Determining the Harmonic Impacts of Multiple Harmonic-Producing Loads

Hooman E. Mazin, *Student Member, IEEE*, Wilsun Xu, *Fellow, IEEE*, and Biao Huang

***Abstract*—Identifying harmonic sources in a given power system is an important task for utility power-quality (PQ) management. This paper presents a new class of harmonic source identification problems: how to quantify the harmonic impact of several known harmonic-producing loads on the harmonic levels observed at a network location. This paper first defines the problem and proposes a harmonic impact index to theorize the problem. This paper then presents a statistical-inference-based method to estimate the index. The data required for this analysis are the harmonic voltage and current magnitudes continuously collected by the existing PQ monitors. The characteristics of the proposed method are investigated through case studies. Finally, additional applications and improvements of the proposed method are discussed.**

***Index Terms*—Correlation analysis, harmonic source identification, harmonics, power quality (PQ), statistical inference.**

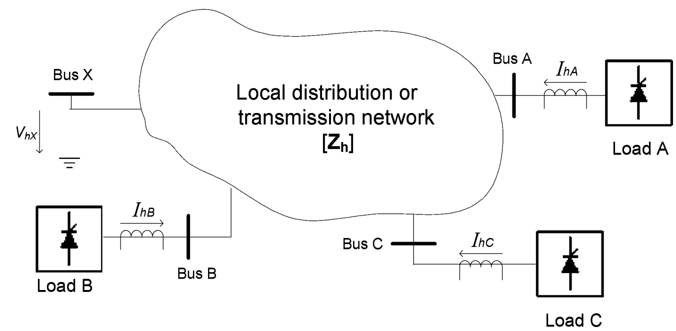


Fig. 1. Typical power distribution or transmission system.

I. Introduction

DEVELOPING methods and techniques to quantify the harmonic contributions of the customers and the utility system, especially a harmonic problem occurs in a system, is highly important for power-quality (PQ) management. In the past, this problem was approached from a single-point perspective: the harmonic contribution of a customer was separated from that of the supply system at the customer-utility interface point [1], [2]. While this approach is still very important and worthwhile, another type of harmonic-source-detection problem has emerged, due primarily to the situation where more and more loads contain some harmonic sources. It has become very useful to determine which loads cause a particular harmonic problem in a system. This situation can be illustrated by using the example shown in Fig. 1. A harmonic problem is reported in bus X of a power distribution or transmission system. The system is known to contain, for example, three major harmonic-producing customers, A, B and C. It is necessary to determine if these three suspicious loads are causing the problem and, if so, which load is producing the most significant impact. In this paper, this problem is called a multi-point harmonic-source-detection problem. The challenge here is to quantify the harmonic impacts of multiple harmonic-producing loads. Our extensive literature review found that little work has been done in this area.

Two classes of methods have been proposed to quantify the harmonic contributions of loads: the model-based and data-based methods. The model-based methods try to establish an equivalent circuit of the system by using the measured data [3]–[5]. Once the equivalent circuit is available, the harmonic contributions can be estimated from the circuit. Extensive research work has revealed that, due to a number of factors such as the signal strength and load variations, establishing an equivalent circuit with adequate accuracy is very difficult. The data-based methods try to establish the cause-and-effect relationship directly from the measured data. For example, [6], [7] presented a linear correlation method to identify the harmonic contribution of a customer at the customer-utility interface point. In [8], the correlation concept was extended to solve the multi-point problem. However, the paper presented only an intuitively sound concept. A rigorous theoretical support for the concept was missing, and the data-selection problem is not fully solved.

In this paper, a rigorous theory and associated method to quantify the harmonic impact of multiple loads are established. Based on the theory of statistical inference [9], quantitative indices are proposed to measure the harmonic impact of each load on a specific bus in a system. The paper is organized as follows: Section II describes the problem and establishes an index to quantify the harmonic impacts of loads. Section III presents our proposed method to solve the problem. The proposed method is further characterized through case studies in Section IV. Section V discusses for the further improvements and applications of the method. Finally, conclusions are drawn in Section VI.

Manuscript received June 08, 2010; revised October 14, 2010; accepted November 10, 2010. Date of publication December 30, 2010; date of current version March 25, 2011. This work was supported in part by the National Sciences and Engineering Research Council of Canada and in part by the Alberta Power Industry Consortium. Paper no. TPWRD-00437-2010.

W. Xu and H. Erfanian are with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 2V4, Canada (e-mail: wxu@ualberta.ca; herfania@ece.ualberta.ca).

B. Huang is with the Department of Chemical and Material Engineering, University of Alberta, Edmonton, AB T6G 2G6, Canada (e-mail: biao.huang@ualberta.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2010.2093544

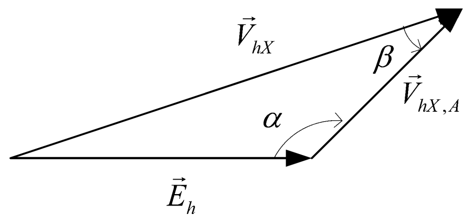


Fig. 2. Phasor diagram of the harmonic voltage at bus X.

II. Problem Description and Definition

The multi-point problem to be solved by this paper can be formally stated as follows: A harmonic distortion problem is reported in bus X of a power distribution or transmission system. This point (*Bus* X) is named as the observation point. The system is known to contain, for example, three major harmonic-producing customers A, B and C, as shown in Fig. 1. These customers are named as suspicious loads. The problem is to determine if these three suspicious loads are the cause of the problem. The impact of each suspicious load needs to be quantified. A qualitative Yes or No answer is not sufficient in this case since all the suspicious loads are likely to impact on the voltage distortions at the observation point.

