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A New Assessment for the Total Harmonic Contributions at the Point of Common Coupling

Jong-Hoon Han*, Kyebyung Lee*, Chong Suk Song*, Gilsoo Jang†, Gilsung Byeon and Chang-Hyun Park*****

Abstract - A new method to determine the total harmonic contributions of several customers and the utility at the point of common coupling is presented. The proposed method can quantify the individual harmonic impact of each suspicious harmonic source at the point of common coupling. The individual harmonic impact index is then used to assess the total harmonic contribution of each harmonic source. This index can be calculated by the results processed from instantaneous harmonic voltage and current phasor values. The results demonstrate the performance of the proposed method in terms of steady-state accuracy and response to time-varying operating conditions. The proposed index can be used for billing purposes to control harmonic distortion levels in power systems.

Keywords: Harmonic analysis, Harmonic distortion, Harmonic source, Parameter estimation, Point of common coupling, Power quality.

1. Introduction

Power electronic loads have contributed greatly to the efficiency and controllability of modern electric power systems. However, harmonic disturbances are generally produced by them, with nonlinear voltage-current characteristics. Non-sinusoidal currents are drawn from AC power systems, and these currents react with system impedances to create voltage harmonics. It is clear that harmonic distortion levels in distribution feeders rise as power electronic loads continue to proliferate.

In line with the proliferation of various sources of harmonic pollution, electric utilities and end users of electric power are becoming increasingly concerned about harmonic distortions. The current international standards of power quality such as IEEE Std. 519 and the IEC 61000-3 suggest limits on the amount of harmonic currents and voltages generated by customers and utilities. They also define measurement methods for the evaluation of harmonic distortion with respect to individual or total harmonic distortion factors. However, a major concern is the need to separate the harmonic contribution at the point of common coupling (PCC) if the limits are exceeded.

Even though several studies have been introduced to identify harmonic sources, a problem arises when there are several suspicious loads that can be candidates for harmonic sources. A qualitative Yes or No answer is not sufficient in this case, since all the suspicious loads including linear loads are likely to create voltage distortions at the PCC. Methods using harmonic active power or nonactive power components of the apparent power provide only positive or negative value to detect the dominant harmonic sources upstream or downstream from metering sections [1, 2]. Such approaches cannot provide correct information about the identification of the harmonic sources in some practical situations [2].

A method for the quantitative allocation of responsibility among a utility and customers connected at a PCC has been recently presented [3]. This technique was proposed for estimating the contribution of all participants to voltage waveform distortion at the PCC. However, this method is controversial, as it is based on new concepts that still need thorough investigations before confirming complete success. These basic assumptions, such as constant impedance of the electricity supply network, are only intuitively sound. In addition, there is some vagueness in quantifying the contributions of the customer and the utility using complex numbers. If these contribution values, which are out of phase, are compared with one another, it can be unfair to charge a penalty that is commensurate with harmonic pollution level for harmonic sources.

Therefore, based on the basic state estimation technique, the identification algorithm for the Thevenin equivalent circuit parameters was used to quantify the harmonic impact of each suspicious harmonic source at the PCC in this paper. The total harmonic contribution index of each participant at a specific PCC is proposed by using an

† Corresponding Author: School of Electrical Engineering, Korea University, South Korea. (gjang@korea.ac.kr)
* School of Electrical Engineering, Korea University, Seoul, Korea. ({hanpro, keybyung, chong_suk}@korea.ac.kr)
** Smart Distribution Research Center, Korea Electrotechnology Research Institute, Changwon, Korea. (gsbyeon@keri.re.kr)
*** Dept. of Electrical Engineering, Pukyung National University, Pusan, Korea. (spch@pknu.ac.kr)
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individual harmonic impact index. This index can be used for the billing purposes to control harmonic distortion levels in power systems. The results show that the proposed algorithm provides good steady-state accuracy performance and response to time-varying operating conditions.

This paper is organized as follows: Section II describes the problem and establishes an index to quantify the total harmonic impacts of loads. Section III presents the proposed method. The proposed method is further characterized through case studies in Section IV. Finally, conclusions are drawn in Section V.

2. Problem Description

Harmonic voltages at the PCC on a distribution network are not only determined by the harmonic currents produced by harmonic sources, but also related to network impedance variations. The focus of this paper is to improve the technical problems of the previous works. These problems are:

To isolate the influence of the network impedance variations on the harmonic current at a PCC. These changes in the network impedance can have a positive or negative impact on the harmonic voltage distortion at the PCC. However, the customers connected at the PCC cannot be responsible for the effect.

To intuitively quantify the responsibility of several customers and utility to the total harmonic disturbance level at the PCC. Accordingly, harmonic sources can be reasonably penalized for the contribution for which only they are responsible.

