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Phasor-based assessment for harmonic sources in distribution networks

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ABSTRACT

Phasor-based interdependencies of multiple harmonic sources, especially Distributed Energy Resources, on distribution networks are analyzed in this paper. A new index, Phasor Harmonic Index (IPH), is proposed by the authors. IPH considers both harmonic source magnitude and phase angle for different harmonic orders. Other commonly used harmonic indices are based solely on magnitude of waveforms. A very detailed model of a distribution network is used in the harmonic assessment. With the help of the detailed distribution network model, the phase couplings and the phase balancing impacts on harmonic propagation between three phases are investigated. Moreover, effects of harmonic source phase angle deviations are analyzed at both the customer side and the substation side. This paper investigates the importance of phase angles in harmonic assessment and how distribution network characteristics can be analyzed appropriately with phasor-based harmonic studies. In addition to device level harmonics, system level harmonic propagation need to be considered.

1. Introduction

The resultant harmonics from Distributed Energy Resources (DER) inverters and the spread of power-based appliances create concerns for power system operators and engineers. Harmonic propagation causes distortion in voltage and current waveforms in different parts of distribution networks. Harmonics generated by different harmonic sources can interact to either increase or decrease the effects of harmonics.

The harmonic impact on power systems is a well-researched topic. Harmonic measurement and filtering in power systems are discussed in many literatures like [1,2]. However, existing researches mostly consider harmonics as a local phenomenon with local effects [3,4]. There are a few papers that focus on harmonics from Distributed Energy Resources (DER) [5–7]. Authors in [8,9] focus on harmonic filter design for DER units. However, the proposed solutions are local approaches for controlling each inverter. Even less literature investigates the impact of harmonic propagation in distribution networks. Authors in [10] proposed a method to find locations of major harmonic sources in distribution networks. The authors use the Norton equivalent model for the distribution network which is not a full representative of the network. [11] analyzes harmonic distortion in different types of distribution transformers. [12] conducts a sensitivity analysis to find vulnerable buses in distribution networks. But, the authors use the Thevenin equivalent model at each bus instead of the full topological model of the circuit. [13,14] shows the impact of aggregated harmonics from Distributed Generation units in distribution networks. However, they use a single-phase equivalent line model and do not consider multi-phase line models.

The novelty of this paper is in investigating the system-wide harmonic interaction between different harmonic sources, mainly DERs. In the literature there has been a lack of physical-based, detailed models in harmonic studies. The harmonic investigation in this paper benefits from a detailed distribution network model. The model employed has large numbers of single phase, multi-phase, and unbalanced loads. These details of distribution system modeling have not been addressed in previous harmonic analysis found in the literature.

This paper proposes a new index based on the harmonic source phase angle. In terms of harmonic distortion quantization, the Total Harmonic Distortion (THD) is the most common index in

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Nomenclature

V_h	voltage magnitude for frequency order h
I_h	current magnitude for frequency order h
V_{Total}	total value for voltage magnitude
I_{Total}	total value for current magnitude
V_h^{Ph}	phasor form of voltage for frequency order h
I_h^{Ph}	phasor form of current for frequency order h
θ_h	harmonic current phase angle
φ_h	harmonic voltage phase angle
h	harmonic frequency order
THDV	voltage total harmonic distortion
THDI	current total harmonic distortion
IPHV	voltage index of phasor harmonics
IPHI	current index of phasor harmonics
IHDI	individual harmonic index for current
IHDV	individual harmonic index for voltage
PTM	phase Thevenin equivalent matrix

the literature [15,16]. But, THD is based only on the magnitude of the distorted waveforms. In this paper a new index is proposed called the Index of Phasor Harmonics (IPH). IPH incorporates both magnitude and phase angle information in evaluating distorted waveforms resulting from the interaction of multiple harmonic sources. The advantages of IPH as compared to common harmonic indexes are illustrated in case studies.

This paper also analyzes the interactions of multiple harmonic sources in a three phase, asymmetrical and unbalanced distribution network. The way DER inverters can work together to either decrease or increase harmonic distortion throughout the distribution network is investigated.