As [11], [12] show, components of the power system network can be modeled by a set of impedances and harmonic current sources. The h-th harmonic voltage at bus X can be calculated by using the harmonic impedance matrix of the network ($[\mathbf{Z_h}]$) as follows:

$$\vec{V}_{hX} = Z_{hXA}\vec{I}_{hA} + Z_{hXB}\vec{I}_{hB} + Z_{hXC}\vec{I}_{hC} + \vec{V}_{hX,0} \quad (1)$$

where Z_{hXi} is the element of row X and column i of the harmonic impedance matrix of the network. The harmonic currents I_{hA}, I_{hB} and I_{hC} are the harmonic currents at the customer-utility interface point. They can be measured by using the PQ monitors. These currents result from the interactions between the utility system (including the impedances and harmonic current sources) and customer loads. The harmonic voltage caused by the unknown harmonic loads is presented by $V_{hX,0}$. This voltage is named as the background harmonic voltage. To quantify the specific impact of load A on the harmonic voltage at bus X, $\vec{V}_{hX}$ is decomposed into two components: $\vec{V}_{hX,A}$ (caused by load A) and E_h (caused by other loads):

$$\vec{V}_{hX} = \underbrace{Z_{hXA}\vec{I}_{hA}}_{\vec{V}_{hX,A}} + \underbrace{Z_{hXB}\vec{I}_{hB} + Z_{hXC}\vec{I}_{hC} + \vec{V}_{hX,0}}_{\vec{E}_h}. \quad (2)$$

The harmonic impact of load A on the bus X can be quantified by using the projection of $\vec{V}_{hX,A}$ on the $\vec{V}_{hX}$ (see Fig. 2). The harmonic impact index (HI) of $\text{Load}\, A$ on $\text{Bus}\, X$ is defined as follows:

$$\begin{aligned} HI_{\text{Load }A}^{\text{Bus}X} &= \frac{|V_{hX,A}|}{|V_{hX}|}\cos\beta \times 100\% \\ &= \frac{\vec{V}_{hX,A}\cdot\vec{V}_{hX}}{|V_{hX}|^2} \times 100\%. \end{aligned} \quad (3)$$

The same procedure can be applied to quantify the harmonic impacts of other loads (B, C, etc.). In this proposed definition, a customer without a harmonic source but with a capacitor could be labeled as a harmonic-impact producer. Switching of a capacitor can cause a change in harmonic voltage distortion of the local network. As this harmonic-voltage change coincides with harmonic current change of the capacitor, this load can be classified as a harmonic source. This conclusion makes sense from the perspectives of troubleshooting and harmonic management since capacitors do cause harmonic problems. The harmonic impact of the load can be negative (by acting as a filter and decreasing the harmonic voltage distortion) or positive (by causing resonance in the network and increasing the harmonic voltage distortion).

The final goal of this paper is to propose a practical method to estimate the harmonic impact indices of loads by using the field measurement data. Utility companies currently routinely perform continuous harmonic monitoring. The most common PQ-monitoring systems have multiple monitors placed at various points in a system. The monitors can collect data continuously. The data are synchronized to the accuracy of seconds. This level of synchronization does not provide adequate accuracy to determine the phase differences among the measured quantities. In view of the current condition of PQ monitoring systems, it is assumed that only the magnitudes of harmonic voltages and currents are accessible for harmonic-impact determination. Using these data, this paper proposes a statistical-inference-based method to estimate the harmonic impact of loads.

The presented harmonic impact index assumes that the impact of concern is the harmonic voltage V_{hX}. This definition is just an example and can be further expanded to include the harmonic current of a particular branch. In this regard, the impact of load A on the harmonic current of branch J can be defined as follows:

$$HI_{\text{Load }A}^{\text{Branch }J} = \frac{\vec{I}_{hJ,A}\cdot\vec{I}_{hJ}}{|I_{hJ}|^2} \times 100\% \quad (4)$$

where $\vec{I}_{hJ}$ is the harmonic current in branch J. $\vec{I}_{hJ,A}$ is the portion of harmonic current in branch J that is caused by load A. This new index is beyond the scope of this paper and can be studied in future work.

III. Proposed Method

The proposed method uses field measurement data to determine the harmonic-impact index. Our experience shows that data-recording resolutions of one sample per 1 to 5 seconds are acceptable for the proposed method. The data recording resolution is not the sampling rate of a waveform. The sample rate nowadays is typically 256 points per cycle. The data recorded should include the harmonic voltages and currents and should not be normalized with respect to the fundamental frequency component. For example, the field measurement data for the 5th harmonic voltages in bus X and the 5th harmonic currents of load A taken from 10:00 A.M. to 10:30 A.M. in the described system in Fig. 1 are shown in Fig. 3.

Based on the aforementioned assumption of the available data, the following data-processing algorithm is developed.

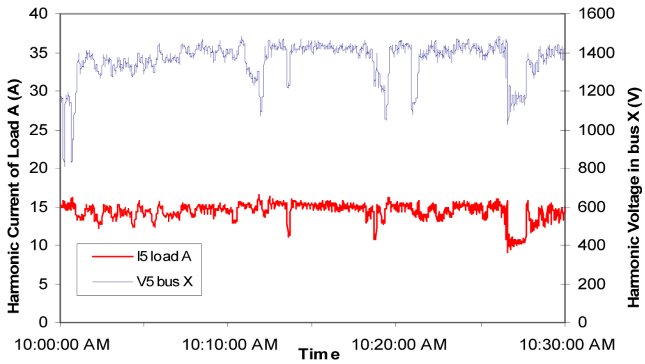


Fig. 3. Example of the field measurement harmonic voltage and current.

Applying the law of cosine to Fig. 2 for the ith sample of the measured data, the following equation can be derived:

$$|V_{hX}(i)|^2 = |V_{hX,A}(t_i)|^2 + |E_h(t_i)|^2 - 2|V_{hX,A}(t_i)||E_h(t_i)|\mathrm{Cos}\left(\alpha(t_i)\right).$$

Since $|V_{hX,A}(t_i)| = |Z_{hXA}||I_{hA}(t_i)|$, the following equation can be obtained:

$$|V_{hX}(t_i)|^2 = |Z_{hXA}|^2|I_{hA}(t_i)|^2 + |E_h(t_i)|^2 - 2|Z_{hXA}||I_{hA}(t_i)||E_h(t_i)|\mathrm{Cos}\left(\alpha(t_i)\right). \quad (5)$$

As the system/load always varies, all quantities of (5) will change. A group of data selected for analysis ($\mathrm{i} = 1, \ldots \mathrm{n}$) has an average value of α. This value is labeled as α_{eq}. If α_{eq}, instead of the true α, is used in the above equation, an error will appear. Equation (5) can be rewritten as shown

$$|V_{hX}(t_i)|^2 = |Z_{hXA}|^2|I_{hA}(t_i)|^2 + |E_h|^2 - 2|Z_{hXA}||I_{hA}(t_i)||E_h|Cos(\alpha_{\mathrm{eq}}) + \varepsilon_i. \quad (6)$$