2.1 Network impedance model

The network impedance can be defined as a Thevenin equivalent model as viewed from the PCC. Fig. 1 shows a single phase utility's equivalent circuit of general distribution systems at the PCC. We assume that large industrial customers are normally supplied by an exclusive feeder, and the impedance of $Z_{h,T}$ is considered to be the constant sum of the impedance of the transformer and the feeder's impedance up to the PCC. Several methods and techniques for the estimation of the Thevenin equivalent impedance model have been proposed. Such methods usually require two or more sets of measurements for the voltage and current at the monitoring location [4]. In addition, one study introduced that the network impedance at the point of connection should be measured [5], using one of the methods described in previous studies [6, 7]. The method of estimating the network impedance is still an important challenge, and discussion of this issue is beyond the scope of this paper.

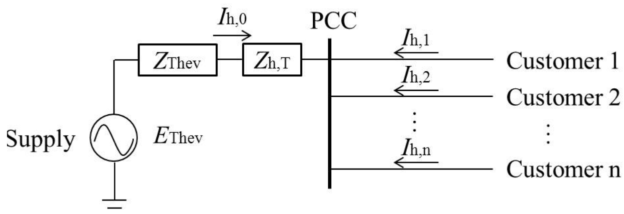


Fig. 1. Simple distribution network with several feeders connected to a PCC

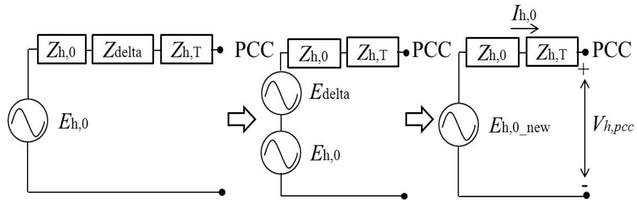


Fig. 2. New equivalent circuit for the utility feeder considering network impedance variation

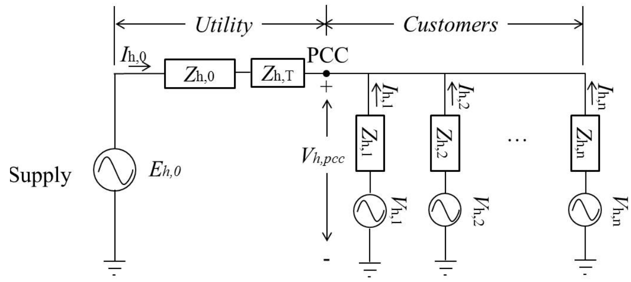


Fig. 3. Equivalent circuit of a common distribution feeder with several composite customers

Since the impedance of the electricity supply network at any time is determined by the characteristics of all the network components, small variations of the network impedance may increase or decrease harmonic current injection into the supply system. One simple idea proposed with a few modifications was to convert the Thevenin impedance variation into an equivalent voltage source variation to prevent the effect of network impedance change on the harmonic contribution from customers, as shown in Fig. 2 [8]. Using Kirchhoff's voltage law, the new equivalent voltage source $E_{h,0\_new}$ can be determined as follows:

$$E_{h,0\_new} = V_{h,pcc} + I_{h,0}(Z_{h,0} + Z_{h,T}) \quad (1)$$

where the subscript h means harmonic frequency, $V_{h,pcc}$ is the voltage phasor at the PCC, $I_{h,0}$ stands for the current phasor at the utility side, and $Z_{h,0}$ represents the network impedance. This allows the influence of the network impedance change and the harmonic contribution from customers to be decoupled.

2.2 Individual harmonic impact

A common feeder in a distribution system is considered as illustrated in Fig. 1, which represents an individual customer or several customers supplied by a main feeder in the system. Since each customer may contain any harmonic source or linear loads, the measured currents of the feeder may contain the composite harmonic impact. Fig. 3 shows the equivalent circuit of Fig. 1 at the PCC. Applying the superposition principle, the individual harmonic current emission level $IHC_{h,k}$ and the individual harmonic voltage emission level $IHV_{h,k}$ of feeder k ($k=0,1,\ldots,n$) at the h^{th} harmonic frequency can be described by the following equations:

$$IHC_{h,k} = \frac{V_{h,k}}{Z_{h,k} + Z_{h,k,shunt}} \tag{2}$$

$$IHC_{h,0} = \frac{E_{h,0}}{Z_{h,0} + Z_{h,T} + Z_{h,0,shunt}} \tag{3}$$

$$IHV_{h,k} = \frac{Z_{h,k,shunt}}{Z_{h,k} + Z_{h,k,shunt}} \times V_{h,k} \tag{4}$$

$$IHV_{h,0} = \frac{Z_{h,0,shunt}}{Z_{h,0} + Z_{h,T} + Z_{h,0,shunt}} \times E_{h,0} \tag{5}$$

$$Z_{h,k,shunt} = \frac{1}{\dfrac{1}{Z_{h,0} + Z_{h,T}} + \sum_{j=1, j\neq k}^{n} \dfrac{1}{Z_{h,j}}} \tag{6}$$

$$Z_{h,0,shunt} = \frac{1}{\sum_{j=1}^{n} \dfrac{1}{Z_{h,j}}} \tag{7}$$

where $Z_{h,0}$ and $Z_{h,k}$ are the equivalent impedances of a utility and a feeder k at the h^{th} harmonic frequency, $E_{h,0}$ and $V_{h,k}$ are the equivalent voltage sources of a utility and a feeder k at the h^{th} harmonic frequency, and $Z_{h,0,shunt}$ and $Z_{h,k,shunt}$ are the equivalent impedances as viewed from a utility and a feeder k at the h^{th} harmonic frequency, respectively.