The phase coupling impact on harmonic propagation has not been addressed in previous works, especially for distribution networks. Because of short distances between conductors in overhead lines and underground cables, phase coupling in distribution networks needs to be considered in harmonic analysis. In this paper, the IPH index is used to measures the impact of a harmonic sources attached to one phase on other phases.

There are a few papers that consider the impact of phase balance on harmonics [17–19]. However, they are all at the device level. That is, they focus on harmonic and load balancing in transformers and inverters. Another novelty of this paper is analyzing the impact of phase balance at the feeder level on harmonic distortion throughout the whole feeder.

The paper is organized as follows: Section 2 discusses harmonics analysis. Section 3 describes the impacts of source and network characteristics on harmonics. Section 4 presents conclusions and observations.

2. Harmonic analysis in distribution networks

2.1. Indices for measuring harmonic distortion

Harmonic components in AC power systems are sinusoidal waveforms that are integer multiples of the fundamental frequency. The summation of harmonic components results in distorted current and voltage waveforms. Periodic functions of distorted voltage and current are defined by Fourier series as follows

$$I_{\text{Total}} = \sum_{h=1}^{\infty} \sqrt{2} I_h \sin(h\omega_0 t - \theta_h) \tag{1}$$

$$V_{\text{Total}} = \sum_{h=1}^{\infty} \sqrt{2} V_h \sin(h\omega_0 t - \varphi_h) \tag{2}$$

where I_{Dist} and V_{Dist} are the distorted current and voltage at the measurement point, respectively. I_h and V_h are current and voltage r.m.s. values for the hth harmonic order. θ_h and φ_h are harmonic current and voltage phase angles. ω_0 is the fundamental angular frequency and h is the harmonic frequency order. n is number of harmonic orders considered.

The most common index used for measuring harmonics in standards and literature is Total Harmonic Distortion (THD) [16]. THD includes the contribution of the magnitude of each harmonic component as given by

$$\text{THDI} = \frac{1}{I_1}\sqrt{\sum_{h=2}^{\infty} I_h^2} \tag{3}$$

$$\text{THDV} = \frac{1}{V_1}\sqrt{\sum_{h=2}^{\infty} V_h^2} \tag{4}$$

where THDI and THDV are THD values for current and voltage, respectively. I_1 and V_1 are the current and voltage r.m.s. values for the fundamental frequency, respectively.

Another widely used index is Individual Harmonic Distortion (IHD). IHD represents the percentage of each harmonic order amplitude relative to the fundamental voltage or current, as given by

$$\text{IHDI} = \frac{I_h}{I_1} \times 100 \tag{5}$$

$$\text{IHDV} = \frac{V_h}{V_1} \times 100 \tag{6}$$

where IHDI and IHDV are the IHD index for voltage and current, respectively. The THD and IHD are addressed in IEEE-519, IEEE-1547, IEC-610000, and EN50160 and other standards for power quality and distribution network related products [20–22].

In some standards, the conventional definition of power factor is modified to account for the contribution of higher frequencies [16]. The modified power factor is called Total Power factor (TPF). Eq. (7) shows the relationship between TPF and THD [23]:

$$\text{TPF} = \frac{\cos\delta_1}{\sqrt{1 + \text{THDI}^2}} \tag{7}$$

where δ_1 is the angle between voltage and current at the fundamental frequency, where $\cos(\delta_1)$ is called the displacement power factor and the factor $1/\sqrt{1+\text{THDI}^2}$ is called the distortion power factor.

The THD and IHD indices are only based on the magnitude of harmonic components. The TPF only considers the phase angle difference between the fundamental voltage and current vectors. Therefore, the most common indices for harmonic analysis do not account for the phase angles of the higher frequencies harmonic components in harmonic distortion assessment. However, the vectorial characteristics of the harmonic waveforms with higher frequencies do have an impact on the total distorted current or voltage waveforms.

In this paper a new harmonic assessment index, Index of Phasor Harmonic (IPH), is used. The IPH is proposed by authors. More mathematical insight into the index is presented in [24] by authors. The IPH considers information related to both magnitudes and phase angles of the harmonic components based on the waveform orthogonal decomposition. The purpose is to resolve voltage or current values along directions of in-phase component of the