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Harmonic state estimation for distribution networks using phasor measurement units

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ABSTRACT

This paper presents a novel approach for harmonic state estimation for unbalanced three-phase distribution systems using Phasor Measurement Units (PMUs), considering the presence of harmonic sources connected to the system. Harmonic branch currents in rectangular coordinates are the state variables to be estimated by the proposed methodology. Harmonic voltages and branch currents phasors are measured at monitored buses by PMUs. For the non-monitored buses, load pseudomeasurements are considered as inequality constraints in a proposed optimization problem solved via Safety Barrier Interior Point Method. The main contribution of the method is providing satisfactory estimation results considering non-fully observable power distribution networks with long feeders, requiring a small number of field measurements. Tests on the modified Baran and Wu's 33-bus test system are used to validate the methodology and demonstrate its effectiveness on evaluating power quality indexes, identifying harmonic sources and monitoring harmonic components and their propagation through the network.

1. Introduction

Due to the increasing use of non-linear loads and electronic devices in the power systems, the generation of harmonic current injections into the electrical power networks has been increased significantly, causing serious problems such as overheating in transformers and conductors, malfunction of electronic equipments and increasing of power demand. As a consequence, harmonic monitoring has notoriously become an important task for power quality management [1,2].

PMUs (Phasor Measurement Units) represent one of the most promising technological developments within the context of power systems monitoring. They provide high accuracy measurements and can be used for the smart grid state estimation [3] and data management [4]. The use of PMUs has also been considered as viable solution to power system harmonic monitoring, as detailed in Refs. [5,6], which deeply discuss real impacts of using synchronized measurements by GPS (Global Positioning System) to monitor power grids. Indeed, these meters are capable of monitoring signals distorted by harmonic components at high sampling rates. The literature addresses the number of 2880 samples per seconds being measured by PMUs considering the system frequency as 60 Hz [7]. Applying Fourier analysis, it is clearly possible to evaluate each harmonic component individually in the frequency domain [8]. Synchronized measurements gathered from the network, using a common time source for synchronization provided by GPS, are sent to a PDC (Phasor Data Concentrator), in which the obtained data are used for several applications such as power system operation, control and state estimation [7].

A harmonic monitoring system based on PMUs and harmonic state estimation is presented in Ref. [9]. The system determines harmonic states of a network in real time, and the acquired synchronized waveform data provided by PMUs are evaluated at every 15 min in a control center, where a state estimation technique is applied in order to obtain an optimal estimative of the harmonic state of the system [9]. For harmonic monitoring systems, the signal is Fourier transformed to get all the amplitudes and phases of harmonic components [8]. The system generally consists of PMUs and personal computers installed at monitored buses of the system. Each local system consists of a GPS receiver to synchronize harmonic phasor measurements, PMUs and a local computer to complete the real time harmonic analysis as well as the correction of systematic errors associated to transducers (potential/current transformers) [9] analysing their calibration based on their frequency response [9] or by an on-line correction of errors introduced by instrument transformers as presented in [10].

The challenge in monitoring harmonic components in power distribution systems is identifying the harmonic sources and their

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propagation through the power grid using few meters located along the distribution feeder. Due to peculiarities of distribution networks, like its radial or weakly-meshed topology, a huge number of meters are necessary to make the system fully observable [11]. However, harmonic instrumentation is expensive and it is rarely installed. Another difficulty is the lack of a monitoring system implemented at distribution level. Currently, the only telemetered quantities available are the voltage and current measurements at the substation. There are fewer actual measurements than state variables to be estimated [12].

Synchronized measurements, also known as synchrophasors, are used in [13] which proposes the use of independent component analysis for harmonic sources identification in deregulated meshed power networks. The traditional weighted least squares method (WLS) is used in [14] also considering the use of PMUs. However, the system under analysis is fully observable, requiring a large number of measurements to provide reliable results. In [15], evolutionary strategies are used for the purpose of estimating harmonic components in distribution networks. Harmonic state estimation (HSE) based on genetic algorithm, particle swarm optimization and honey bee mating is presented in [11,16,17], respectively. Despite of providing satisfactory results, the computational time associated to these heuristic/meta-heuristic techniques is a disadvantage of the proposed methodologies.

The main purpose of this paper is to present a methodology for harmonic state estimation (HSE) for a real time monitoring of non fully observable power distribution networks with radial topology and long feeders. Harmonic branch currents are considered as state variables to be estimated. An objective function is defined for each harmonic order analysed individually aiming to minimize the quadratic difference between the measured values and their corresponding ones estimated by the methodology, according to the weighted least squares (WLS) method.

In order to supplement a limited number of field measurements, load historical data (pseudomeasurements defined for the fundamental frequency [12]) are treated as bounded inequality constraints varying between predefined maximum and minimum limits determined for each harmonic order. The harmonic state of the system is determined by the solution of these optimization problems solved by Safety Barrier Interior Point Method (SBIPM) [18].