Since there are some ambiguities in quantifying the contributions of the utility and customers using the complex number in equations (2-5), it is reasonable to refer to scalar quantities using the scalar projection onto the harmonic current or voltage at the PCC. Using the dot product of complex vectors, the individual harmonic current impact $IHCI_{h,k}$ and the individual harmonic voltage impact $IHVI_{h,k}$ of feeder k at the h^{th} harmonic frequency can be described by the following equations:

$$IHCI_{h,k} = \frac{Re(IHC_{h,k} \cdot IHC_{h,pcc})}{|IHC_{h,pcc}|} \tag{8}$$

$$IHVI_{h,k} = \frac{Re(IHV_{h,k} \cdot V_{h,pcc})}{|V_{h,pcc}|} \tag{9}$$

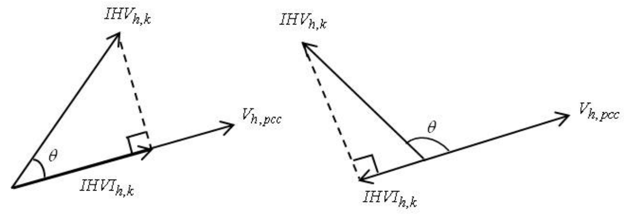


Fig. 4. Scalar projection of *IHVh, k* on to the harmonic voltage at a PCC

$$IHC_{h,pcc} = \sum_{k=0}^{n} (\mathrm{IHC}_{h,k}) \tag{10}$$

where Re( ) is the real part of a complex number, a symbol ‘ ’ is the dot product defined by $\mathrm{a} \cdot \mathrm{b} = \sum_{i=1}^{m} \mathrm{a}_i \overline{b_i}$ (m is the dimension of the vector space, $\overline{b_i}$ is the complex conjugate of b_i), and the symbol $|\,|$ is an absolute value of the complex number. Because both $IHCI_{h,k}$ and $IHVI_{h,k}$ can have positive or negative values, they can encourage or discourage the harmonic current and voltage at the PCC as shown in Fig. 4.

2.3 Total harmonic contribution

The total harmonic contribution for the current and voltage at a feeder k (0~n) can be described as follows:

$$THC_{I,k}^{sign} = \frac{\sqrt{\sum_{h=2}^{h\max} \left(IHCI_{h,k}^{sign} \right)^2}}{\left| IHCI_{1,total} \right|} \times 100\% \tag{11}$$

$$THC_{V,k}^{sign} = \frac{\sqrt{\sum_{h=2}^{h\max} \left(IHVI_{h,k}^{sign} \right)^2}}{\left| IHVI_{1,total} \right|} \times 100\% \tag{12}$$

$$IHCI_{1,total} = \sum_{k=0}^{n} IHCI_{1,k} \tag{13}$$

$$IHVI_{1,total} = \sum_{k=0}^{n} IHVI_{1,k} \tag{14}$$

where the superscript $sign \in \{positive, negative\}$, and h max is the highest harmonic order. A positive $IHCI_{h,k}$ or $IHVI_{h,k}$ indicates the same direction as the harmonic current or voltage of the PCC, respectively, and vice versa for a negative sign. It is recommended to use the same sign of an individual harmonic impact to calculate the total harmonic contribution.

From the perspective of the harmonic current, $\mathrm{THC}_{I,k}^{positive}$ represents the normalized Euclidean norm of the $\mathrm{IHCI}_{\mathrm{h,k}}^{\mathrm{positive}}$ set, which has the effect of adding the harmonic flow at the PCC. In contrast, $\mathrm{THC}_{\mathrm{h,k}}^{\mathrm{negative}}$ includes the $\mathrm{IHCI}_{h,k}^{negative}$ set, which has the effect of decreasing the harmonic flow at the PCC. $THC_{V,k}^{sign}$ also has identical notions. This index can be used for billing purposes to charge harmonic sources an amount in proportion to their harmonic contribution level when the limits are exceeded.

3. Proposed Approach

The proposed technique is based on the measurement of the waveforms of the single-phase voltages and currents at the PCC. The block diagram of the proposed method is given in Fig. 5. In the first step, the original raw voltage and current signals are acquired by data acquisition devices at the PCC. The measured signals are denoted by $V(t)$, the voltage phasor at the PCC, and $I(t)$, the current phasor of each feeder. The voltage and current measurement noise are assumed to be zero-mean Gaussian white noise with variance σ^2. In the second step, an extended Kalman filter (EKF), a linear Kalman filter (LKF), and a constrained recursive least-squares (RLS) algorithm are implemented for the data processing. After the fundamental frequency (f_1) of measured input signals is estimated by the EKF, the harmonic voltage and current phasors ($V_{h,pcc}, I_{h,k}$) are estimated using the LKF. Then, a constrained RLS estimation algorithm is used to estimate the Thevenin equivalent model of customers connected at the PCC. Finally, the total harmonic contributions for current and voltage, $THC_{I,k}$ and $THC_{V,k}$, are calculated according to (11) and (12) in the third step.

