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Harmonic disturbance location by applying Bayesian inference

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ABSTRACT

Harmonic pollution is one of the most important power quality issues in electric power systems. Correct location of the main harmonic disturbance source is a key step to solve the problem. This paper presents a method to detect the location of harmonic disturbance source in low voltage network through Bayesian inference. The harmonic state is estimated based on the measurement data from limited measurement points whereby the measurement error is also considered. The performance of the proposed method is assessed through a case study applied in a typical low voltage network. Monte Carlo simulation is used to obtain the statistical results. The influence of different parameters like disturbance level, measurement accuracy level, etc. is discussed. The proposed method shows the adequacy for the analysis of distribution networks.

1. Introduction

One of the significant changes in current distribution network is the large applications of power electronic devices due to the rapid development of semiconductor technology. Therefore more and more nonlinear loads are connected to the system which results in higher harmonic pollution levels. According to [1], the survey conducted by the Electric Power Research Institute shows that only 15–20% of the total loads were nonlinear in 1992 while the percentage of nonlinear loads will be over 50% of all loads in the future. Harmonic pollution may have serious consequences to the system such as overheating and damaging of equipment, unexpected tripping of sensitive loads, failure of protective relays, and disturbance to the communication circuit.

Locating the main harmonic disturbance source is important to improve the power quality (PQ) level of the network. Moreover, it is crucial for the distribution system operator (DSO) to share the responsibilities. There are many literatures discussing the identification and detection of harmonic sources in distribution systems. In [2], the vector-matrix form the Kirchhoff law is solved with a hybrid weighted least squares estimator, and then the harmonic signal magnitudes are obtained. The harmonic power direction-based method is one of the most common tools to figure out the solution [3,4]. The principle of the method is to investigate the direction of harmonic active power. If it is from the utility to customer, the utility is considered to be dominant to the pollution, and vice versa. The harmonic power approach is improved according to [5] in which several concerns are addressed for the application to radial system and a modification is proposed to generalize its application to non-radial systems. Simulations and experiments carried out in [6] present that the single-point strategy can give useful indications for the detection of the dominant harmonic source, upstream or downstream the measurement point. The strategy is improved in [7] which has been proved to be successful in several simulations. In [1], Saxena et al. proposed a method based on the direction of harmonic power flow at system nodes with the measurement of voltage phasor measuring unit, which are used to categorize and rank the suspected buses. In [8], sensitivity analysis and the minimum variance criterion are utilized to determine the optimal locations of measurement devices for locating harmonic sources. It is proposed in [9–12] to calculate the harmonic sources of the utility and customer with the measured harmonic impedances at point of connection (PoC). The Norton model is applied to represent the harmonic equivalent circuit. In [13], Ma and Girgis addressed two problems: the optimal locations of a limited number of harmonic meters and the optimal dynamic estimation of harmonic source locations, and it is solved by the Kalman-filtering-based technique. The principle of critical impedance is applied to identify the harmonic disturbance according to [14,15]. The exact information of the internal impedances or admittance both of the supplier and customer sides' equivalent circuits is demanded for this method. In [16], a combined approach of superposition and critical impedance is reported which is considered as an improvement of critical impedance method. In [17], Dan proposed a method of monoparameter variation for the identification of the existence of a harmonic source. Harmonic state estimation (HSE) which is capable to calculate the harmonic

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generation and penetration throughout the grid is applied to locate the nonlinear load in the network [18–20]. Modern techniques are also applied to harmonic characterization and detection. The neural network algorithm is applied in [21–23], the fuzzy logic is utilized in [24], the method based on independent component analysis and mutual information theory [25] and Yang et al. introduced a data clustering method in [26].

This paper proposes a harmonic disturbance location (HDL) approach based on Bayesian inference which takes the measurement errors and load diversities into account. Bayesian inference is a method of inference in which Bayes' theorem is applied to calculate the probability distribution. The inference applies existing information (based on expert knowledge, past studies, etc.) into the data analysis. This existing information is represented as a prior distribution, and the data likelihood is effectively weighted by the prior distribution when the data analysis results are calculated. Statistical results can be obtained which are the rankings of suspected loads. In Section 2, the mathematical model behind the problem and the location method framework are presented. In Section 3, the prior distribution of the harmonic background distortion and injection is calculated. Section 4 defines the grid condition and the measurement framework. In Section 5, the solution of the posterior distribution of the harmonic disturbance source is given. Section 6 addresses on the numerical concerns for the high-dimensional integral. In Section 7, the detailed parameters of the network modelling and the simulation algorithm for the case study are presented. In Section 8, several scenarios are carried out to investigate the impacts of different factors, like levels of harmonic disturbance, the number and locations of measurement devices, measurement parameters and measurement accuracy levels as well as the definition of the prior distribution. Comparing with other methods, the advantages of the proposed method are discussed.