Defining

$$\begin{cases} \theta_0 = |E_h|^2 \\ \theta_1 = -2|Z_{hXA}||E_h|\mathrm{Cos}(\alpha_{\mathrm{eq}}) \\ \theta_2 = |Z_{hXA}|^2 \end{cases}$$

the following set of equations are derived:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\theta} + \varepsilon, \quad (7)$$

where

$$\mathbf{Y} = \left[|V_{hX}(t_1)|^2 \quad |V_{hX}(t_2)|^2 \quad \cdots \quad |V_{hX}(t_n)|^2\right]^T;$$
$$\boldsymbol{\theta} = [\theta_0 \quad \theta_1 \quad \theta_2]^T;$$
$$X = \begin{bmatrix} 1 & |I_{hA}(t_1)| & |I_{hA}(t_1)|^2 \\ 1 & |I_{hA}(t_2)| & |I_{hA}(t_2)|^2 \\ \vdots & \ddots & \vdots \\ 1 & |I_{hA}(t_n)| & |I_{hA}(t_n)|^2 \end{bmatrix}.$$

In (6), E_h and Z_{hXA} are assumed to be constant for the instants $\mathrm{i} = 1 \ldots \mathrm{n}$ when the correlation analysis is to be performed. This assumption is critical for the proposed method. The physical meaning is that when one conducts correlation analysis between two variables X and Y, no other variables will change. Since other variables do change, the simplest approach is to select data that can guarantee this condition. This approach is adopted in the proposed method. The method of data selection is described later. The unknown parameters $\boldsymbol{\theta}$ can be estimated by using the following linear regression:

$$\hat{\boldsymbol{\theta}} = (\mathbf{X^T X})^{-1}\mathbf{X^T Y}. \quad (8)$$

In order to use the aforementioned results to determine the harmonic impact, the following equation can be written according to Fig. 2:

$$|E_h(t_i)|^2 = |V_{hX}(i)|^2 + |V_{hX,A}(t_i)|^2 - 2|V_{hX,A}(t_i)||V_{hX}(i)|Cos(\beta(t_i)).$$

With the above equation and (3), the harmonic impact index can be estimated as follows:

$$HI_{\mathrm{load}\ A}^{\mathrm{Bus}\ X}(t_i) = \frac{|Z_{hXA}|^2|I_{hA}(t_i)|^2 + |V_{hX}(t_i)|^2 - |E_h|^2}{2|V_{hX}(t_i)|^2} \times 100\%. \quad (9)$$

Equation (9) shows that the harmonic impact varies with time. Since it is more useful to know the average harmonic impact over a specified period, the following simple average is proposed for this purpose:

$$HI_{\mathrm{load}\ A}^{\mathrm{Bus}\ X} = \left(\frac{1}{2} + \frac{1}{n}\sum_{i=1}^{n}\frac{-\theta_0 + \theta_2|I_{hA}(t_i)|^2}{2|V_{hX}(t_i)|^2}\right) \times 100\%. \quad (10)$$

Based on the analytical (i.e., least square) solution of $\boldsymbol{\theta}$, the equation to determine the harmonic impact can be concisely written as

$$HI_{\mathrm{load}\ A}^{\mathrm{Bus}\ X} = \left(\frac{1}{2} + \boldsymbol{\beta}\hat{\boldsymbol{\theta}}\right) \times 100\% \quad (11)$$

where

$$\boldsymbol{\beta} = \left[-\tfrac{1}{2n}\sum_{i=1}^{n}\frac{1}{|V_{hX}(t_i)|^2} \quad 0 \quad \tfrac{1}{2n}\sum_{i=1}^{n}\frac{|I_{hA}(t_i)|^2}{|V_{hX}(t_i)|^2}\right].$$

In other words, if one has the measured data series I_{hA} and V_{hX}. ($\mathrm{i} = 1, \ldots, \mathrm{n}$), the aforementioned equation will be able to calculate the harmonic impact of load current I_{hA}. After estimating the harmonic impact of a load, the confidence interval of the estimated parameter can be calculated as an indication of the reliability of the estimated parameter. For example, if the estimated harmonic impact of a suspicious load is 32% and the confidence interval is ±7% for a 90% confidence level. It means that the harmonic impact of the suspicious load is between 25% and 39% (with the probability of more than 90%). The confidence interval of the estimated harmonic impact can be calculated as follows [9]:

$$CI_{\mathrm{load}\ A}^{\mathrm{Bus}\ X} = \pm t_{n-3,1-\alpha/2}\sqrt{\mathrm{Var}\left(\widehat{HI}_{\mathrm{load}\ A}^{\mathrm{Bus}\ X}\right)} \quad (12)$$

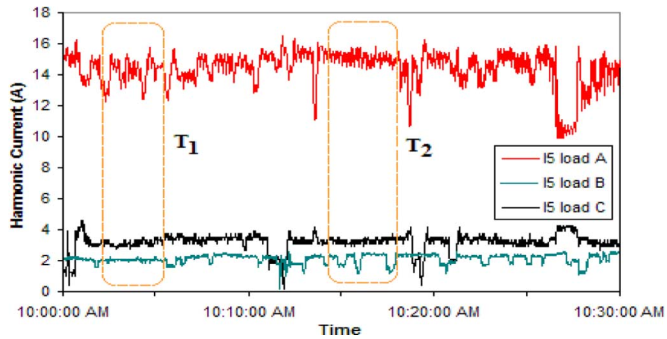


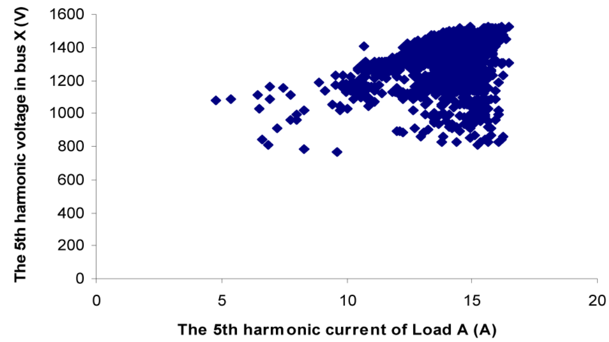
Fig. 4. Selecting appropriate time intervals for estimation analysis.