3.1 Extended kalman filter

Various relevant techniques have been introduced. Such methods including Kalman filtering, least squares, PLL, and Prony-based approaches have been used to estimate power systems' fundamental frequencies. These methods had strengths and drawbacks [9], but a modified EKF algorithm [10] was used to track the fundamental frequency f_1 for the convenience of implementation in this paper.

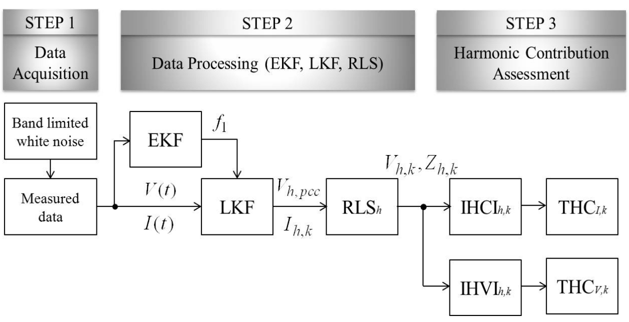


Fig. 5. Block diagram of the proposed total harmonic contribution estimation method

3.2 Linear kalman filter

The harmonic spectral decomposition was obtained by applying an LKF. The optimal tracking of harmonic components based on the Kalman filtering approach is provided in detail in another study [11]. In the proposed LKF algorithm, however, f_1 is used as an input of LKF, so as to more accurately define harmonic frequencies, since accurate harmonic spectral analysis relies much on the correct identification of the fundamental frequency of the measured signals. The proposed LKF can detect any harmonic components which are concerned by user because a harmonic order can be an input parameter to compute LKF algorithm regardless of integer or not. The LKF can give an optimal estimation that considers the presence of white noise in the measurement process and no spectral leakage, which is very critical when the system frequency deviates from the nominal value.

3.3 Recursive least square

The estimated harmonic voltage and current phasors ($V_{h,pcc}, I_{h,k}$) are used to identify Thevenin equivalent parameters ($V_{h,k}, Z_{h,k}$) for customers by the RLS algorithm [12]. The proposed RLS with a forgetting factor is able to track the changes of the Thevenin equivalent circuit parameters of feeders, regardless of the composition of nonlinear and linear loads. The RLS algorithm continues to iterate until all customer's individual harmonic current/ voltage impact values are calculated in parallel for each harmonic frequency.

In addition, the proposed methods can be extended to the case of unbalanced power systems using the symmetrical component transformation:

$$\begin{bmatrix} V_{pcc,h}^{p} \\ V_{pcc,h}^{n} \\ V_{pcc,h}^{z} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_{pcc,h}^{a} \\ V_{pcc,h}^{b} \\ V_{pcc,h}^{c} \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} I_{h,k}^{p} \\ I_{h,k}^{n} \\ I_{h,k}^{z} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_{h,k}^{a} \\ I_{h,k}^{b} \\ I_{h,k}^{c} \end{bmatrix} \tag{16}$$

where superscripts *p, n,* and *z* mean positive, negative and zero sequences, and superscripts *a, b,* and *c* stand for three phases, with $\alpha = 1\angle 120°$, respectively. The equations described in the previous section for estimating the total harmonic contribution can be applied to each sequence at each harmonic frequency. For example, the positive-sequence voltage and current phasors measured at a PCC are used to estimate the positive sequence total harmonic contribution for voltage and current. In a similar manner, the zero and negative sequence total harmonic contribution can be calculated.

4. Case Studies

The proposed algorithms are tested in four case studies which are summarized in Table 1. The three-phase 13.2kV-60Hz test system is assumed to be balanced in all its components. A main feeder supplying two industrial customers is considered, as shown in Fig. 6. The PSCAD/ EMTDC is used to generate the instantaneous waveforms of the voltages and currents in the test system for each case. The voltage and current data with 20000 samples of each waveform over a 2-s window were measured by at the PCC of the test system and were processed using MATLAB. The basic execution procedure with key variable quantities is simplified in Fig. 7 [13].

