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A dynamic approach to identification of multiple harmonic sources in power distribution systems

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ABSTRACT

This paper provides a novel algorithm for identifying harmonic sources in power distribution systems. This algorithm is developed based on an observer design to carry out harmonic estimation for a combination of suspicious nodes. The estimation error is analyzed to determine the existence of harmonic sources in the specified node combinations. This approach is used to determine the source of both single and multiple harmonic sources in distribution systems with time varying load parameters. For systems with a large number of suspicious nodes, the system may be divided into sub-systems and the algorithm is applied to each sub-system to identify the harmonic sources present. Simulations are carried out on a benchmark IEEE distribution test feeder for both single and multiple harmonic sources and a number of scenarios are simulated to verify the accuracy and robustness of the proposed approach. The results show that the node combinations which represent the harmonic sources yield an estimation error which approaches zero asymptotically.

Introduction

The proliferation of power distribution systems with harmonic disturbances is as a result of the increasing use of power electronic devices in the design of household and industrial equipment. IEEE Std 519-1992 [1] provides specifications for the allowable harmonic content in power systems. To comply with these standards, utility companies need to be aware of the exact source of harmonic injections in the system at any given time. This information may be instrumental in the design of an appropriate mechanism to extract or nullify the effects of the harmonic injections or penalizing those responsible.

A number of methods have been reported in literature for determining the source of harmonic injections in power systems. In general, two major approaches to harmonic source identification are proposed: single point methods and multiple point methods. In single point methods, the source of harmonic injections are determined by taking measurements at a single point in the system, usually the point of common coupling (PCC), and the harmonic source is determined to either be upstream or downstream from that point. This method apportions the responsibility of harmonic injection either to the customer or the utility. Some techniques based on single point methods include critical impedance [2–5], neural networks [6] and nonactive power [7]. Another single point method, proposed in [8], utilizes a Norton equivalent circuit to represent a model of the power system comprising of the customer side and the utility side. A general review of various single point methods of harmonic source identification was carried out in [9]. As much as the single point method is effective in providing a general overview of the source of harmonic disturbances, it does not give accurate information about the exact node where the harmonic injections occur. For systems with multiple harmonic sources, the harmonic distortion at the PCC is usually the result of an aggregate of the multiple distortions coming from various parts of the system. A major concern is that the multiple harmonic sources may offset each other due to the phase angle differences and the time varying nature of the loads. Hence, the distortion at the PCC may not accurately represent the harmonic injections emanating from the various nodes in the system. Therefore, the multiple point approach to harmonic source identification is preferred to the single-point method due to its ability to identify the exact nodes where the harmonic injections occur as well as the intensity of the harmonic injections.

The most common method of multiple-point harmonic source identification is harmonic state estimation (HSE). HSE involves the estimation of the states of the system using available measurements. The states may be chosen to be the voltage magnitudes and phase angles at all nodes in the system or the current injections, depending on the method used to carry out HSE. Two approaches to HSE are available in literature: static HSE [10,11] and dynamic

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HSE [12–14]. With dynamic HSE, a dynamic representation of the time evolution of the system is used for state estimation. Utility companies are thereby able to detect rapid changes in the system and respond accordingly. In addition dynamic HSE gives a more accurate representation of state estimation when there are load changes compared to static HSE. The most common method of dynamic HSE is the Kalman filter [15,16] and its modifications such as adaptive Kalman filter [13] and robust extended Kalman filter [14]. The adaptive Kalman filter proposed in [13] uses two process noise covariant, Q, models to carry out harmonic estimation and this eliminates the requirement for the calculation of an optimal Q model. A time domain approach to HSE was proposed in [17,18]. This method applies the numerical differentiation approach to determine a fast periodic steady-state solution in the time domain and the Kalman filter is used to solve the HSE problem. The Kalman filter HSE methods are applied for estimation of the harmonic node voltages in a given system. However, they have not been applied to distribution system harmonic source identification. Also, the time domain approach proposed in [17] was not extended to harmonic source identification.

