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Tracing harmonic contributions of multiple distributed generations in distribution systems with uncertainty

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ABSTRACT

With an increasing number of inverter-interfaced distributed generations (DG) being integrated into distribution systems, significant harmonics could be injected to bring an adverse impact on distribution system operation. These harmonics usually fluctuate due to the variability and intermittency of DG outputs. However, different DGs, depending on their locations and sizes, may present different harmonic contributions in distribution systems, and it is important to identify which DG has the largest influence on a specific bus. In this paper, a Complex Affine arithmetic based Three-phase Harmonic Power Flow method (CATHPF) is proposed to trace the harmonic contributions of individual DGs to distribution systems. The contribution of each DG to harmonic voltage (CDGHV) is calculated based on CATHPF. The CATHPF method is tested on an IEEE 33-bus distribution system. The proposed CATHPF method can quantitatively evaluate harmonic contributions of individual DGs in distribution systems, and in turn guide the effective allocation of harmonic control equipment.

1. Introduction

Along with the increasing electricity consumption throughout the world, many countries have begun to meet their electric energy needs with renewable energy sources (RES). Distributed generations (DG) is an efficient means to utilize RESs [1,2]. However, as DGs incorporate power conditioning units, which can generate harmonic, so DGs may cause problems such as electrical power quality, reliable operation of system equipment, and component life expectancy [3,4]. With an increasing deployment of non-linear loads and DGs, harmonic pollution has become a serious concern [5]. For system power quality analysis and management, developing methods to quantify individual harmonic sources' harmonic contributions is of great importance [6].

Existing harmonic analysis mostly concentrate on defining and calculating various harmonic contribution indices. Commonly used indices are the harmonic-injected current, the contribution index of harmonic voltage, and the contribution index of harmonic current [7]. The authors in [8] presented a weighted power quality index to quantify harmonic distortion. The authors in [9] established an index to quantify the harmonic impacts of multiple loads.

Many studies have been done on the harmonic contribution of a single harmonic source. Ref. [5] discussed a method to calculate utility harmonic impedance and harmonic responsibility at the point of common coupling (PCC), meanwhile taking the load harmonic impedance into consideration. The method presented in [10] was based on the covariance characteristics of random vectors, which can effectively eliminate negative effects of the background harmonic fluctuation. The authors in [11] proposed a method to evaluate customer and utility responsibilities for mitigating violations caused by changes of either harmonic sources or harmonic impedances. Ref. [12] discussed a harmonic current vector based approach to quantify harmonic contributions of the customer and utility at the PPC. The authors in [13] proposed an Artificial Neural Network based method to quantify the influence of source impedance change without interrupting any loads' operation.

Harmonic voltage at each bus is contributed by all harmonic sources in the power grid. Distinguishing contributions of individual harmonic source to harmonic voltage at particular buses is very important for responsibility partition in harmonic analysis and management [2,9,14,15]. Ref. [2] assessed the impact of DGs on harmonic distortion in low voltage power networks. In [9], a strict theory and a corresponding method to evaluate multiple loads' harmonic impact were presented. The authors in [14] presented a technique to determine scattered harmonic-producing loads' harmonic impact on the power system. In [15], a "non-invasive"

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method to distinguish harmonic contributions of individual sources was proposed.

Variability and intermittency of DGs, such as wind turbine generators and photovoltaic (PV) panels, have profound impacts on system operation [16–28]. Ref. [16] proposed a robust UC model to integrate high-level dispatchable renewable DGs in power system operation. The authors in [17] proposed a complex affine arithmetic based unbalanced three-phase power flow method for tracing uncertainties of individual DGs on voltage quality. Stochastic fluctuations of harmonics generated by DGs could also lead to the random variation of harmonics distribution [1,4,18]. Since DGs inverters have nonlinear behavior, harmonic interactions between DGs and the distribution systems become for significant [19]. The authors in [4] aimed to capture the harmonic behavior of small photovoltaic systems as a function of variations in solar radiation. In [20–23], the harmonic distortion caused by PV systems was studied. To deal with the variability and intermittency of DGs, harmonic power flow calculation while considering uncertainties is a common way for harmonic analysis. Consequently, probabilistic harmonic power flow (PHPF) methods were presented [24–26], and the fuzzy harmonic power flow (FHPF) methods were studied in [27,28]. The accuracy of the PHPF method depends on the preciseness of the presumed probabilistic distribution functions (PDFs). However, it is usually difficult for planners and operators to obtain precise PDF parameters for describing various uncertainties. Fuzzy distribution functions (FDFs) are difficult to obtain as well as PDFs.

The rest of the paper is organized as follows. Section 2 introduces the complex affine arithmetic. In Section 3, complex affine based models for harmonic sources are proposed. Section 4 presents the CATHPF method and two indices to quantify harmonic contributions of DGs. An IEEE 33-bus distribution system is illustrated in Section 5 to test the proposed CATHPF method. Finally, main conclusions are summarized in Section 6.

2. Complex affine arithmetic

In point estimation, the sample data is used to estimate the unknown parameters in overall distribution. One disadvantage of point estimation is that the estimated result can't cover all possible situations. Interval arithmetic (IA) is used in uncertainty analysis when the boundaries of variables are known. It has a complete space of the solution. The intervals obtained from IA can fully reflect the uncertainties. However, the result of IA is usually conservative, which means its result bound is much wider than the actual range. As an improvement on IA, Affine arithmetic (AA) could effectively describe uncertainties in a simple form and properly present the relationship between uncertainties. Hence, its solution conservativeness could be mitigated as compared to IA.