Table 1. The summary of case studies

	Case A	Case B	Case C	Case D
Customer 1	Constant	Constant	Variable	Variable
Customer 2	Constant	Constant	Variable	Variable
Network Impedance	Constant	Variable	Constant	Variable

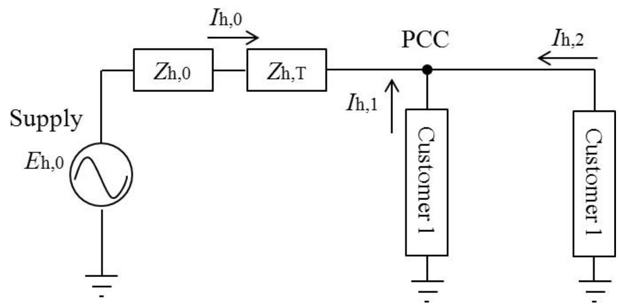


Fig. 6. Test utility feeder with two customers

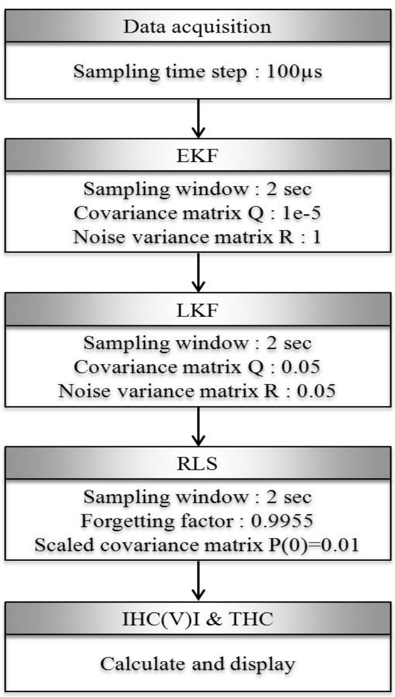


Fig. 7. The execution process with key variable quantity

For simplicity, the network impedance with $Z_{h,T}$ is represented by a series combination of a 1-Ω resistor and a 1-mH inductor. The impedances of the two customers comprise the series combination of a 5-Ω resistor and a 10-mH inductor, and a 3-Ω resistor and a 5-mH inductor, respectively. We assume that the voltage source of the utility side generates sinusoidal waveforms with random white noise. The voltage source behind the customer's impedance comprises the fifth, seventh, eleventh, and thirteenth harmonic components for nonlinear loads. The harmonic components of input data are shown in Table 2.

4.1 Case A: Steady-state conditions

Table 3 shows the estimated customer's parameters and their exact values. The calculated individual harmonic impact and total harmonic contribution are shown in Table 4. The scalar values of IHCI and IHVI are the average kA and kV in a steady state condition, respectively. In the case of IHVI, customer 2 is responsible for around 78% of the 5th harmonic voltage at the PCC. Customer 1 and the utility are responsible for 21% and 0.1% of the 5th harmonic voltage at the PCC, respectively. IHVI normalized by $|IHVI_{1,total}|$ is displayed graphically by bar graph in Fig. 8. It is worth noting that this normalized value can be directly

Table 2. The harmonic components of input data

Harmonic Order (h)	$V_{h,pcc}$ [kV]	$I_{h,1}$ [kA]	$I_{h,2}$ [kA]
5th	0.64∠81.93°	0.05∠20.36°	0.25∠19.68°
7th	0.47∠83.71°	0.03∠14.47°	0.14∠14.32°
11th	0.14∠85.48°	0.016∠7.72°	0.016∠9.93°
13th	0.05∠96.10°	0.005∠6.43°	0.004∠8.60°

Table 3. Simulation results for the customer model estimation

Harmonic Order (h)	$Z_{h,1}$[Ω] (Exact)	$Z_{h,1}$[Ω] (Estimated)	$V_{h,1}$[kV] (Exact)	$V_{h,1}$[kV] (Estimated)
5th	5+ j20.48	5.00+ j20.45	1.41 ∠79.2°	1.36 ∠86.84°
7th	5+ j28.68	5.00+ j29.21	1.13 ∠90.29°	1.08 ∠87.70°
11th	5+ j45.06	5.00+ j46.45	0.71 ∠90.25°	0.67 ∠88.26°
13th	5+ j53.26	5.00+ j56.30	0.28 ∠97.37°	0.27 ∠88.64°
Harmonic Order (h)	$Z_{h,2}$[Ω] (Exact)	$Z_{h,2}$[Ω] (Estimated)	$V_{h,2}$[kV] (Exact)	$V_{h,2}$[kV] (Estimated)
5th	3+ j10.24	2.95+ j10.38	2.82 ∠79.2°	2.62 ∠86.26°
7th	3+ j14.34	2.99+ j15.06	2.12 ∠90°	1.99 ∠87.39°
11th	3+ j22.53	3.00+ j23.99	0.42 ∠92.72°	0.42 ∠88.40°
13th	3+ j26.63	3.00+ j28.94	0.14 ∠105.6°	0.14 ∠88.77°

Table 4. Results of steady-state condition

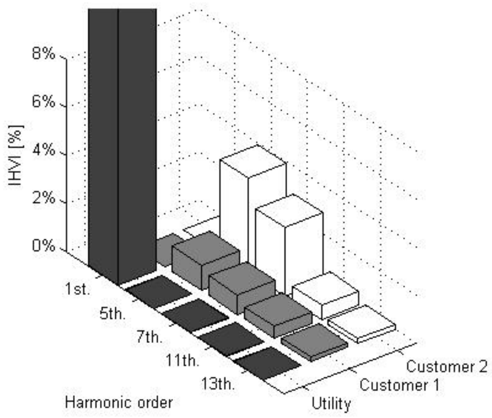
Harmonic Order (h)	5^{th}	7^{th}	11^{th}	13^{th}	THC [%]
$IHCI_{h,0}$	0.0005	0.0003	0.0001	6.3E-5	0.01
$IHCI_{h,1}$	0.0804	0.0462	0.0183	0.0061	1.56
$IHCI_{h,2}$	0.2676	0.1467	0.0201	0.0057	5.04
$IHVI_{h,0}$	0.0024	0.0019	0.0015	0.0009	0.03
$IHVI_{h,1}$	0.1349	0.1037	0.0624	0.0246	1.43
$IHVI_{h,2}$	0.5011	0.3654	0.0760	0.0253	4.90

compared with different harmonic orders. The THCs of the utility and each customer gives comprehensive quantities about how much they are responsible for the total harmonic pollution. In this steady-state condition, customer 2 is a dominant harmonic source disturbing the PCC voltage. Similarly, IHCI in each harmonic order can be interpreted in the same way.

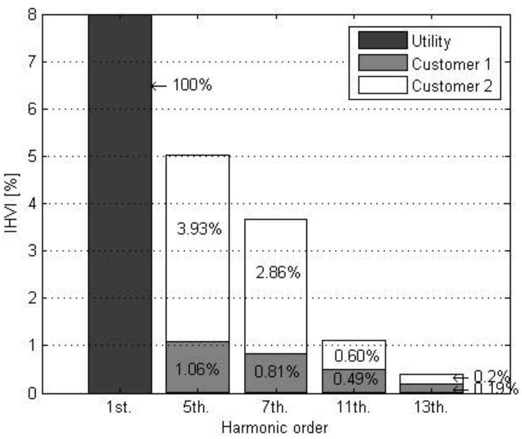
4.2 Case B: Network impedance change

In most cases, the supply network reactance is a result of the inductive and capacitive elements status within the network. We assumed that the inductive component of the reactance tends to be predominant, and therefore, a typical situation pertaining to this condition is when utility shunt capacitors are switched on or off depending on the state of the network. A reduction of network impedance $Z_{h,0}$ can induce customers to inject more harmonic currents into the utility side. However, the effect of $Z_{h,0}$ change should be isolated when considering the contribution of the customer.

This case study was done only for the 5^{th} harmonic using the same test system of Fig. 6. The results show that the PCC voltage becomes increasingly dominated by the utility source under such a condition. Fig. 9 and Fig. 10 indicate that the IHVI changes with time-varying network impedance. Fig. 9 shows that the customers increasingly affect harmonic voltage distortion at the PCC when network impedance is changed from 1+j1.885[Ω] to 1+j2.827[Ω] at 0.93 sec. In Fig. 10, the customers decreasingly affect harmonic voltage distortion at the PCC when the network impedance is changed from 1+j1.885[Ω] to 1+j1.319[Ω] at 0.93 sec. Since the customer has no control over the network impedance change, the customer's IHVI should remain the same magnitude. It is worth noting



(a) Distributed bar graph



(b) Stacked bar graph

Fig. 8. Normalized individual harmonic voltage impact for the steady-state condition

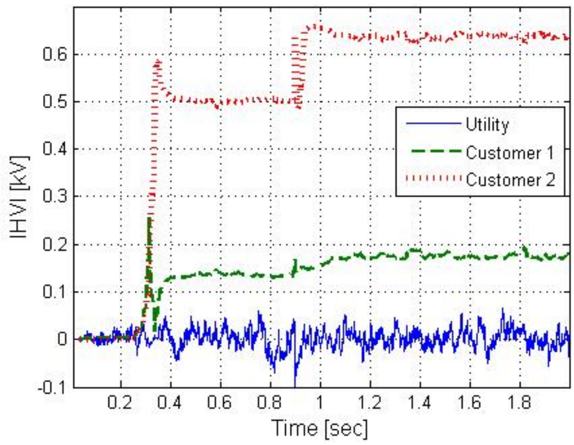


Fig. 9. IHVI when $Z_{h,0}$ increases without $E_{h,0}$ conversion

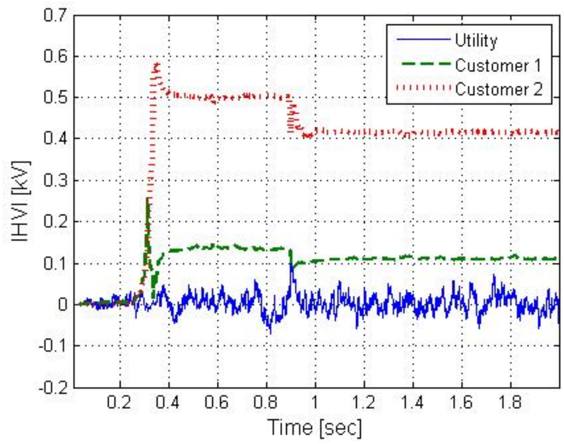


Fig. 10. IHVI when $Z_{h,0}$ decreases without $E_{h,0}$ conversion

that $E_{h,0}$ should be converted by (1) when the change of network impedance $Z_{h,0}$ is detected in the sampling window. Figs. 11 and Fig. 12 show the change of IHVI after $E_{h,0}$ is converted by (1).