2. Harmonic disturbance problem and its location framework

2.1. Harmonic disturbance problem

Distribution grids are mostly operated in radial structure. The power is delivered to the customers connected along the feeder. Fig. 1 shows the equivalent circuit for harmonic disturbance location. The harmonic characteristic of each load is represented by the Norton equivalent model and the grid side is represented by the Thevenin equivalent model. The high level of harmonic pollution may be caused by the grid voltage (U_s) or a disturbing customer which produces extremely high level of harmonic current (I_{dh}) when the other customers' injections are under certain values (I_{h1} to I_{hn}). Z_{c1} to Z_{cn} represent the cable parameters. Z_{l1} to Z_{ln} give

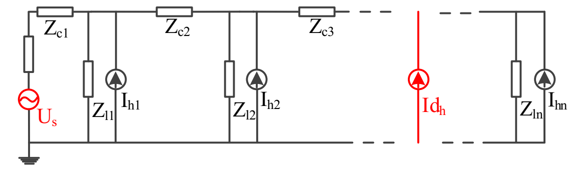

Fig. 1. The equivalent circuit for harmonic disturbance location.

the load parameters. If one of these customers deteriorates the power quality, it is necessary to analyze the disturbance for the responsibility-sharing and problem-solving.

2.2. Harmonic disturbance location framework

Fig. 2 shows the methodology framework, which illustrates the proposed HDL approach. It includes 3 parts; (1) the pre-processing to obtain the prior distribution of harmonic background distortion and injection, (2) the Bayesian inference to acquire the posterior distribution, and (3) the ranking of possible harmonic disturbance locations.

In the pre-processing part, the prior distribution (marginal distribution) of harmonic background distortion and injection is acquired based on several groups of input data. The field measurement database and historical harmonic disturbance statistics are used to determine the harmonic injection distribution. The grid condition for the Bayesian inference is obtained through state estimation [27]. The measured voltages and currents will also be recorded and provided to the inference process. With the network parameters, the grid condition and measured quantities, the posterior distribution (conditional distribution) can be obtained with the application of Bayesian theorem. The network parameters give the information of components (cable, transformer) parameters, the grid impedance, the number of customers, and the length of cable sections between each pair of customers. In the post-processing part, the probability that the main harmonic disturbance is from the background distortion or each customer is calculated. Eventually, the ranking of possible harmonic disturbance location is acquired.

Bayesian inference is applied to detect the exact location of the disturbance source and the Bayes formula is given in (1) [28]. Bayesian probability models compute a conditional probability based on new data information and former probabilistic beliefs. The model parameters in Bayesian inference are usually treated as random rather than fixed quantities which are applied in classical statistics.

$$f_{\boldsymbol{\Theta}}(\boldsymbol{\Theta}|x_1,\ldots,x_n) = \frac{f_{\boldsymbol{x}}(x_1,\ldots,x_n,|\boldsymbol{\Theta})f_{\boldsymbol{\Theta}}(\boldsymbol{\Theta})}{\int_{\Omega_{\boldsymbol{\Theta}}} f_{\boldsymbol{x}}(x_1,\ldots,x_n,|\boldsymbol{\Theta})f_{\boldsymbol{\Theta}}(\boldsymbol{\Theta})d\boldsymbol{\Theta}} \tag{1}$$

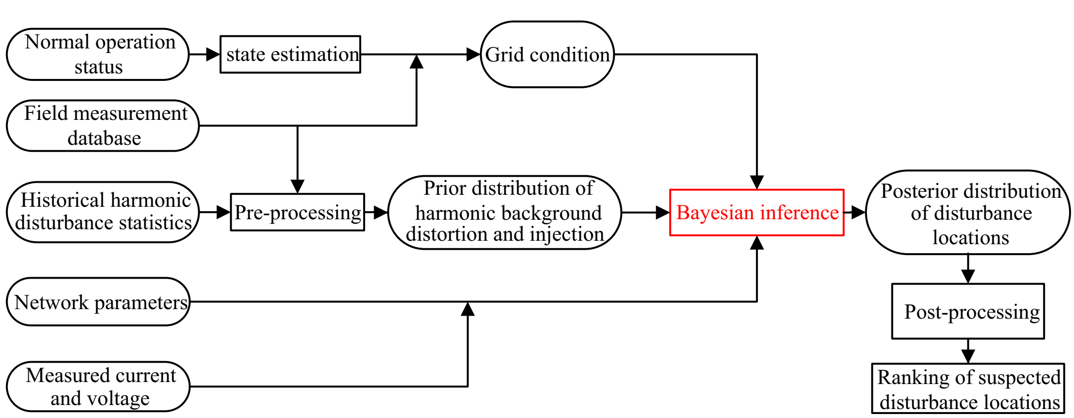

Fig. 2. The framework of harmonic disturbance location.