where $t_{n-3,1-\alpha/2}$ stands for t-distribution with $\mathrm{n}-3$ degree of freedom, n presents the number of analyzed samples, and α is the confidence level that usually sets on 90%. The variance of the estimated harmonic impact of load A on Bus X $(\hat{HI}_{\text{load }A}^{\text{Bus }X})$ can be achieved by

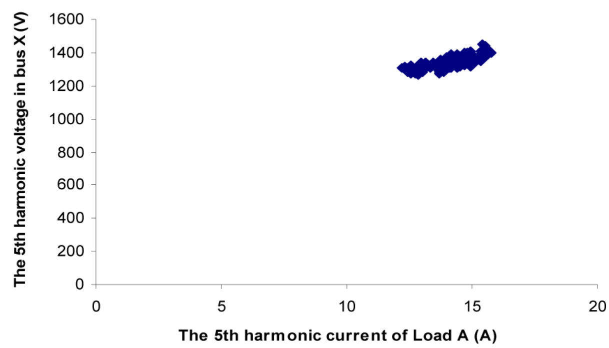
$$\mathrm{Var}\left(\hat{HI}_{\text{load }A}^{\text{Bus }X}\right)=\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{n-3}\times\boldsymbol{\beta}\left(\mathbf{X}^{\mathbf{T}}\mathbf{X}\right)^{\mathbf{-1}}\boldsymbol{\beta}^{\mathbf{T}}. \tag{13}$$

As discussed earlier, E_h must be constant in order to use the proposed method. This pre-requisite transforms the problem of harmonic-impact determination into the problem of selecting the proper data set for the least square estimation. The basic idea adopted in this work is to find the time intervals in which only one of the harmonic loads changes. For example (see Fig. 4), in time interval T_1, the harmonic load A varies, and other harmonic loads are roughly unchanged (the variation is less than 5%). This time interval can be used by our proposed method to estimate the harmonic impact of load A. Similarly, the time interval T_2 can be used to estimate the harmonic impact of load B. It is assumed that finding a proper data set with sufficient length among the measurement data is possible. In case that the proper set of data is not available, the estimation is not possible. However, our analysis on the real field-measurement data showed that this set of data is usually available when there are less than six major harmonic loads within the local power network. It is important to mention that in multiple harmonic source identification, only major harmonic loads should be investigated. In this analysis, the minor harmonic loads are considered as background harmonic.

Fig. 5 shows the effect of applying the aforementioned data selection algorithm to the measurement data. The correlation of the 5th harmonic current of load A and the 5th harmonic voltage of bus X (presented in Fig. 3) is shown in Fig. 5(a). When applying the data-selection algorithm, only those data within the time interval T_1 are selected. The correlation of the harmonic voltage and current of these selected data is shown in Fig. 5(b), which reveals that the selected data are less spread and more strongly correlated than the data shown in Fig. 5(a). between the studied harmonic voltage and current. By applying (8) on the selected data, parameters can be estimated. For this case, $|E_h|$ is 883.12 V and Z_{hXA} is 42.4 Ohm and α_{eq} is 130.1°. By using



(a)



(b)

Fig. 5. Correlation of harmonic current of load A and harmonic voltage of bus X. (a) Before data selection. (b) After data selection.

(10), the harmonic impact of load A on bus X is estimated to be 36.7%. The confidence interval of this estimation is ±5.2%. The p-value of the estimated parameter is almost 0.0001 that shows strong correlation between the analyzed data. The coefficient correlation parameter (r^2) is almost 0.82 that shows a good explanation of data by estimators.

The entire procedure of the proposed technique is shown in Fig. 6. First, harmonic monitoring should be performed on all suspicious loads and at the observation point(s). The next step is the data selection. In this paper, only the key idea for data selection is explained. The development of efficient data-selection algorithms can be considered as a future improvement of this work. The last step of this procedure is to apply the estimation method to the selected data.

IV. CASE STUDIES

A. IEEE 13-Bus Test System

The IEEE test system No. 3 for harmonic modeling and simulation [10] is used in this case study. This test system consists of 13 buses and is representative of a medium-sized industrial plant (see Fig. 7). The plant is fed from a utility supply at 69 kV (Bus 1, slack bus) and the local plant distribution system that operates at 13.8 kV (Bus 4, PV bus). Seven PQ loads are supplied by the system. In our study, loads 7, 10, and 13 were considered as harmonic producing loads. These harmonic loads were modeled by using the current source model [11]. The harmonic spectrum of the loads is presented in Table I. The magnitudes were scaled based on the fundamental component of the load current,

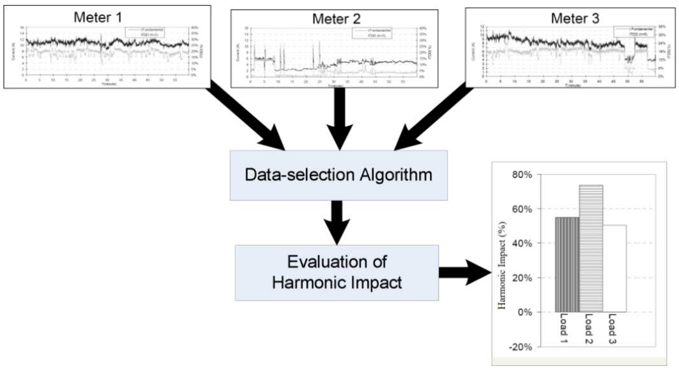


Fig. 6. Procedure of the proposed technique.

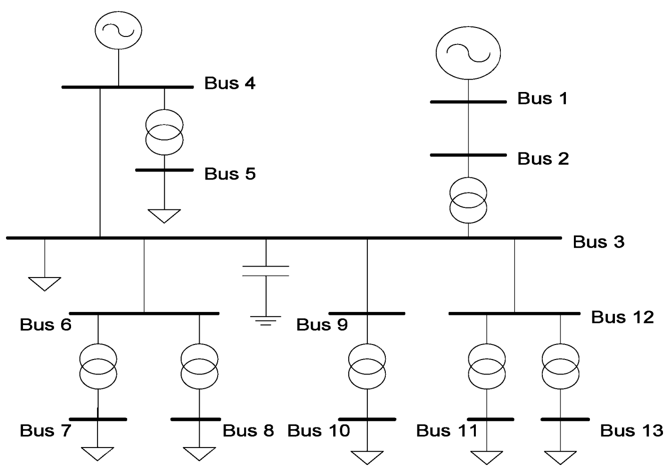


Fig. 7. A 13-bus power system.