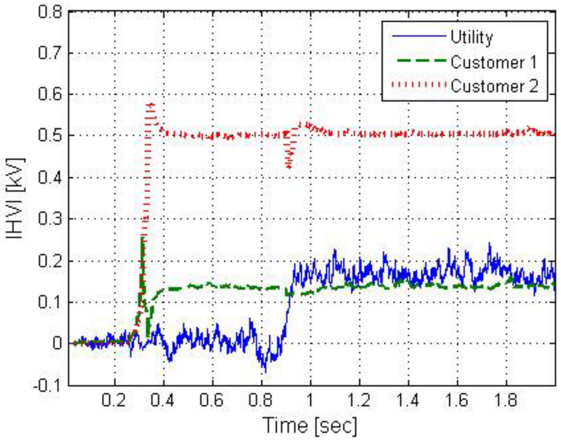


Fig. 11. IHVI when $Z_{h,0}$ increases with $E_{h,0}$ conversion

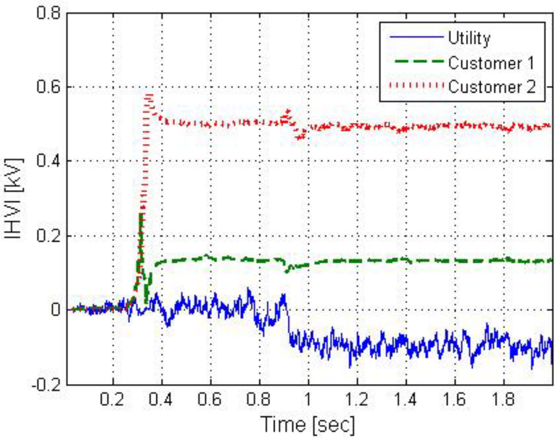


Fig. 12. IHVI when $Z_{h,0}$ decreases with $E_{h,0}$ conversion

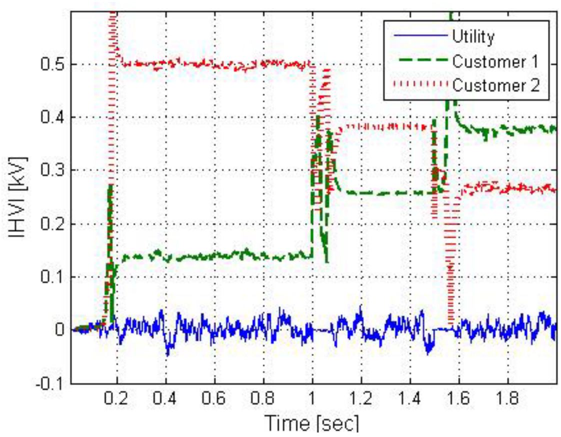


Fig. 13. IHVI caused by customers' harmonic voltage source change

4.3 Case C: Customer's harmonic source change

The time-varying operating conditions of the customer's 5^{th} harmonic voltage source are considered in this case study. Customer 1 increases as a harmonic voltage source by 200% at 1 sec., and by 300% at 1.5 sec. However, customer 2 reduces as a harmonic voltage source by 75% at 1 sec. and by 50% at 1.5 sec. The Thevenin equivalent impedance values of the network and customers are identified in the initial operating condition. As expected, the customer has increased responsibility as its harmonic source increases, and vice versa, as in Fig. 13. It can be also seen that the utility's IHVI maintains normality in the time-varying operating conditions of customers.

4.4 Case D: Both network impedance and customer's harmonic source change

The time-varying operating conditions of the customer's 5^{th} harmonic voltage source with network impedance change are considered in this case study. The network

