,\phi^1) \end{aligned} \tag{1}$$

$$\begin{aligned} (P_{NL})^{SP} &= P_{NL}(U,\phi) \\ (S_{NL})^{SP} &= S_{NL}(U,\phi) \end{aligned} \tag{2}$$

$$\begin{aligned} \left(P_{GEN}^1\right)^{SP} &= P_{GEN}^1(U^1,\phi^1) \\ \left(U_{GEN}^1\right)^{SP} &= U_{GEN}^1 \end{aligned} \tag{3}$$

$$\begin{aligned} 0 &= I_r(U,\phi) \\ 0 &= I_\infty(U,\phi) \end{aligned} \tag{4}$$

$$\begin{aligned} 0 &= g_r(U,\phi,X) \\ 0 &= g_\infty(U,\phi,X) \end{aligned} \tag{5}$$

$$0 = R(U,\phi,X) \tag{6}$$

where $\left(P_L^1\right)^{SP}, \left(Q_L^1\right)^{SP}$ are input vectors of active and reactive powers specified at fundamental for each linear load bus-bar, $(P_{NL})^{SP}, (S_{NL})^{SP}$ are input vectors of total active and apparent powers specified for each nonlinear load bus-bar, $\left(P_{GEN}^1\right)^{SP}$ is the input vector of active power specified at fundamental for each generator bus-bar without the slack, $\left(U_{GEN}^1\right)^{SP}$ is the input vector of voltage magnitude at fundamental specified for each generator bus-bar, U, ϕ are input vectors of voltage magnitude and argument at all harmonics and at fundamental, U^1, ϕ^1 are input vectors of voltage magnitude and argument at fundamental and X is the vector of the nonlinear loads variables such as converter variables. The Eqs. (1) and (2) represent the power balance equations (active, reactive and apparent) at linear and nonlinear load bus-bars, the Eq. (3) represents the active power and voltage regulation balance equations at generator bus-bars, the Eq. (4) represents the harmonic current balance equations at generator and linear load bus-bars, the Eq. (5) represent the harmonic and fundamental current balance equations at nonlinear load bus-bars and, finally, the Eq. (6) represents the additional equations at nonlinear load bus-bars, for example, commutation angle equations at converter bus-bars.