The proposed method has the advantage of providing satisfactory results for distribution harmonic state estimation requiring a small number of measurement units installed in the power grid.

This paper is subdivided into six main sections. The first is an introductory one. The second is about the development of the proposed methodology. The third one discusses about the computational simulations. Results and discussions are presented in the fourth and fifth sections, respectively. Conclusions are highlighted in the last one.

2. The proposed methodology

2.1. Measured values vector

A signal with harmonic distortions can be measured by PMUs [9]. By Fourier Analysis, each harmonic component (magnitudes and phase angles) can be extracted from the original signal with an adequate data processing based on Fourier transform [19,20].

All the harmonic synchrophasors obtained from field measurements are used to form the measured values vector, Z^h for harmonic order h as expressed by Eq. (1). A phasor measurement $(z_r^h + jz_i^h)$ for a given harmonic order h is considered in rectangular coordinates (divided into real and imaginary parts).

$$Z^h = \left[z^{s,h}_{(1,r)}, z^{s,h}_{(1,i)}, z^{s,h}_{(2,r)}, z^{s,h}_{(2,i)}, \ldots, \quad z^{s,h}_{(N_m,r)}, z^{s,h}_{(N_m,i)}\right]^T \quad s \in \{A, B, C\} \tag{1}$$

where index s represents the three phases A, B and C.

A measurement vector, Z^h has a total number of elements $(2 \times 3 \times N_m)$, in which N_m represents the total number of three-phase measured signals, comprising information of the three monitored phases (A, B and C), both real and imaginary parts of the measured harmonic phasor.

The measurements can be divided into real and imaginary parts and analysed altogether only because the phasors provided by PMUs are all synchronized. If the measurements would not be provided by PMUs, the measured values vector could not be formed that way.

2.2. State variables vector

Harmonic branch currents of the system are the states to be estimated in rectangular coordinates. They form the state variables vector, $\hat{x}^h$ similarly to Ref. [21]. Then, the number of states to be estimated is $(2 \times 3 \times N_b)$ for a given harmonic order h, being N_b the total number of branches of a three-phase system.

Branch current phasors $(I^h_{b,r} + jI^h_{b,i})$ for a given branch b of the system are considered in rectangular coordinates to form the state variables vector, $\hat{x}^h$ for a harmonic order h, as in Eq. (2), for the three phases A, B and C:

$$\hat{x}^h = \left[I^{s,h}_{(1,r)}, I^{s,h}_{(1,i)}, I^{s,h}_{(2,r)}, I^{s,h}_{(2,i)}, \ldots, \quad x^{s,h}_{(N_b,r)}, x^{s,h}_{(N_b,i)}\right]^T \quad s \in \{A, B, C\} \tag{2}$$

Distribution lines are modelled according to Ref. [22], in which a harmonic power flow is developed considering a system modelling for harmonic analysis and simulations. Based on the assumed network model and on the harmonic branch currents, it is possible to calculate other electrical quantities.

By Kirchoff's laws, voltage phasors can be obtained for each busbar k: $V^{s,h}_{k,r}$ and $V^{s,h}_{k,i}$ (real and imaginary parts of voltage phasor, respectively) as function of the state variables and based on the assumed harmonic network model, considered in the frequency domain according to [22].

A harmonic current injection is the sum of all branch currents, meeting at a given bus k. Then, it can also be calculated in rectangular coordinates: $I^{s,h}_{inj.,k,r}$ and $I^{s,h}_{inj.,k,i}$ (real and imaginary parts, respectively).

Eq. (3) is used to calculate active/reactive power at busbar k, $P^{s,h}_k$ and $Q^{s,h}_k$, respectively for each harmonic order and phase s.

$$\begin{aligned} P^{s,h}_k &= V^{s,h}_{k,r} I^{s,h}_{inj.,k,r} + V^{s,h}_{k,i} I^{s,h}_{inj.,k,i} \\ Q^{s,h}_k &= -V^{s,h}_{k,r} I^{s,h}_{inj.,k,i} + V^{s,h}_{k,i} I^{s,h}_{inj.,k,r} \end{aligned} \tag{3}$$

2.3. Objective function

One objective function is defined for each harmonic order h individually, as in Eq. (4), based on the weighted least squares method:

$$\min \quad J(\hat{x}^h) = \sum_{j=1}^{2\times 3\times N_m} \frac{1}{2}\left(\frac{z^h_j - f_j(\hat{x}^h)}{\sigma_j}\right)^2 \tag{4}$$

where σ is the standard deviation associated to the aleatory error of a measured value z^h and $f(\hat{x}^h)$ is the function relating the state variables, $\hat{x}^h$ to its corresponding measured value z^h. The summation in