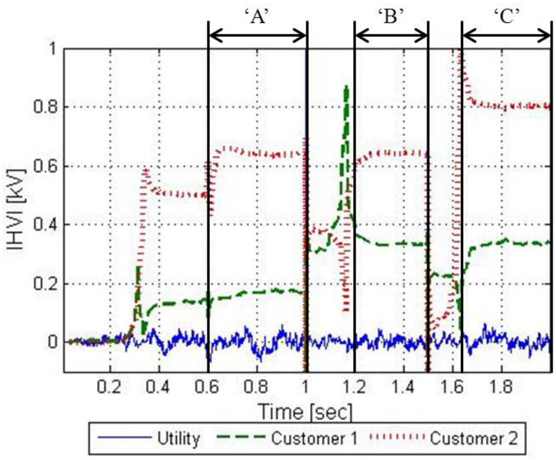


Fig. 14. IHVI changes without $E_{h,0}$ conversion in case D

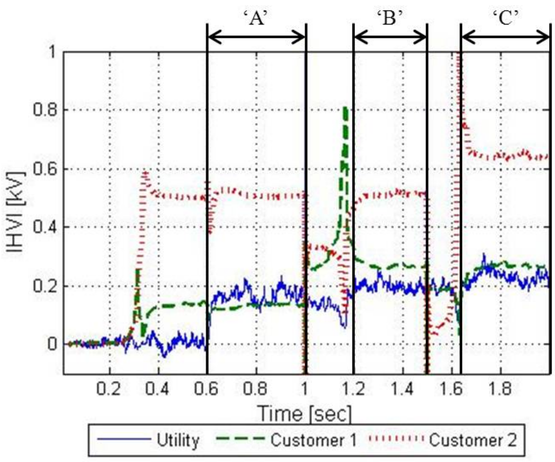


Fig. 15. IHVI changes with $E_{h,0}$ conversion in case D

impedance is changed from 1+j1.885[Ω] to 1+j2.827[Ω] at 0.6 sec. Then, customer 1 increases as a harmonic voltage source by 200% at 1 sec., and customer 2 increases as a harmonic voltage source by 125% at 1.5 sec. There are no changes of the Thevenin equivalent impedance values of customers in this sampling window. Fig. 14 shows that the IHVI of customer 1 is increased in time interval 'A,' and more increased by the same magnitude in time intervals 'B' and 'C' in comparison with the previous status. For customer 2, there are two IHVI step-ups in time intervals 'A' and 'C'.

Fig. 15 clearly shows good performance of the proposed method in the time-varying operating conditions of the customers' harmonic voltage source with network impedance change. It can be seen that the IHVI of customer 2 is not increased due to a network impedance change in time intervals 'A' and 'B,' but is increased due to its harmonic source rise in time interval 'C.' The IHVI change of customer 1 has a similar inclination to customer 2, but the IHVI step-up in time interval 'B' is not due to a network impedance change but due to a harmonic source rise. As discussed in case B, the step-up of the utility's IHVI in time interval 'A' reflects the PCC voltage increase due to the network impedance change.

Similar results for the IHCI can be obtained in the cases of B, C, and D. The case studies with different harmonic orders can also be executed in the same way. In order to determine the representative IHCI in a sampling window, discussion on the choice of sampling window size and time-aggregation method remains open.

5. Conclusion

A new assessment method for the total harmonic contribution of each suspicious harmonic source at the PCC has been presented. By using the measured harmonic voltage and current phasors at the PCC, the individual harmonic impact index was estimated, and the total harmonic contribution of each participant at a specific PCC was proposed. The proposed method was developed under ideal conditions, and its validity was investigated through case studies. The proposed algorithm provides good performance in steady-state accuracy and response to time-varying operating conditions. The method needs to be further verified using field measurements as well.

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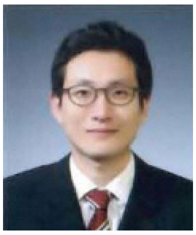

Jong-Hoon Han He received a B.S., M.S., and Ph.D. degrees in electrical engineering from Korea University, Seoul, Korea, in 2003, 2009, and 2013, respectively. He was an Engineer with the Telecommunication System Division, Samsung Electronics, Suwon, Korea, from 2003 to 2007. Currently, he is a senior engineer with the Korea Electrotechnology Research Institute, Uiwang, Korea. His research interests include short-circuit testing and signal processing for power quality analysis.

Kyebyung Lee He received B.S. and M.S. degrees from Dong-Eui University, Busan, Korea in 2006 and 2008, respectively. Currently, he is pursuing his Ph.D. degree in Korea University. His research interests include energy storage system, microgrid system modeling and control.

Chong Suk Song He received the received B.S. and M.S. degrees from Korea University, Seoul, Korea in 2008 and 2010, respectively. Currently, he is pursuing his Ph.D. degree in Korea University. His research interests include transmission and distribution system analysis, power system visualizations and hybrid simulation of power systems.

Gilsung Byeon He received a B.S., M.S. and Ph.D. degrees in electrical engineering from Korea University, Seoul, Korea, in 2006, 2008, and 2012, respectively. Currently, he is a senior researcher with the Korea Electrotechnology Research Institute, Chang won, Korea. His research interests are power system modeling as well as control and simulation algorithm analysis.

Chang-Hyun Park He received a B.S. degree from Inha University, Incheon, Korea, in 2001 and M.S. and Ph.D. degrees in electrical engineering from Korea University, Seoul, in 2003 and 2007, respectively. Currently, he is an Assistant Professor in the Department of Electrical Engineering, Pukyong National University, Pusan, Korea. His research interests include power-quality assessment, data visualization, and computer simulation of power systems.

Gilsoo Jang He received B.S. and M.S. degrees in electrical engineering from Korea University, Seoul, Korea, in 1991 and 1994, respectively, and a Ph.D. degree in electrical and computer engineering from Iowa State University, Ames, in 1997. He was a Visiting Scientist at Iowa State University from 1997 to 1998 and a Senior Researcher with the Korea Electric Power Research Institute, Daejeon, Korea, from 1998 to 2000. Currently, he is a Professor in the School of Electrical Engineering, Korea University. His research interests include power quality and power system control.