Actual power grid operates in a complex environment with various uncertainty factors. Specifically, much information in power grid cannot be expressed as certain values because of reasons such as uncertain load switching, load prediction errors, randomness of weather, etc. Therefore, complex AA could be used to express uncertainty information in power grid.

An uncertain quantity x can be expressed as a linear polynomial in complex AA, denoted as $\hat{x}$:

$$\hat{x} = x_0 + x_1\varepsilon_1 + x_2\varepsilon_2 + \ldots x_n\varepsilon_n = x_0 + \sum_{m=1}^{n} x_m\varepsilon_m \tag{1}$$

where x_m is a real coefficient, ε_m is a noisy symbol which lies in the interval $[-1,1]$, and x_0 is the central value corresponding to an interval number.

Relationship between different uncertain quantities can be similarly established in the complex affine based linear polynomials of uncertainties via common noisy symbols. Take two uncertain quantities for instance, which are expressed as $\hat{x} = x_0 + x_1\varepsilon_1$ and $\hat{y} = y_0 + y_1\varepsilon_1$ in complex AA. They both have a same noisy symbol ε_1 to indicate their coupling relationship. Projecting real coefficients x_0 and x_i in $x = x_0 + \sum_{m=1}^{n} x_m\varepsilon_m$ to the complex domain, a complex uncertainty can be expressed as a complex affine based linear polynomial.

Fundamental operations in complex AA are introduced as follows. Given two uncertainties expressed as complex affine-based linear polynomial: $\hat{x} = x_0 + \sum_{m=1}^{n} x_m\varepsilon_m$, $\hat{y} = y_0 + \sum_{m=1}^{n} y_m\varepsilon_m$, there exist:

$$\hat{x} + \hat{y} = (x_0 + y_0) + \sum_{m=1}^{n}(x_m + y_m)\varepsilon_m \tag{2}$$

$$\alpha\hat{x} = \alpha x_0 + \alpha\sum_{m=1}^{n} x_m\varepsilon_m \tag{3}$$

$$\hat{x} \pm \alpha = x_0 \pm \alpha + \sum_{m=1}^{n} x_m\varepsilon_m \tag{4}$$

$$\begin{aligned}\hat{x}\times\hat{y} &= \left(x_0 + \sum_{m=1}^{n} x_m\varepsilon_m\right)\times\left(y_0 + \sum_{m=1}^{n} y_m\varepsilon_m\right)\\ &= x_0y_0 + x_0\times\left(\sum_{m=1}^{n} y_m\varepsilon_m\right) + y_0\times\left(\sum_{m=1}^{n} x_m\varepsilon_m\right) + \left(\sum_{m=1}^{n} x_m\varepsilon_m\right)\times\left(\sum_{m=1}^{n} y_m\varepsilon_m\right)\\ &= x_0y_0 + \sum_{m=1}^{n}(x_0y_m + y_0x_m)\varepsilon_m + \left(\sum_{m=1}^{n} x_m\varepsilon_m\right)\times\left(\sum_{m=1}^{n} y_m\varepsilon_m\right)\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{\hat{x}}{\hat{y}} &= \frac{Re(\hat{x}) + i\mathrm{Im}(\hat{x})}{Re(\hat{y}) + i\mathrm{Im}(\hat{y})} = \frac{(Re(\hat{x}) + i\mathrm{Im}(\hat{x}))(Re(\hat{y}) - i\mathrm{Im}(\hat{y}))}{Re(\hat{y})^2 + \mathrm{Im}(\hat{y})^2}\\ &= (Re(\hat{x}) + i\mathrm{Im}(\hat{x}))(Re(\hat{y}) - i\mathrm{Im}(\hat{y}))\times\frac{1}{Re(\hat{y})^2 + \mathrm{Im}(\hat{y})^2}\end{aligned} \tag{6}$$

where $\alpha \in R$. A quadratic term derived in the multiplication operation is replaced by a new noisy symbol ε_k with the new coefficient uv, where $u = \sum_{m=1}^{n}|x_m|$ and $v = \sum_{m=1}^{n}|y_m|$.

According to the operations defined above, conservativeness of uncertain quantity calculation in complex AA can be effectively reduced as compared to IA. Taking two uncertainties $\hat{x} = (1+2j) + (3+1j)\varepsilon_1 = [-2+1j, 4+3j]$ and $\hat{y} = (1+2j) + 3\varepsilon_2 = [-2+2j, 4+2j]$ as an example, according to the operations above, the following results can be derived $\hat{x} - \hat{x} = 0$ and $(\hat{x}+\hat{y}) - \hat{x} = \hat{y} = [-2+2j, 4+2j]$. However, according to operations in IA, the results are $[-6-2j, 6+2j]$ and $[-8, 10+4j]$. It is obvious that complex AA based method obtains more accurate results with much narrower bounds.

3. Complex affine based models for harmonic sources

3.1. Complex affine based constant-current source model

Constant-current source is the most simple and general model for harmonic source, in which the influence of harmonic voltages on the produced harmonic currents is ignored. As filters are widely applied in electricity grid, magnitudes of harmonic voltages are much smaller than that of the fundamental voltage, which justifies rationality of the simplification. The harmonic injections can be obtained via methods such as measurement, simulation, and spectrum in practical engineering. Once the intervals of harmonic injections are obtained, they could be expressed in the form of complex affine based linear polynomials, denoted by $\hat{I}h_j^{(h)}$ as shown in Fig. 1.

The complex affine form of an uncertain power injection is determined as: