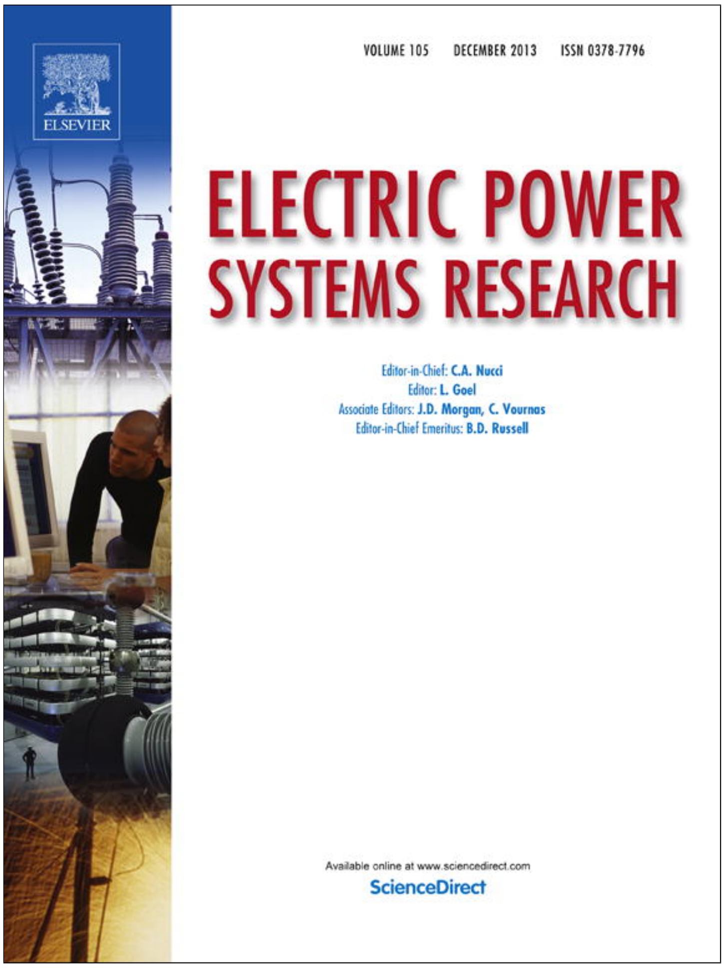
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Harmonic interactions of multiple distributed energy resources in power distribution networks

Reza Arghandeh[a,*], Ahmet Onen[b], Jaesung Jung[b], Robert P. Broadwater[b]

[a] California Institute of Energy and Environment, University of California-Berkeley, Berkeley, CA, USA
[b] Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

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ABSTRACT

The harmonics generated by DER devices can cause distortion in power system voltages and currents. In addition to the power quality issues, loss, and component failures harmonics can have an economic impact on distribution networks. In this paper the authors analyze harmonics produced from multiple sources such as solar, wind and energy storage systems. The aim is simulating harmonic interactions that can lead to concern in distribution networks. Accordingly, a new index for harmonic analysis is proposed to simultaneously consider magnitude and angle of waveform. The effect of generated harmonics from DER is evaluated quantitatively on distribution circuits with the help of data visualization approaches. Harmonic propagation is simulated in a detailed distribution network model to analyze how circuit topology varies harmonics effects. Due to the interaction of different harmonic sources, the sensitivity analysis is conducted to show the impact of each harmonic source magnitude and angle on the overall distribution network total harmonic distortion. Phase balancing impact on harmonic distortion in distribution networks is also considered.

1. Introduction

Smart Grid realization involves a steady increase in inverter-based components like distributed energy resources (DER), energy storage systems, and plug-in electric vehicles. The harmonics related to DER inverters and the spread of power electronic devices raises concerns for power system engineers and operators. The harmonics generated by DER devices and plug-in electric vehicles (PEV) can cause distortion in power system voltages and currents. In addition to the power quality issues, harmonics can have economic impacts on distribution networks. Harmonics can decrease efficiency, create thermal losses and may overload network components. These effects cause premature aging and failure in power system devices.

The harmonic impact study for a single harmonic source is a well-researched topic. Harmonic measurement and filtering are discussed in plenty of literatures. However, conventional researches mostly consider harmonic as a local phenomenon with local effect [1,2]. There are few papers that demonstrate harmonics produced by DER sources like PV and energy storage [3–5]. Even fewer papers study harmonic effects on large scale distribution networks [6–8]. However, the interactive effect of harmonics produced by multi DER sources on each other and their aggregated effect on the distribution system are not addressed in previous literatures. The other uniqueness of this paper is application of the detailed multi-phase model of the distribution network that considers all circuit components, including distribution transformers and secondary distribution. Here harmonics are calculated for each phase throughout the multi-phase system, taking into account the mutual impedances among the phases. This detailed model provides for a more realistic analysis.

Published studies on phase balancing and harmonics have focused on particular devices, such as transformers, or on three-phase unbalanced loads [9,10]. In this paper, the effect of three phase balance on harmonic distortion at the distribution network level is addressed.

This paper discusses harmonics produced from multiple DER sources such as solar, wind and energy storage systems. The aim is simulating and analyzing multi-source produced harmonic interactions that could lead to concern in distribution networks from the view point of voltage and current harmonic content and total harmonic distortion (THD). Traditionally, THD is the most used index for harmonics evaluation in standards and literatures [11,12], but THD is only based on the harmonic magnitude. In this paper a new index is proposed to consider the impact of interactive multi-source phase angle on the harmonic distortion. The proposed index is called index of phasor harmonics (IPH). The sensitivity analysis is

* Corresponding author at: 2087 Addison St, Berkeley, CA 9470, USA. Tel.: +1 949 943 5600.
E-mail address: arghandeh@Berkeley.edu (R. Arghandeh).

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Nomenclature

V_h	voltage magnitude order h
I_h	current magnitude order h
V_{Total}	total value for voltage magnitude
I_{Total}	total value for current magnitude
V_h^{Ph}	phasor form of voltage magnitude order h
I_h^{Ph}	phasor form of current magnitude order h
θh	harmonic current phase angle
φ_h	harmonic voltage phase angle
h	harmonic order
$\alpha_{1ph}, \alpha_{2ph}$	scale coefficients
THDV	voltage total harmonic distortion for each phase
THDI	current total harmonic distortion for each phase
IPHV	voltage index of phasor harmonics for each phase
IPHI	current index of phasor harmonics for each phase
IHDI	current individual harmonic index
IHDV	voltage individual harmonic index

conducted to show the impact of each harmonic source magnitude and angle on overall distortion in the distribution network.

The paper is organized as follows: Section 2 discusses harmonics phenomena in distribution networks. Section 3 describes the principle factors for harmonic analysis in distribution networks. Section 4 presents simulations and results.

2. Harmonics characteristics in distribution networks

2.1. Harmonics and distribution network malfunctions

High level adoptions of distributed generation technologies like solar, wind, fuel cells and microturbines in addition to energy storage, PEVs, and power electronics based components, all within close proximity of one another, create concerns of how harmonics generated by one set of devices may interact with harmonics generated by other devices.

Harmonics can result in various malfunctions and failures in distribution networks. Transformer and conductor overheating and pre-mature aging, neutral conductor overloading, capacitor bank overstressing, abnormalities in protection system operation, thermal effects in electric machines, and control system errors are among the challenges for distribution network operation under harmonics emission [12,13].

From an economic perspective, the harmonics resultant loss will increase the network operational cost. The pre-mature aging of network components caused by harmonics results in higher maintenance costs [14]. Moreover, harmonic distortion can affect energy metering equipment and decrease metering accuracy that can change electricity market transactions [15,16].

2.2. Harmonic measurements and assessments

The AC electricity supply should ideally be a perfect sinusoidal voltage and current signal to every customer. The deviation from the perfect sinusoidal waveform is expressed in distortion terms. Harmonics in voltage and current waveforms can be represented as sinusoidal components with higher integer multiples of the fundamental frequency. Based on the IEEE Standard 1459-2010 [17], nonsinusoidal periodical voltage and current waveform are expressed by Fourier series as given by

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

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

where I_{Total} and V_{Total} are the nonsinusoidal current and voltage. I_h and V_h are current and voltage r.m.s values for the h_{th} 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 harmonics order.

Total harmonic distortion (THD) is an index that is widely used for power quality assessment in distribution and transmission networks. THD is defined for current and voltage respectively as [18]:

$$THDI = \frac{1}{I_1}\sqrt{\sum_{h=2}^{\infty} I_h^2} \quad (3)$$

$$THDV = \frac{1}{V_1}\sqrt{\sum_{h=2}^{\infty} V_h^2} \quad (4)$$

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.

The individual harmonic distortion (IHD) index presents the percentage ratio of current or voltage in the hth harmonic order with respect to the fundamental value. IHDI and IHDV are the IHD for current and voltage respectively as given by

$$IHDI = \frac{I_h}{I_1} \times 100 \quad (5)$$

$$IHDV = \frac{V_h}{V_1} \times 100 \quad (6)$$

Harmonics is a challenging and serious problem in distribution networks. However, interactive harmonic effects of DERS can intensify the problem. The total harmonic distortion (THD) index is only based on signal magnitude [17]. To help quantify the distortion caused by multiple harmonic source interactions, there is a need to consider phase angles of current and voltage waveforms.

The sine identity helps rewrite (1) and (2) in the orthogonal form:

$$I_{Total} = \sqrt{2}\sum_{h=1}^{\infty} I_h \cos(\theta_h)\sin(h\omega_0 t) - \sqrt{2}\sum_{h=1}^{\infty} I_h \sin(\theta_h)\cos(h\omega_0 t) \quad (7)$$

$$V_{Total} = \sqrt{2}\sum_{h=1}^{\infty} V_h \cos(\varphi_h)\sin(h\omega_0 t) - \sqrt{2}\sum_{h=1}^{\infty} V_h \sin(\varphi_h)\cos(h\omega_0 t) \quad (8)$$

In (7) and (8), total current and voltage are separated into two in-phase and in-quadrature components. This waveform separation method is similar to some of apparent power calculation methods for nonsinusoidal apparent power calculation in [19,20]. The (7) and (8) are rewritten as follows:

$$I_{Total} = \sum_{h=1}^{\infty} I_{hP} \sin(h\omega_0 t) - \sum_{h=1}^{\infty} I_{hQ} \cos(h\omega_0 t) \quad (9)$$

$$V_{Total} = \sum_{h=1}^{\infty} V_{hP} \sin(h\omega_0 t) - \sum_{h=1}^{\infty} V_{hQ} \cos(h\omega_0 t) \quad (10)$$

where

$$I_{hP} = \sqrt{2} I_h \cos(\theta_h) \quad (11)$$

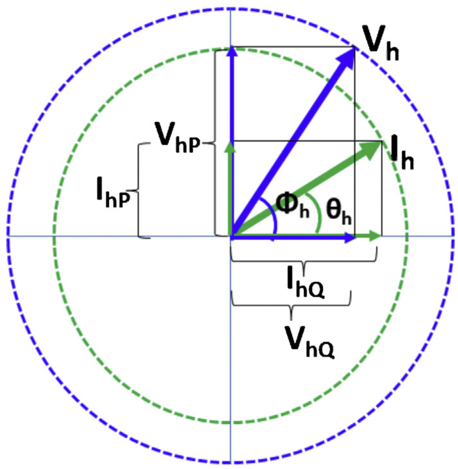


Fig. 1. Phasor diagram for harmonic current and voltage separation.

$$I_{hQ} = \sqrt{2} I_h \sin(\theta_h) \tag{12}$$

$$V_{hP} = \sqrt{2} V_h \cos(\varphi_h) \tag{13}$$

$$V_{hQ} = \sqrt{2} V_h \sin(\varphi_h) \tag{14}$$

The I_{hP} and V_{hP} called in-phase current and voltage components. Similarly, I_{hQ} and V_{hQ} called in- quadrature current and voltage components. In some references in-phase components are called active components and in-quadrature components are called non-active components [21].

In this paper, with help of Eqs. (9)–(14), the index of phasor harmonics (IPH) is proposed. The IPH is obtained by dividing the summation of in-phase harmonic components by the algebraic sum of harmonic waveform magnitudes. The IPH equations are:

$$IPHI = \frac{\sum_{h=1}^{\infty} |I_{hP}|}{\sum_{h=1}^{\infty} |I_h|} \tag{15}$$

$$IPHV = \frac{\sum_{h=1}^{\infty} |V_{hP}|}{\sum_{h=1}^{\infty} |V_h|} \tag{16}$$

where *IPHI* and *IPHV* are index of phasor harmonics for current and voltage waveforms. The purpose is to resolve voltage or current values along directions of in-phase component of the nonsinusoidal waveform. Fig. 1 shows the separation of voltage and current on phasor diagram for the *h*th harmonic order voltage and current.

To compare the total harmonic distortion at downstream (customers) and upstream (substation) of distribution network, the indices of downstream distortion factor (DDF) are proposed as following:

$$DDFV = \frac{THDV_{Customer}}{THDV_{Substation}} \times 100 \tag{17}$$

$$DDFI = \frac{THDI_{Customer}}{THDI_{Substation}} \times 100 \tag{18}$$

where *DDFV* and *DDFI* are downstream distortion factor for voltage and current.

2.3. Harmonics and standards perspective

Harmonic emissions are addressed in a number of standards and recommendations. The most widespread harmonic standards in the United States and the European Union are issued by IEEE and IEC. The harmonics standards can be classified into three categories: (1) standards related to power quality in distribution networks, (2) standards related to devices and harmonic sources, and (3) standards related to distribution network equipment installation and operation [14].

The IEEE-519, IEC-61000-6 and EN-50160 belong to the first group of standards. The IEEE-519 presents a joint approach for customers and utilities to limit nonlinear load harmonics [11]. The EN-50160 focuses on voltage characteristics of public electricity distribution networks [22]. The IEC-61000-6 is mostly focused on harmonic limits for power quality at the planning level [23].

The IEC-61000-3-2 and IEC-61000-3-12 are subsets of the second group. They advocate harmonic limitations for low-voltage equipment [24].

The IEEE-1547-4.3 and IEC-61000-2 are classified under the third group of standards. The IEEE-1547 defines the requirements for distributed resource (DR) interconnections including harmonic distortions in DR applications [25]. The IEC-61000-2 defines harmonic limits for equipment immunity in LV and MV installations [26].

2.4. Architecture of harmonic analysis

In order to conduct harmonic analysis in power systems, the harmonic current propagation in circuits needs to be calculated. The power flow analysis at fundamental frequency is the base for harmonic calculations. The power flow study provides steady-state circuit performance under the normal operating condition.

In addition to the fundamental power flow, the power flow at higher frequency (PFHF) is conducted to determine harmonic current and voltage emissions in the modified circuit for higher frequencies than the fundamental frequency. It means all conductors, transformers, capacitor banks and loads impedances are adjusted with a higher order of fundamental frequency. Moreover, the Thevenin impedance of the substation is modified in order of the higher frequency. Then, harmonic sources inject harmonic current to calculate harmonic propagation in that specific frequency. The steps for harmonic analysis are following.

To represent harmonic currents in Eq. (1), harmonic current sources, including magnitude and phase angle, are applied. These current sources inject harmonic currents at the location of the harmonic source. They are superimposing harmonic currents on top of the fundamental current waveform. The degree of voltage distortion depends on the harmonic current source characteristics and current propagation inside the distribution network. Harmonic current flow is affected by inductive and capacitive impedances, transformers and conductor configurations.

The major steps of harmonic analysis algorithm used here are as follows:

Step 1: Initialize the distribution circuit parameters
Step 2: Run power flow for the fundamental frequency
Step 3: Modify the circuit for calculation of next higher harmonic order
Step 4: Run power flow
Step 5: Store power flow results
Step 6: Check if the specified maximum harmonic order has been reached. If not, go Step 3. If yes, quit.
Step 7: Calculate harmonic indexes

For the power flow calculation, the Distributed Engineering Workstation software package is used. Fig. 2 depicts the algorithm for the harmonic analysis.

2.5. Physical network model and circuit topology

One of the important factors in harmonic propagation is circuit topology. The harmonic simulation results are highly dependent

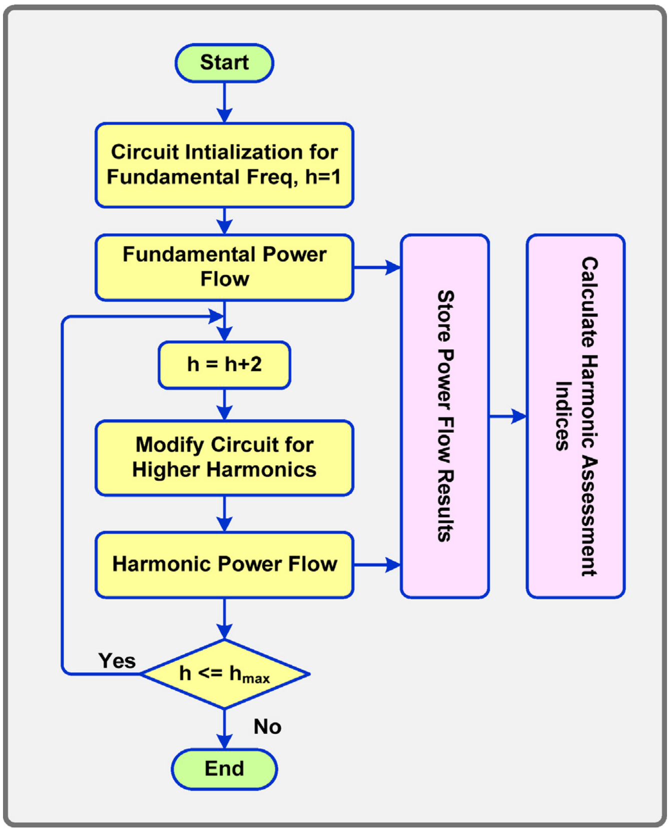


Fig. 2. Harmonic analysis flow chart.

on the circuit model. In this study, the circuit is 13.2 kV, *Y*-connected with 329 residential and commercial customers. The peak load is 9.5 MVA. The circuit model includes unbalanced, multiphase and single phase loads. The circuit contains two sets of three phase harmonic sources. Fig. 3 presents the circuit model.

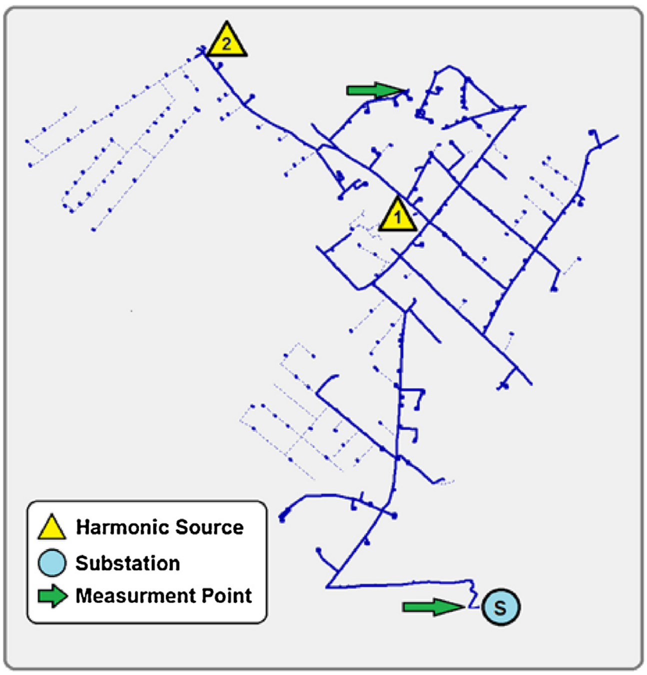
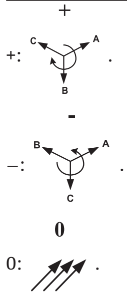


Fig. 3. Schematic of distribution network model.

Table 1
Three phase harmonic angle sequence.

Order	Frequency	Sequence
0	60	+
3	180	0
5	300	–
7	420	+
9	540	0
11	660	–



3. Simulations, results, and discussions

Harmonic current emission through the distribution network is influenced by a number of factors related to the harmonic source and circuit characteristics. In this section, multi harmonic source interactions based on different values of harmonic source magnitudes and angles are analyzed. To investigate three phase circuit loading effects on harmonic distortion, two case studies for unbalanced and balanced circuit are presented.

3.1. Features of simulation

The research objective is to study harmonic impact apart from harmonic source technology. There are two 3-phase harmonic sources in the circuit which represent inverters connected to DER sources. There is no background harmonic distortion in presented scenarios. The phase rotation sequences of the harmonic source phase angles are presented in Table 1, where positive, zero, and negative sequence rotations are indicated with +, 0, and −, respectively [18]. The dominant current and voltage harmonic observed through the simulation are of the 3ed, 5th, 7th, 9th and 11th orders. Harmonics of higher orders are neglected due to their small values [12].

3.2. Impact of harmonic source amplitudes

To show the effects of harmonic current source magnitude on the THD at the substation level, the simulation is conducted for different current magnitudes in the range from zero to ten (0, 2, 4, 6, 8, 10) amperes for both harmonic sources. In this section for harmonic amplitude impact study purpose, it is assumed that all harmonic orders have the same current magnitude. The phase angles follow the sequences in Table 1.

Figs. 4 and 5 show respectively the variation of phase B THDI and THDV at the substation as a function of variation of the harmonic current source magnitudes. The HS in plots means harmonic source.

Both Figs. 4 and 5 illustrate that the THD increases with increasing harmonic source amplitudes, and that the two sources act together to increase the THD. In Figs. 4 and 5, the surface cuts along the *X* (HS1) and *Y* (HS2) axes showing the rate of THDI and THDV increase versus magnitude of each harmonic source. The HS1 and HS2 slopes for THDI are 2.46 and 2.38 respectively. This means HS1 has more impact on total THDI at substation. The HS1 and HS2 slopes for THDV are 0.06 and 0.055 respectively. It is similar to the slopes observed with THDI. The IPHV for phase B is illustrated in Fig. 6.

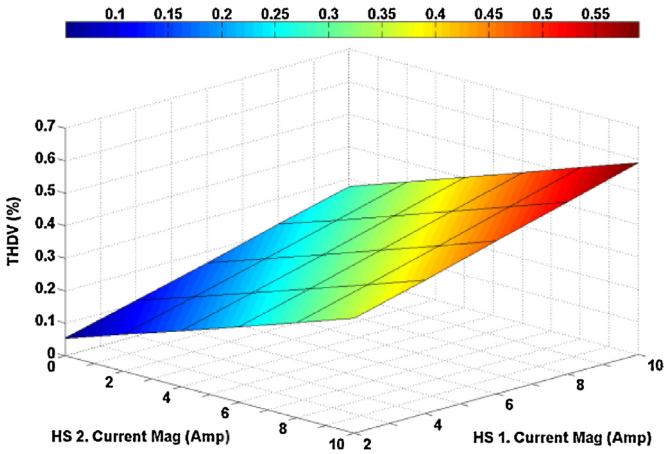


Fig. 4. THDV for phase B as a function of harmonic sources different amplitudes, HS1 and HS2.

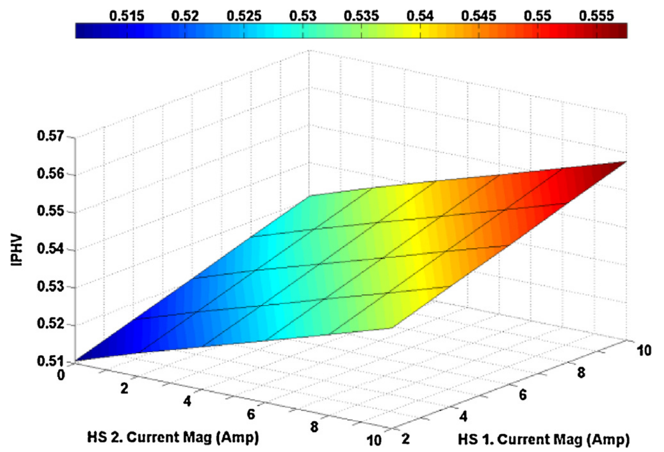


Fig. 6. IPHV for phase B as a function of harmonic sources different amplitudes, HS1 and HS2.

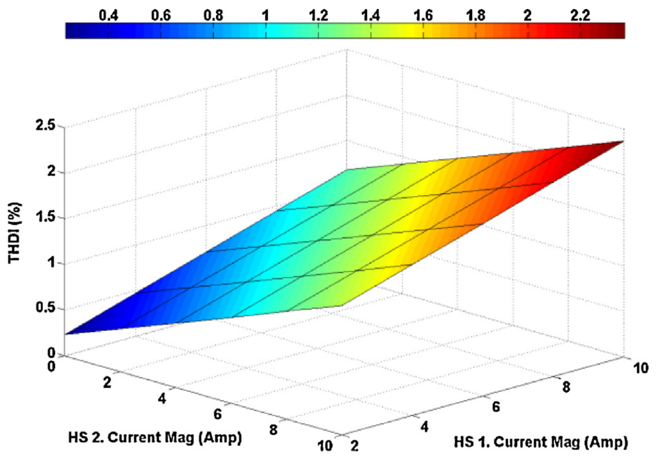


Fig. 5. THDI for phase B as a function of harmonic sources different amplitudes, HS1 and HS2.

Similar THD and IPH trends are observed for phases A and C.

3.3. Impact of harmonic source phase angles

In systems with multi harmonic sources, the injected harmonic current from each source add vectorally. Therefore, it is crucial to study the impact of each harmonic source phase angle on the total harmonic distortion. To perform a sensitivity analysis against phase angle values, a number of harmonic simulations were performed with the phase angles steps for both harmonic sources being varied as follows: (0°, 15°, 30°, 45°, 60°, 75°, 90°). These angles steps are added to the phase angle sequences presented in Table 1. When varying the angles of the harmonic sources, the amplitude of both harmonic sources are maintained at 4 A for all harmonic orders. Fig. 7 depicts the THDV and THDI plots for different phase angle values.

Fig. 7A–C presents THDV for each of the three phases. As it is seen from Fig. 7, the THDV versus angle plot for each phase is significantly different than the other phases. Reasons for the alteration are the different phase loadings (see Table 2), the three phase mutual couplings (see Table 2), and network topology. For example, the portion of single phase lines and underground cables in the distribution network affects the harmonic emissions because of the capacitance characteristics of such conductors.

The distribution network is unbalanced and its phase loading at the substation is presented in Table 2. The values are achieved from the power flow analysis at the fundamental frequency. Table 3 shows the network sequential Thevenin impedance as seen by harmonic source 1 and the harmonic source 2 in Fig. 3.

The THDV surface shapes are similar to the hyperbolic geometrical functions. Fig. 7A shows the THDV for phase A. It is a semispherical cliff with the minimum values at zero phase angles for both sources. The maximum values achieved with 90° phase angle in both sources (*THDV* = 1.27). Fig. 7B presents THDV for phase B. It is a saddle-shaped surface with saddle point at 45° phase angle in both sources (*THDV* = 0.799), the maximum THDV values happen in 0° and 90° angles for both sources. Fig. 7C is similar to a hemispherical plane with its maximum at 45° phase angle for both sources (*THDV* = 1.1).

Fig. 8A–C shows the THDI surfaces for the phases at the substation for the variation over the harmonic source phase angles. Fig. 8A especially has interesting characteristics. There is a canyon on the surface where the THDI values are almost zero. In those near zero points, the harmonic sources cancel out each other and cause the

Table 2
Unbalanced circuit loading.

	Ph. A	Ph. B	Ph. C
Connected load (kW)	818.25	429.58	476.29
Connected load (kVar)	468.53	254.45	273.17
Current flow (A)	126.86	67.31	73.29

Table 3
Network Thevenin impedance as seen by harmonic sources.

		0	1	2
Harmonic source 1	0	0.8063 + 2.9308j	−0.0102 + 0.0138j	0.0086 + 0.0155j
	1	0.0086 + 0.0155j	0.8063 + 2.9308j	−0.0102 + 0.0138j
	2	−0.0102 + 0.0138j	0.0086 + 0.0155j	0.8063 + 2.9308j
Harmonic source 2	0	1.0368 + 3.6547j	−0.0122 + 0.0155j	0.0098 + 0.0179j
	1	0.0098 + 0.0179j	1.0368 + 3.6547j	−0.0122 + 0.0155j
	2	−0.0122 + 0.0155j	0.0098 + 0.0179j	1.0368 + 3.6547j

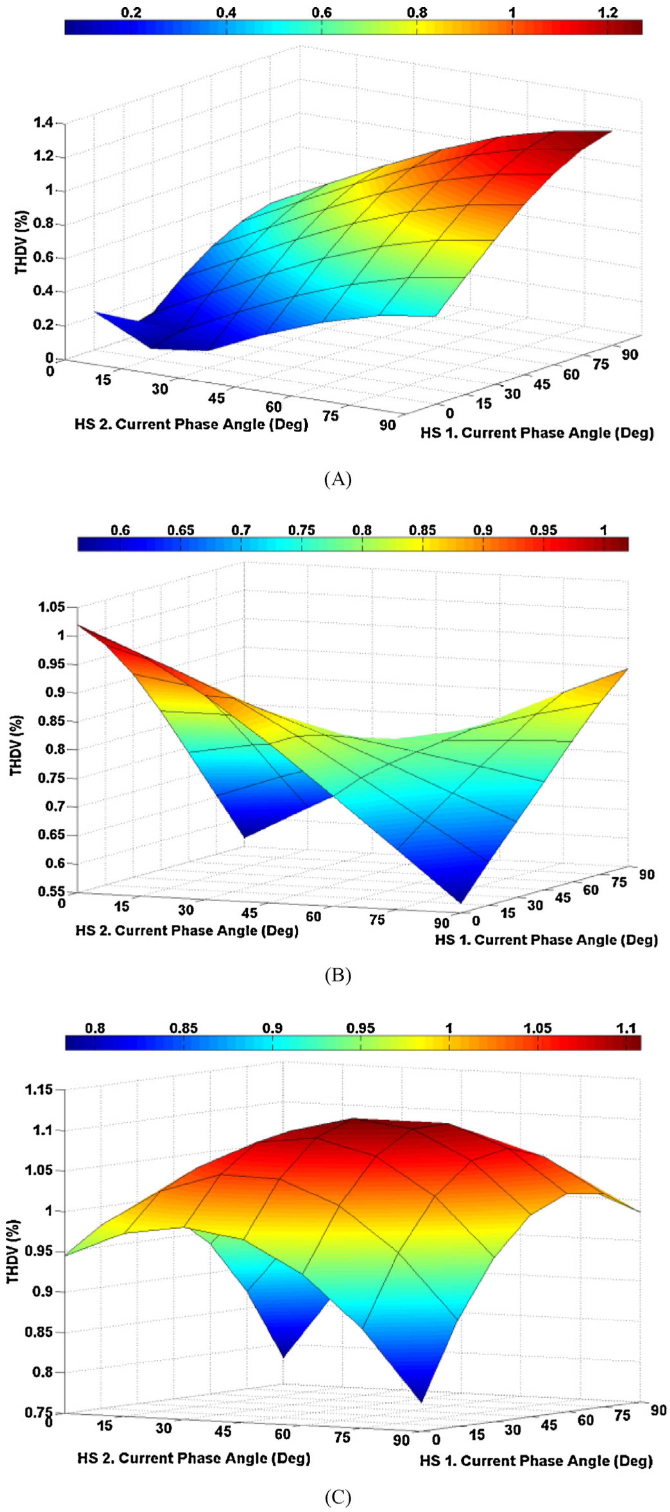


Fig. 7. THDV for phase A (fig. A), B (fig. B), and C (fig. C) as a function of harmonic source 1 (HS1) and harmonic source 2 (HS2) phase angles.

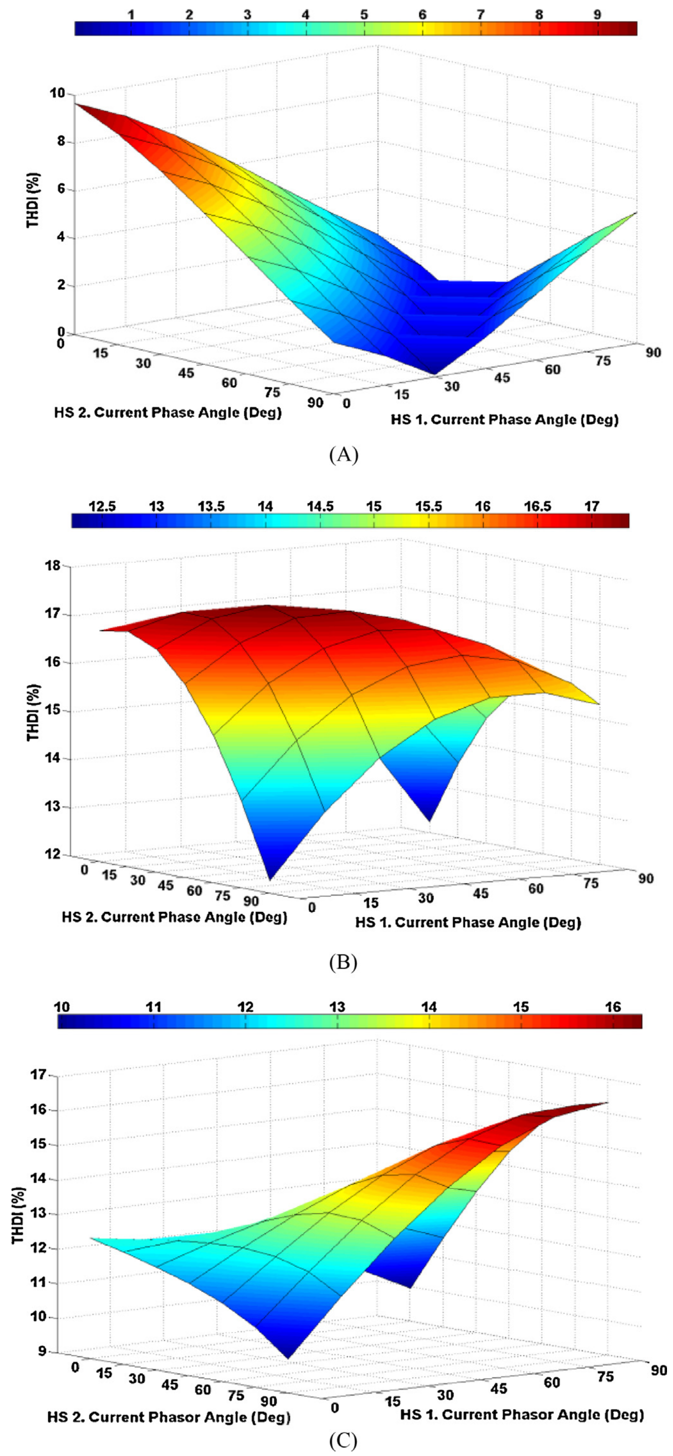


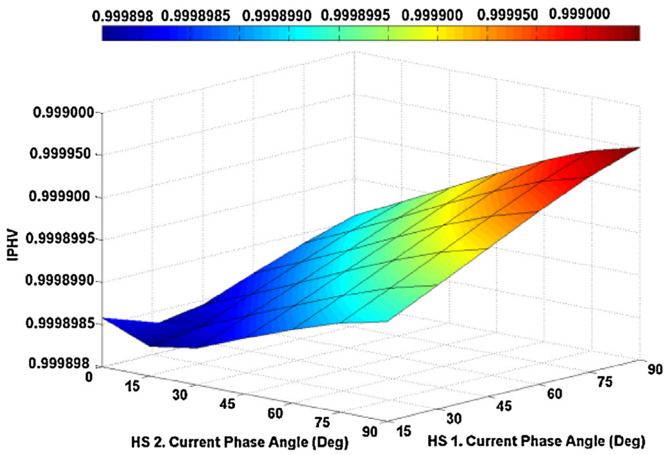
Fig. 8. THDI for phases A (fig. A), B (fig. B), and C (fig. C) as a function of harmonic source 1 (HS1) and harmonic source 2 (HS2) phase angle.

minimum current harmonic distortion. It is an important observation for harmonic distortion cancelation in mutli-source harmonic analysis. Table 4 shows the near zero points (minimum THDI points) for phase A that the canyon in Fig. 8A passes through.

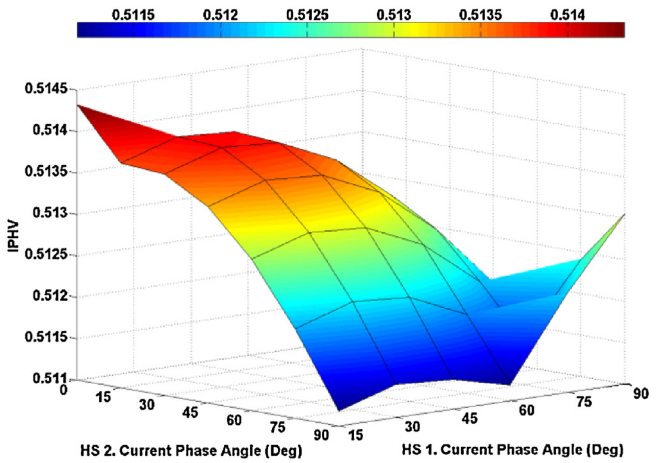
The THDV and THDI observations show the maximum distortion values are around 0°, 45°, and 90° phase angles. For these harmonic source angles, the maximum THDV versus phase angle has the following trend: (Max THDV-Phase A at 90°, Max THDV-Phase B at

Table 4
THDI cancelation for phase A with different phase angles.

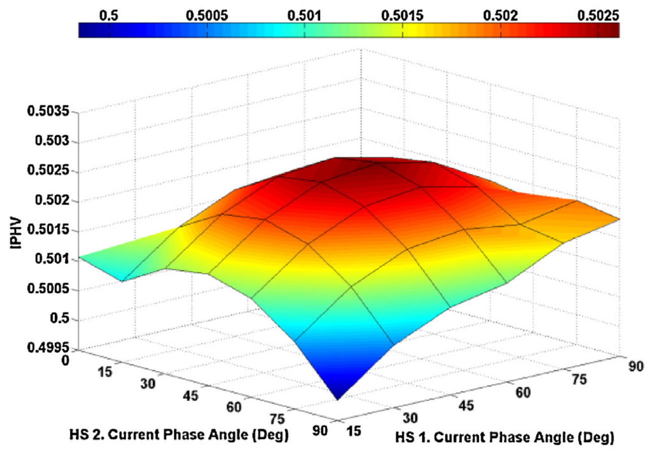
	H source 1 angle (°)	H source 2 angle (°)	Delta angle	THDI (%)
Min THDI 1	30	90	−60	0.074
Min THDI 2	45	75	−30	0.049
Min THDI 3	60	60	00	0.042
Min THDI 4	75	45	+30	0.039
Min THDI 5	90	30	+60	0.043



(A)



(B)



(C)

Fig. 9. IPHV values for harmonic sources 1 and 2 for different phase angles: phase A (fig. A), phase B (fig. B), and phase C (fig. C).

0°, Max THDV-Phase C at 45°). A similar trend for THDI is: (Max THDI-Phase A at 0°, Max THDI-Phase B at 45°, Max THDI-Phase C at 90°).

The presented THD sensitivity analysis shows the harmonic sources' critical angles for voltage and current distortion. It is a helpful tool for harmonic minimization and harmonic control purposes.

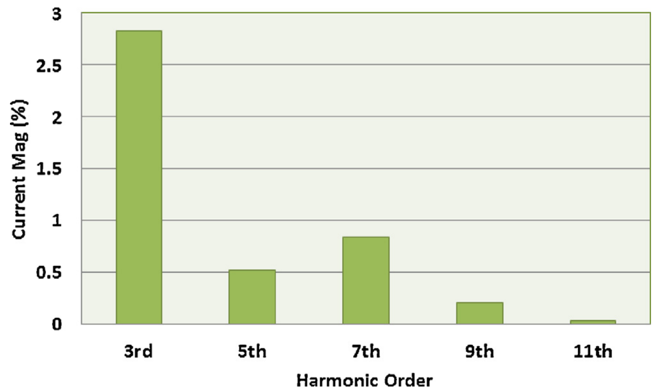


Fig. 10. Harmonic source amplitudes from field measurement data.

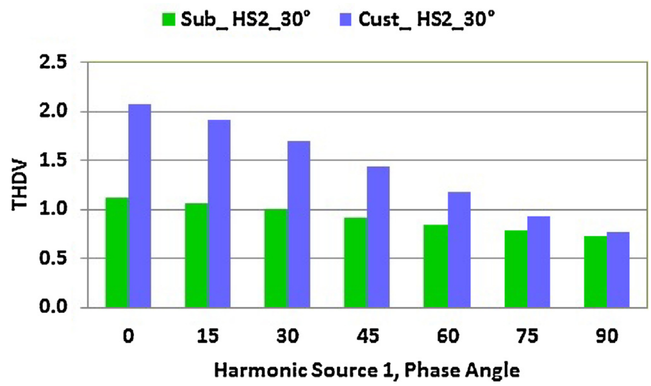


Fig. 11. THDV at the substation and a customer side for phase B.

Fig. 9 shows the proposed index of phase harmonic for voltage (IPHV) which is defined in (10). Because of the contribution of the phase angle in the IPH numerator, IPH contains more information than THD. The IPH values are smaller or equal to 1, because of the "Triangle Inequality" property in a vector space. Comparing the IPHV surfaces in Fig. 9 and THDV and THDI surfaces in Figs. 7 and 8 shows an interesting relationship between IPHV, THDV and THDI geometrical representations for each phase. The IPHV surface geometry is similar to the summation of THDI and THDV surfaces with a different scale.

Fig. 9A presents IPHV for phase A. It shows IPHV increases with phase angle increase in both sources. The trend is less curvy than the THDV. In Fig. 9B, higher IPHVs occur in smaller phase angles. Its geometrical shape is a mix of THDV and THDI. Fig. 9C depicts the IPHV for phase C. It shows the highest IPHV happens at a 45° phase angle for both harmonic sources.

The IPHV observations illustrate that IPH has more information than THDI and THDV, because it contains phase and magnitude values. It simultaneously quantifies aspects of the THDI and THDV characteristics in one index.

3.4. Harmonic impacts at customer side

In this section, the analysis is done on buses located at the far corners of the grid, customer site, to see how harmonic propagation would affect consumers (secondary of distribution transformer). The measurement point is illustrated in Fig. 3. The harmonic amplitudes are based on measurement data from field tests as shown in Fig. 10. The customer side measurement point is between the harmonic sources.

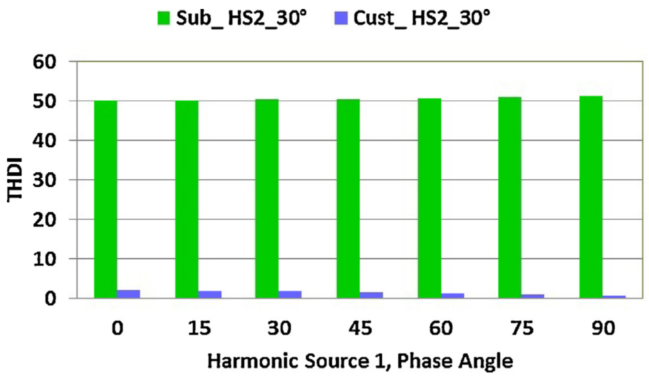


Fig. 12. THDI at the substation and a customer side for phase B.

Table 5
DDFV and DDFI for HS1 different phase angles and HS2 30° phase angle.

Harm source 1 phase angle	DDFV	DDFI
0°	185.79	4.15
15°	179.37	3.82
30°	169.65	3.37
45°	155.96	2.85
60°	138.48	2.31
75°	119.61	1.84
90°	104.85	1.50

The phase angle for harmonic source 1 is varied from 0° to 90° degrees and the harmonic source 2 has 30° phase angle. Fig. 11 shows the THDV values at the substation and at the customer load. Fig. 12 presents the THDI values at the substation and at the customer load.

To have a quantified comparison among substation and customer harmonic distortion, the downstream distortion factor for voltage and current (DDFI and DDFV) are calculated. Table 5 provides DDFV and DDFI values. Figs. 11 and 12 and Table 5 show the substation experiences more distortion in current than the customer load. However, the customer load is exposed to higher harmonic voltage distortion.

Since the impedance looking back into the substation is much smaller than the customer load impedance, a higher portion of harmonic currents flow to the substation than to the customer site. Therefore, the substation has more THDI. In this case study, the voltage distortion is larger at the customer load. Voltage is the product of impedance and current. The customer load impedance is much larger than the impedance of the path to the substation. The current through the load side is less, but the product of current and impedance for the customer side is higher than for the substation side. Therefore, more voltage distortion is realized at the customer side.

The presented results in this section show the importance of system-wide harmonic distortion analysis from substation till customer sides. At the time that harmonic level at customer side seems normal, substation may experience high level of harmonic distortion. Moreover, the appropriate voltage distortion at any point can be simultaneous with high current distortion. Such this observations need to be consider in distribution networks harmonic analyses.

3.5. Impact of three phase balancing on harmonics

Three phase unbalance can affect harmonic distortion. In this section three phase balancing impacts on harmonics are assessed with THDI, THDV and IPHV before and after phase balancing. Table 6 shows the three phase currents at the substation for the unbalanced and balanced cases. Note that the balancing changes the phase impedances throughout the circuit [27].

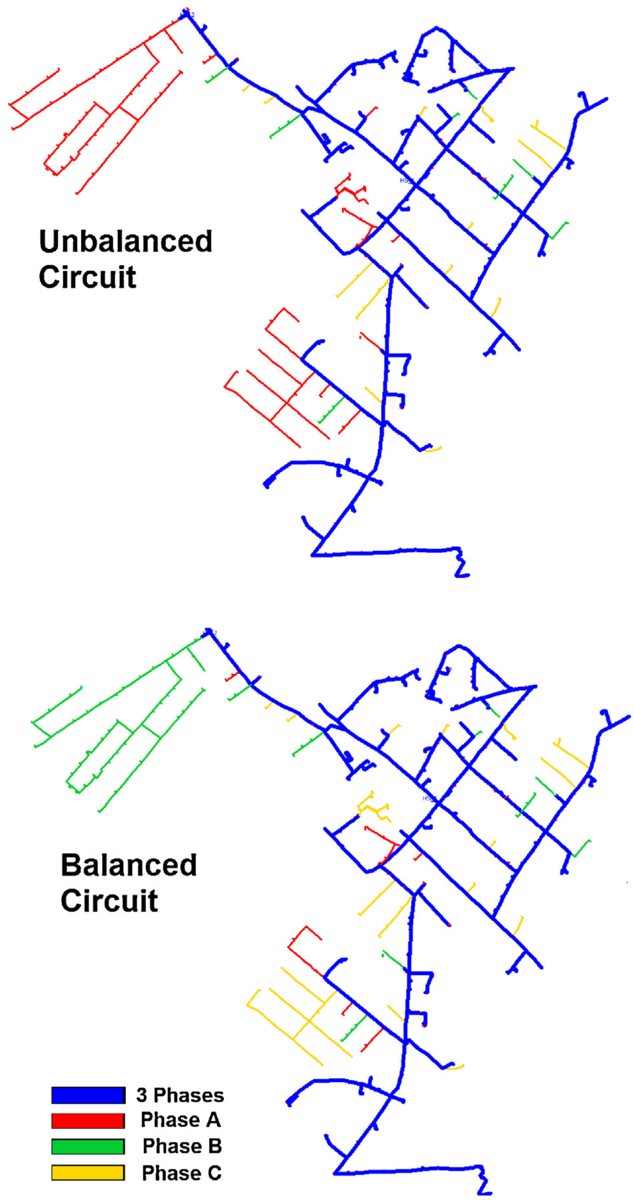


Fig. 13. Circuit colored by phases before and after phase balancing, red = phase A, green = phase B, yellow = phase C. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

To balance the circuit, 9 phase moves are conducted to migrate current from phase A to phase B and phase C. Fig. 13 shows circuit phasing before and after phase balancing, (compare phase A with red color in balanced and unbalanced circuits).

Fig. 14 compares the THDV for the balanced and unbalanced conditions, where the THDV is calculated at the substation. The THDV in balanced condition decreased slightly for all phases.

In Fig. 15, THDIs for the balanced and unbalanced conditions are compared. THDI in phases B and C decreased, but it increased in phase A. It is worthwhile to mention that the maximum THDI at

Table 6
Substation three phase currents.

Currents at substation	Ph. A (A)	Ph. B (A)	Ph. C (A)
Balanced circuit	93.52	84.03	90.46
Unbalanced circuit	126.86	67.31	73.29

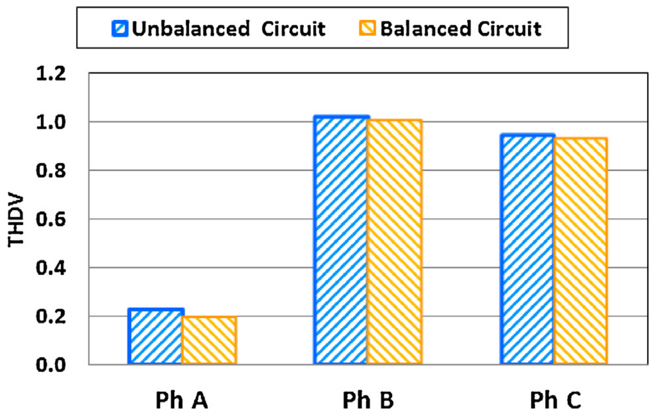


Fig. 14. THDV comparison of balanced and unbalanced conditions.

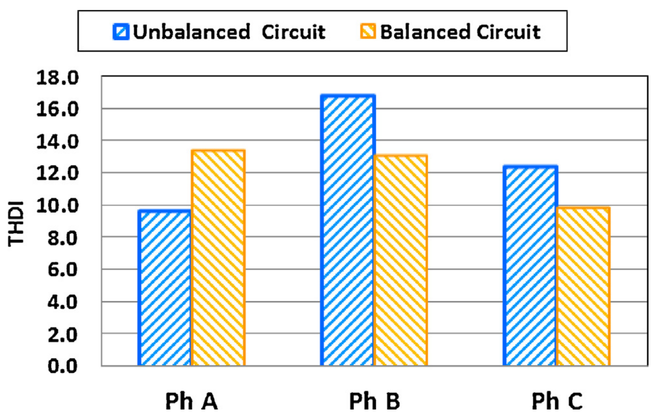


Fig. 15. THDI comparison of balanced and unbalanced conditions.

Table 7
IPHV values by phases before and after phase balancing.

IPHV	Ph. A	Ph. B	Ph. C
Balanced circuit	0.99990	0.51432	0.50107
Unbalanced circuit	0.99994	0.51608	0.49953
ΔIPHV (unbal – bal)	+0.00004	+0.00176	−0.00154
Σ(ΔIPHV) = −0.00026			

the unbalanced condition is 16.79 for phase B, and it decreased to 13.42 for phase A at the balanced condition.

THDI and THDV data presented in Figs. 14 and 15 show three phase balancing decreases distortion in voltage and current waveforms at the substation level. Three phase balancing also reduces the neutral currents and consequently decreases third harmonic components [28].

In Table 7, IPHV values for two cases are compared. The IPHV for phase A and phase B increases and it decreases slightly for phase C. The IPHV shows improvement in phase A and B of balanced circuit in term of harmonic voltages vector addition (with considering angles). The summation of three phases IPHV is a positive number that shows total improvement in balanced circuit from harmonic distortion point of view.

4. Conclusions

The domain of harmonic propagation in distribution networks needs to be extended due to the steady increase in inverter based components in the smart grid. In this paper, the authors evaluate multi-source harmonic distortions with the help of a detailed distribution network model with secondary system customer loading modeled. Moreover, a new index, index of phasor harmonics (IPH), is proposed for harmonic analysis in multi-harmonic source cases. Several simulations and analysis were performed on the distribution network model based on commonly used harmonic indices and the proposed IPH index. The main outcomes of this paper are as follows.

(1) The proposed IPH index presents more information than THD because it incorporates phase angle information in addition to the harmonic source magnitudes, which is crucial in multi-harmonic source cases. The geometrical visualization approach is used to show the effectiveness of IPH in comparison with THDI and THDV.
(2) Multi harmonic source magnitudes act together to change the harmonic distortion in the circuit. In the case of harmonic source magnitude increases, the distortion increases at the substation with increases in the harmonic source magnitudes. The harmonic source that is closer to the substation has more impact.
(3) Multi harmonic source phase angles have a more complex impact on harmonic propagation because of the vectorial impact of injected harmonic currents. The way that phase angles act together is highly dependent on the network topology, mutual conductor impedances and phase balance. The resultant harmonic distortion in the distribution network can increase or decrease due to the deviation of phase angles in different harmonic sources. In some cases, phase angles can result in canceling out the interactive multi harmonic source distortion. Moreover, the phase angles that apparently boost harmonic distortion need to be observed precisely. In this paper, the THD and IPH indices along with the geometrical data visualization show how phase angle variations affect harmonic distortion.
(4) Phase balance is a significant factor for harmonic emission in distribution networks. In this paper it is demonstrated that phase balancing can help reduce harmonic distortion.
(5) Harmonic impacts on customer loads and at the substation are evaluated. THD observations shows more current distortion at the substation than at the customer load. However, more harmonic voltage distortion is experienced at the customer load. In harmonic studies and in harmonic measurements, harmonic values should be considered throughout the circuit.

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