Apart from HSE, other methods have been previously applied to identification of harmonic sources. In [19], the theory of statistical inference is used to determine the harmonic index of a particular load in the system. The direction of harmonic power flow is applied in [20] to rank the nodes in the system to suspicious and non-suspicious nodes. Binary particle swarm optimization is then used to determine the optimum locations to place measurement devices. One drawback of this approach used is that an assumption that harmonic voltage phasor measurements are available for all the nodes in the system is applied. However, it is not cost effective to obtain measurements at all nodes in a given system, hence the need for optimal measurement placement methods and observability analysis. In [21], a Bayesian approach was applied to harmonic source estimation. A dynamic representation of the system was presented and the forcing term (which represents the harmonic current injections) was determined from measured and pseudomeasured data. A cascade correlation system is also presented in [22] for determining multiple harmonic sources in a given system.

In this paper an algorithm is developed to identify multiple harmonic sources in power distribution systems. This algorithm utilizes observer design to estimate the system states. The fundamental frequency is assumed to be known and harmonics are estimated from available measurements. For ideal scenarios, the number of harmonic sources in the system is unknown. The nodes which contain nonlinear loads are determined by using a combinational approach and the estimation errors are analyzed for each combination. Systems with a large number of suspicious nodes are divided into subsystems to improve computational efficiency. The relationship between node current injections and the state variables is then formulated. This is used to calculate the actual current injections at each node. Determination of the exact magnitude and phase of the injected harmonic current may be achieved by using the iterative observer algorithm proposed in [23]. Observers have been widely used to estimate disturbances in various industrial systems [24,25]. The observer based method proposed in this paper accurately determines the source of harmonic injections in a distribution system using a time-domain dynamic model. This time-domain approach is advantageous due to its ability to adapt to the dynamic nature of distribution system loads with time. This method is also able to determine the harmonic sources irrespective of the rapid changes in the harmonic source in the system. In addition, the algorithm presented is able to determine the presence of multiple harmonic sources in real time as well as adapt to rapid changes in the nature of the harmonic sources with time. The observer-based algorithm proposed in this paper takes into account the time varying nature of distribution system loads and harmonic sources. The Kalman filter requires knowledge of the process and measurement noise covariance parameters. This makes the proposed algorithm more straightforward because knowledge of these parameters is not required for implementation. Simulations are included to verify the accuracy of the proposed method.

Problem formulation

Consider a power distribution system represented in state-space form as

$$\dot{x} = Ax + Bu + Ew \tag{1}$$

$$y = Cx + Du \tag{2}$$

where $x \in \mathbb{R}^n$ is the state vector, y represents the measurements, u is the system input, A, B, C, D are known matrices, E represents the disturbance matrix and w is the harmonic disturbance given by

$$w(t) = \sum_{h=2}^{f} H_h \sin(\omega_h t + \phi_h) \tag{3}$$

where for $h = 2 \ldots f, H_h, \phi_h \in \mathbb{R}$ represent the magnitude and phase angles respectively, $\omega_h = 2\pi fh, f$ is the fundamental frequency and h is the harmonic order.

In practical systems, E is unknown. This is because the exact states in the system where the harmonic injections occur are unknown.

Assumption 1. The harmonic source is not directly measured. As a result, the state space representation in (1) and (2) does not indicate any harmonic injection in the outputs.

Remark 1. The existence of a current measurement at the direct source of harmonic injections in the system creates another term in the measurement equation. The coefficient of this harmonic disturbance in the measurement is unknown.

The system state-space matrices are determined using the methods proposed in [26,17]. The states of the distribution system are node voltages and line currents.

The aim of this work is to determine the harmonic sources in a given power distribution system using an observer-based algorithm. A time domain dynamic approach is presented in this paper where the system is modeled as a process at the fundamental frequency and the harmonic injections are taken as disturbances to the system. This time domain representation is effective where the power system has time-varying load and harmonic source parameters.

Power distribution systems are subjected to a wide range of loads, both linear and nonlinear. The assumptions in [27] are applied in this paper for modeling the distribution system parameters. Linear loads may be represented as constant RL impedance while nonlinear loads are modeled as a linear load in parallel with a harmonic current generator [20,28].

Observer based harmonic source identification

An observer-based approach is proposed in this section for determining the harmonic sources in a given power system. The state observer utilizes the state space equations given in (1) and (2) for harmonic source identification. The dynamics of the harmonic disturbance, w, may be described as a linear exosystem:

$$\dot{w} = Sw \tag{4}$$

$$\mu = g^T w \tag{5}$$