TABLE I
SPECTRUM TABLE OF HARMONIC LOADS

Harmonic Order	Magnitude (percent)	Relative Angle (degree)
1	100	0.00
5	18.24	-55.68
7	11.90	-84.11
11	5.73	-143.56
13	4.01	-175.58

and the phase angles were adjusted based on the phase angle of the voltage across the load obtained from the fundamental frequency solution. The harmonic impacts of the harmonic-producing loads on buses 3, 7, 10, and 13 are studied in this case study. By applying the proposed methods, these harmonic impacts are estimated and are compared with the real harmonic impact of the loads calculated by using (3). Before applying the proposed method, a simulation procedure should be done to provide measurement data. The algorithm of the procedure is as follows:

1. Start
2. Until the simulation ends, do the following:
   2.1. Randomly change PQ loads.
   2.2. Perform load flow.

TABLE II
AVERAGE HARMONIC VOLTAGES (PER UNIT) IN STUDIED BUSES

Harmonic Order	Bus 3	Bus 7	Bus 10	Bus 13
5	0.1194	0.1253	0.1045	0.0924
7	0.0247	0.0605	0.0164	0.0237
11	0.0081	0.0226	0.0208	0.0287
13	0.0048	0.0178	0.0194	0.0255

TABLE III
AVERAGE HARMONIC CURRENTS (PER UNIT) OF SUSPICIOUS LOADS

Harmonic Order	Load 7	Load 10	Load 13
5	0.002217	0.002169	0.00720
7	0.001446	0.001416	0.004697
11	0.000696	0.000682	0.002262
13	0.000487	0.000477	0.001583

   2.3. Assign harmonic-injected current sources by using spectrum table.
   2.4. Perform harmonic load flow.
   2.5. Save harmonic currents of suspicious loads and harmonic voltages of observation points.
   2.6. Calculate the harmonic impact of each harmonic load.
   2.7. Save exact harmonic impact for later comparison.
   2.8. Go back to 2.
3. End

In this procedure, all PQ loads were randomly varied to cause variations in the harmonic voltages and currents. In our study, 1000 simulation snapshots were generated. After simulation, the measurement data were ready to be used in our proposed method. The magnitudes of the harmonic currents of the suspicious loads and the harmonic voltage of the studied buses (the observation points) were used by our proposed method as input data. Table II presents the average harmonic voltage distortion (p.u.) in the studied buses, and Table III presents the average harmonic current distortion (p.u.) of suspicious loads. Two scenarios are studied in this case study. In the first scenario, three harmonic loads are known by the utility system and are considered as suspicious loads. Therefore, no unknown harmonic source exists in the system in this scenario. In the second scenario, the harmonic load attached to bus 10 is considered as an unknown harmonic source in the system.

1) First Scenario: No Background Harmonic: In this case, no unknown harmonic source exists in the system. The harmonic currents of all suspicious loads (loads 7, 10, and 13) and the harmonic voltages of the observation points (buses 3, 7, 10, and 13) are used in our proposed method to estimate the harmonic impacts. Table IV presents the estimated harmonic impacts of the suspicious loads on bus 3. For harmonic orders 5 and 7, load 7 shows a negative harmonic impact on bus 3. The harmonic

TABLE IV
ESTIMATED AND EXACT HARMONIC IMPACTS OF THE SUSPICIOUS LOADS ON BUS 3

Harmonic Order	Load 7		Load 10		Load 13	
	Exact	Estimated	Exact	Estimated	Exact	Estimated
5	-18.3	-15.4±5.3	26.3	18.6±10.4	91.9	88.3±4.8
7	-28.6	-26.7±3.7	29.9	27.2±4.3	98.7	98.4±2.9
11	15.3	14.2±3.5	19.9	19.5±2.4	64.7	67.6±3.6
13	19.4	21.1±2.8	17.6	14.4±4.1	63.0	64.6±2.9

TABLE V
ESTIMATED AND EXACT HARMONIC IMPACTS OF THE SUSPICIOUS LOADS ON BUS 7

Harmonic Order	Load 7		Load 10		Load 13	
	Exact	Estimated	Exact	Estimated	Exact	Estimated
5	-13.6	-13.6±1.2	26.6	25.6±2.3	86.9	86.9±1.9
7	47.4	49.3±3.2	12.0	9.0±4.2	40.6	41.4±2.8
11	109.7	117±13.4	-4.3	-8.3±4.9	-5.4	-7.0±4.2
13	121.6	112±12.7	-4.7	-7.8±3.5	-16.9	-13.2±4.6

TABLE VI
ESTIMATED AND EXACT HARMONIC IMPACTS OF THE SUSPICIOUS LOADS ON BUS 10

Harmonic Order	Load 7		Load 10		Load 13	
	Exact	Estimated	Exact	Estimated	Exact	Estimated
5	-11.2	-7.0±6.4	17.47	13.5±4.3	93.7	84.5±11.2
7	15.8	9.0±8.3	166.25	165.4±5.4	-82.1	-90.1±8.7
11	-7.4	-10.3±5.4	128.94	132.4±6.4	-21.5	-26.5±6.7
13	-3.8	-6.2±4.3	116.02	121.6±8.7	-12.2	-18.6±7.0

TABLE VII
ESTIMATED AND EXACT HARMONIC IMPACTS OF THE SUSPICIOUS LOADS ON BUS 13

Harmonic Order	Load 7		Load 10		Load 13	
	Exact	Estimated	Exact	Estimated	Exact	Estimated
5	-9.5	-5.7±5.1	26.0	23.4±4.3	83.4	80.0±4.1
7	28.0	26.6±3.5	-31.2	-36.2±6.4	103.2	103.8±3.9
11	-3.4	-0.7±4.0	-5.3	-10.8±6.2	108.7	106.5±4.3
13	-3.6	-1.0±3.4	-3.2	-6.4±4.5	106.9	106.1±2.6

current injected by this load causes a harmonic voltage in the opposite direction of the harmonic voltage caused by the other loads. In other words, this harmonic load reduces the harmonic voltage distortion in bus 3. As Table IV shows, the proposed method is capable of estimating the negative and positive harmonic impacts of the loads.

The estimated harmonic impacts of the suspicious loads on buses 7, 10, and 13 are presented in Tables V–VII. It is important to mention that the main goal of harmonic-source-identification analysis is to identify the major harmonic-impact producer in a reported harmonic distortion problem. For example, as can be seen in Table VI, load 13 is the main harmonic contributor in the 5th harmonic order. It is responsible for almost 85% of the reported problem on bus 3, and the error is around 10%. The error in estimation of harmonic impacts of loads 7 is a lot higher and is almost 37%. Nonetheless, this load is a minor harmonic producer and its harmonic impact does not play a vital role in the harmonic-management procedure. One way to show the reliability of the estimated results is to calculate the confidence interval of the estimated parameters. For example for the aforementioned case, the confidence interval of load 7 is 6.4, so the estimated harmonic impact is between -7.0–6.4% and $-7+6.4\%$. It shows that the estimated harmonic impact of load 7 is not very reliable. At the same time, the harmonic impact of load 13 is between $84.5 - 11.2\%$ and $84.5 + 11.2\%$. So with high confidence, it can be claimed that load 13 is responsible for more than 73.3% of the harmonic problem. The confidence intervals of estimated-harmonic-impacts are presented for all of the studied cases.

2) Second Scenario: Impact of Background Harmonic: The impact of the background harmonic is studied in this scenario. The harmonic load attached to bus 10 is considered as an unknown harmonic load. This unknown harmonic load creates a background harmonic in the system. The harmonic impacts of the other harmonic loads are estimated without any access to the harmonic current of harmonic load 10. Fig. 8 compares the estimated harmonic impacts of load 7 in both scenarios. The results reveal that the methods still work fine. However, the background harmonic reduces the accuracy of the methods. This reduction of accuracy is more noticeable when the harmonic load has a small harmonic impact (for example, see the harmonic impact of load 7 on bus 13 for harmonic orders 5, 11, and 13). The estimated harmonic impacts of load 13 on the studied buses are also shown in Fig. 9.

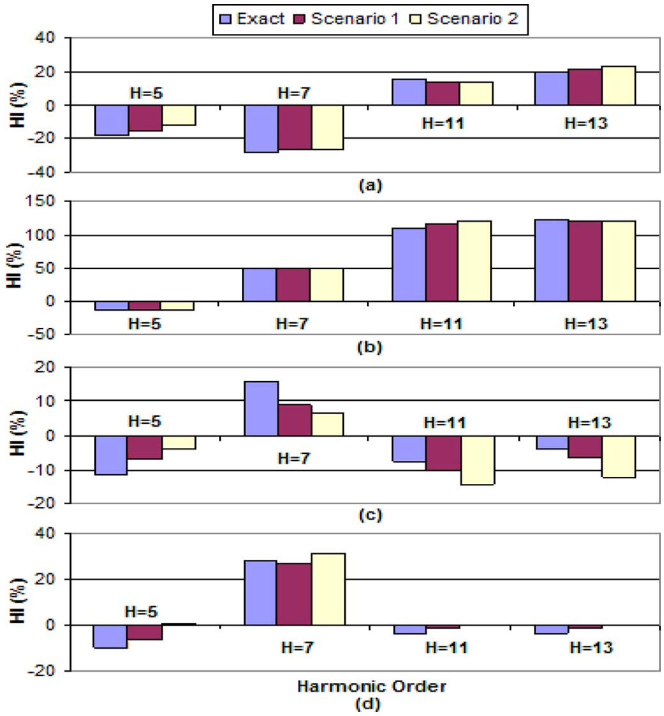


Fig. 8. Harmonic impacts of load 7 on the studied buses: (a) bus 3, (b) bus 7, (c) bus 10, and (d) bus 13.

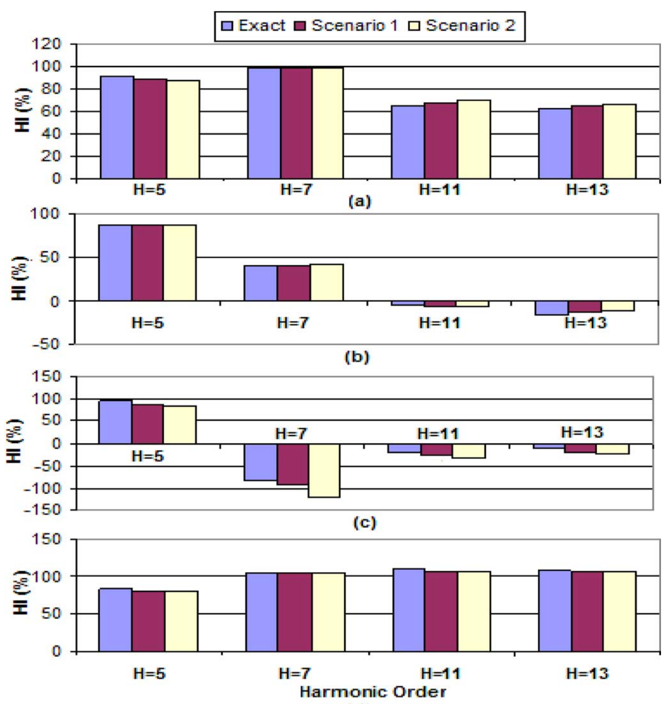
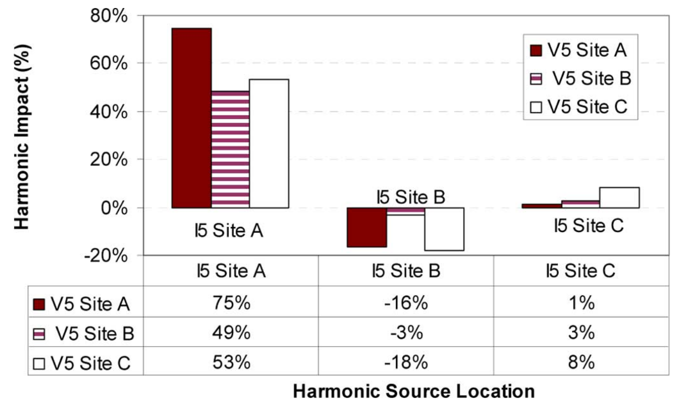


Fig. 9. Harmonic impacts of load 13 on the studied buses: (a) bus 3, (b) bus 7, (c) bus 10, and (d) bus 13.

B. Actual Distribution System

In this case study, the proposed technique was applied to an actual power system in Alberta. Fig. 11 shows the schematic diagram of the studied system. The harmonic voltages and currents of the buses and their corresponding loads are collected from 5 A.M. to 6 P.M. This system has three major harmonic-producing



	I5 Site A	I5 Site B	I5 Site C
V5 Site A	75%	-16%	1%
V5 Site B	49%	-3%	3%
V5 Site C	53%	-18%	8%

Fig. 10. Average harmonic impacts of loads on the buses.

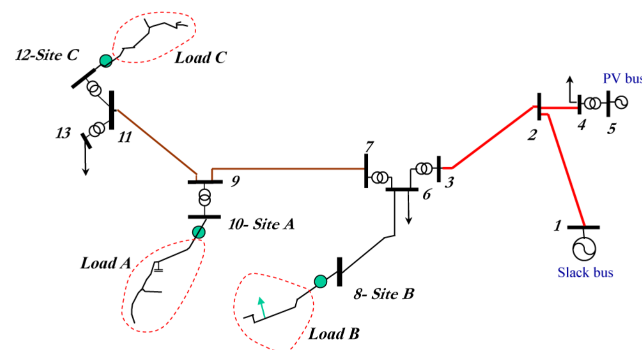


Fig. 11. Schematic diagram of the actual distribution system.

loads in this system. These loads are named load A, B, and C. The harmonic impacts of the loads for the 5th harmonic order were investigated by using field data and our simulated results. Applying the proposed method to the field data is straightforward and is shown in Fig. 6. The results are shown in Fig. 10.

Fig. 10 implies that *Site* A load is responsible for about 75% of the voltage distortion observed at the PCC of *Site* A, for about 49% of the voltage distortion observed at the PCC of *Site* B, and for about 53% of the distortion observed at PCC of *Site* C. The harmonic impact of the *Site* B load is negative, so that the PCC current of *Site* B will help to reduce the voltage distortion levels in the system. These results are in good agreement with the painstakingly obtained manual results reported in [8].

To further verify the results, computer simulations were conducted on the system. For this study, the P and Q of loads are fluctuated by using the real field measurement data. After the load flow, the harmonic injected current of each load is assigned by using the field data. For each harmonic load, the phase angle of the field data harmonic current is synchronized with the fundamental voltage of its corresponding bus. The algorithm of the simulation procedure for this case study is somewhat similar to the algorithm of the previous case study. The main difference is that in this case study, step 2.3 should be changed as follows.

2.3. Assign the harmonic injected current by using field-test data, (synchronize the phase angle of each load with the fundamental voltage of its corresponding bus).

The variation of the total apparent power of the studied loads from 5 A.M. to 5 P.M. is shown in Fig. 12 ($S_{\text{base}} = 500$ MVA).

TABLE VIII
COMPARISON OF THE SIMULATED AND FIELD MEASUREMENT HARMONIC IMPACT OF LOADS

Bus \ Load	Load A		Load B		Load C	
	Field test HI (%)	Simulated HI (%)	Field test HI (%)	Simulated HI (%)	Field test HI (%)	Simulated HI (%)
Site A	74.6	70.2±5.1	-16.3	-22.1±6.7	1.4	4.0±3.1
Site B	48.5	42.7±4.8	-2.9	-0.1±2.1	2.7	5.4±3.5
Site C	53.4	59.14±7.6	-18.0	-25.6±8.3	8.0	14.3±7.2

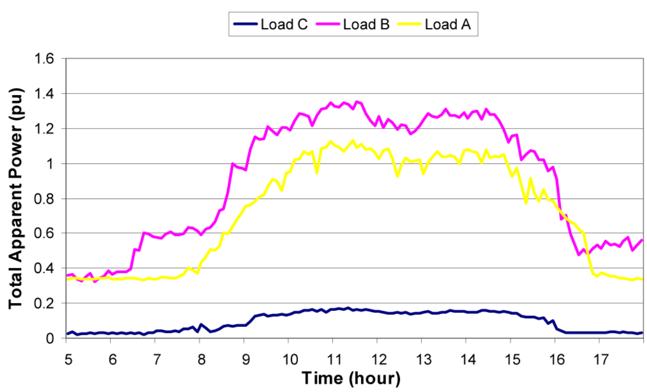


Fig. 12. Variation of the total apparent power of the studied loads (measurement data).

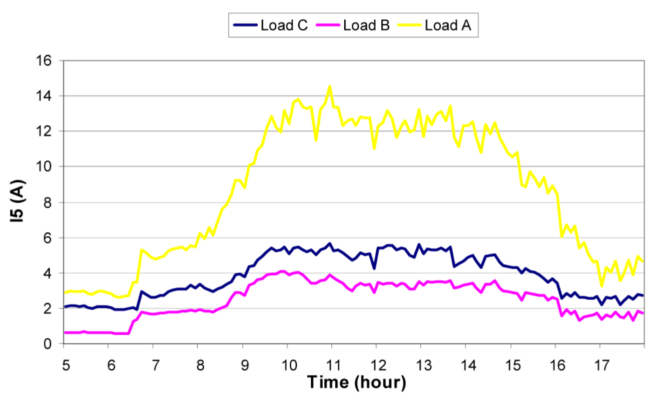


Fig. 13. Variation of the 5th order harmonic current of the studied loads (measurement data).

The loads increase in the morning and decrease in the evening. As the total apparent powers of the loads vary, the harmonic currents of the loads in the system also vary. Fig. 13 shows the variation of the 5th order harmonic current of the loads from 5 A.M. to 5 P.M.. According to our field measurement, the system has almost 50% background harmonic voltage which is propagated from the upstream of the system. This background harmonic is modeled by using a harmonic voltage source located in bus 1 (the slack bus).

Table VIII compares the harmonic impact of the loads achieved by applying the proposed method to the field measurement data with the average harmonic impacts of the loads achieved by our simulation. The simulation results are in good agreement with the field test results. Load A, the main harmonic contributor, is nearly responsible for more than 50% of the harmonic-voltage-distortion problems in the system. Load B has a negative harmonic impact. The harmonic voltage generated by this load partially cancels out the background harmonic voltage of the system and results in reduced harmonic voltage in the system. The results also show that load C does not have much harmonic impact on the system.

V. DISCUSSIONS

The proposed concept and method have room for improvement and future applications. Four issues identified in this paper are discussed here.

A. Data Synchronization

The current PQ monitoring systems are unable to collect synchronized data. For harmonic measurements, the synchronization requirement is higher than that of PMU. However, with the rapid advancement of telecommunication technology, global positioning system (GPS) sampled data will be available in the future. As a result, determining the phase differences among the data will be possible and will open up new ways to utilize the data and likely lead to more accurate harmonic-impact-estimation results.

B. Advanced Application for PQ Monitoring Systems

More utilities are deploying PQ monitoring systems. The current systems can report only what is observed in a power system, but not what is causing harmonic distortions or if two observations are related. The proposed technique pushes PQ monitoring to a higher level that involves identifying patterns and useful information from the observed data. Advanced applications that extract useful information from data will make the PQ monitoring system truly useful to utility companies. For example, the proposed technique can be added as a subroutine into the existing PQ monitoring system. The data server can use this technique to scan for major harmonic polluters in the system.

C. Application for Feeder Harmonic Monitoring

Another potential application of the proposed method is to determine the harmonic impact of each feeder on the common bus in a substation (see Fig. 14). In this case, the observation point is the harmonic voltage of the substation bus. The suspicious "loads" are the feeders connected to the bus.

D. Single-Point Application

In the theory, the proposed method can be applied to the single-point problem—quantifying the harmonic impact of a customer at its utility interface point. However, in practice, this application faces significant challenges. One of them is the data selection. A close examination of the situation reveals that the multi-point problem actually accesses more information than

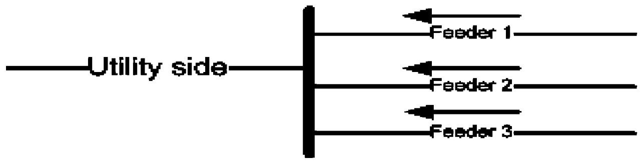


Fig. 14. Identification of the harmonic impact of each feeder on a common bus in a substation.

the single-point problem, so the former is easier to solve. At present, the authors are still working on developing a statistical-inference method for the single-point problem.

VI. Conclusion

This paper presented a new class of practical harmonic-source-identification methods. The paper first proposed an index to quantify the harmonic impact of several known harmonic-producing loads on the harmonic distortion level observed at a specific point in the network, and then a method was proposed to estimate this index. The method proposed here has a general application in PQ disturbance impact quantification. The proposed estimation method requires only the harmonic voltage and current magnitudes continuously collected by the existing PQ monitors (the phase angles are not required). The originality of the proposed method includes: 1) a multi-point statistical-inference approach to determine the harmonic impacts of loads and 2) data-selection criteria to select the data segment for the estimation method. The characteristics of the proposed method were investigated through case studies. Finally, additional applications and improvements of the proposed method were discussed.

References

[1] W. Xu and Y. Liu, "A method for determining customer and utility harmonic contributions at the point of common coupling," *IEEE Trans. Power Del.*, vol. 15, no. 2, pp. 804–811, Apr. 2000.
[2] K. Srinivasan, "On separating customer and supply side harmonic contributions," *IEEE Trans. Power Del.*, vol. 11, no. 2, pp. 1003–1012, Apr. 1996.
[3] A. Robert and T. Deflandre, "Guide for assessing the network harmonic impedances," in *Joint CIGRE/CIRED 97*, Jun. 2–5, 1997, Conf. Publ. No. 438, IEE, 1997.
[4] A. de Oliveira, J. C. de Oliveira, J. W. Resende, and M. S. Miskulin, "Practical approaches for AC system harmonic impedance measurements," *IEEE Trans. Power Del.*, vol. 6, no. 4, pp. 1721–1726, Oct. 1991.
[5] M. Sumner, B. Palethorpe, and D. W. P. Thomas, "Impedance measurement for improved power quality—Part 1: The measurement technique," *IEEE Trans. Power Del.*, vol. 19, no. 3, pp. 1442–1448, Jul. 2004.
[6] A. M. Dán and Zs. Czira, "Identification of harmonic sources," in *Proc. 8th Int. Conf. Harmonics and Quality Power*, Athens, Greece, Oct. 14–16, 1998, pp. 831–836.
[7] CIGRE Working Group 36.05/CIRED 2, "Review of methods for measurement and evaluation of the harmonic emission level from an individual distorting load," Jan. 1999, Working Group CC02.
[8] W. Xu, R. Bahry, H. E. Mazin, and T. Tayjasanant, "A method to determine the harmonic contributions of multiple loads," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 26–30, 2009, pp. 1–6.
[9] R. A. Johnson and D. W. Wichern*, Applied Multivariate Statistical Analysis*. Upper Saddle River, NJ: Prentice-Hall, 1998.
[10] R. Abu-hashim *et al.*, "Test systems for harmonics modeling and simulation," *IEEE Trans. Power Del.*, vol. 14, no. 2, pp. 579–583, Apr. 1999.
[11] Task Force on Harmonics Modeling and Simulation, "The modeling and simulation of the propagation of harmonics in electric power networks—Part I: Concepts, models and simulation techniques," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 452–465, Jan. 1996.
[12] Task Force on Harmonics Modeling and Simulation, "Modeling devices with nonlinear voltage-current characteristics for harmonic studies," *IEEE Trans. Power Del.*, vol. 19, no. 4, pp. 1802–1811, Oct. 2004.

Hooman E. Mazin (S'08) was born in Tehran, Iran, in 1981. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Amirkabir University of Technology, Iran, in 2004 and 2006, respectively, and is currently pursuing the Ph.D. degree in electrical engineering from the University of Alberta, Edmonton, AB, Canada.

Wilsun Xu (M'90–SM'95–F'05), received the Ph.D. degree from the University of British Columbia, Vancouver, BC, Canada, in 1989.

He was an Engineer with BC Hydro from 1990 to 1996. Currently, he is a Professor and an NSERC/iCORE Industrial Research Chair at the University of Alberta, Edmonton, AB, Canada. His research interests are power quality and harmonics.

Biao Hung received the B.Sc. and M.Sc. degrees from Beijing University of Aeronautics and Astronautics, Beijing, China, in 1983 and 1986, respectively, and the Ph.D. degree from the University of Alberta, Edmonton, AB, Canada, in 1997.

Currently, he is a Professor in the Department of Chemical and Materials Engineering, the University of Alberta. His research interests are in the areas of system identification, process control, and control monitoring.