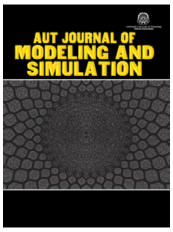

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A New Procedure for Determining Current Harmonic Contribution around an Operation Point at PCC Using Load Modelling Based on Crossed Frequency Admittance Matrix

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ABSTRACT: Today, one of the important issues of power quality (PQ) in power systems is the current harmonics. Increasing expansion of nonlinear loads at different parts of the electric network makes harmonic distortion flow through the network. This causes the network to have background voltage and current harmonic distortion and even affect on the PQ of linear load performance. Therefore, it is important to determine the harmonic contribution between load and network in distribution networks and industrial centers. In this paper, a new procedure for determining the current harmonic contribution around a quiescent point at the PCC is presented using load modeling based on crossed-frequency admittance matrix. The novelty of this paper is that, firstly, instead of using the harmonic Norton model of load, which has often been used in papers related to the harmonic contribution, it uses the crossed-frequency admittance matrix model, which is closed to actual load model; and secondly, considering the fact that a linear load has a diagonal form for its crossed frequency admittance matrix, the separation of harmonic contribution is made.

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1. Introduction

Voltage and current harmonic distortion is expanding due to increasing the nonlinear loads in distribution networks and industrial centers [1]. Today, harmonics are known as a major factor affecting on the power quality and causing many problems in the power system [2]. The harmonics in power systems can cause a lot of damage, such as increasing power losses and equipment heat, resonance phenomena, decreasing power quality, adverse effects on telecommunication equipment, increasing the probability of improper operation of protective systems and, consequently, reducing reliability. To deal with this problem, the first step is to identify harmonic generating sources. The next step is to determine how much each of these sources actually has contributed to the desired harmonic distortion, and in other words, how much has been disturber. In the past years, the harmonic contribution between the network and the customer at the point of common coupling (PCC) connected to the network has been determined in different ways.

In [3], a method is presented to determine the location of a harmonic source based on the direction of real power flow in the PCC bus. In this method, the side with larger harmonic power is identified as the location of harmonic source. It was then proved that this method can not necessarily give the correct determination because the direction of the real power flow is dependent on the angle between the network and customer voltages and is not dependent on their voltages amplitude [4]. Another method used to identify the source of harmonic generation in PCC is the method investigated in this paper, called the "vector projection" method. In this method, the Norton equivalent circuit of network and customer is obtained from side of the PCC bus, and then vector projection of the current or voltage caused by each of the harmonic generation sources in the PCC bus is respectively obtained on the current or voltage vector generated by the simultaneous presence of two harmonic sources. The magnitude and direction of each vector projection represent the harmonic contribution of each source [5]. Papers [6,7] present methods to identify the harmonic source in the PCC bus, which are based on comparison of the voltage amplitude and critical impedance, respectively. In these methods, several switching tests are required to recognize the system impedance. In 2008, a method based on total harmonic distortion (THD) calculation was proposed to determine the contribution of customer and network in the harmonic distortion of distribution networks [8]. This method is not sufficiently precise because it does not consider the harmonic sources phase [9]. [3-8] have focused on radial networks, but [9] has also determined the harmonic contribution of network and customer in weakly meshed networks. In this method, a Norton equivalent circuit of customer is used to model customer RLC components. Determining the harmonic contribution for a special load, taking into account

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background harmonic changes, is presented in [10].

Methods based on harmonic state estimates (HSE) [11,12], independent component analysis (ICA) [13,14], and weighted least squared estimates (WLSE) [15] are some methods that have been applied to transmission networks. The major disadvantages of these methods are heavy calculations and great deal of measurements [9]. In 2014, a new "Vector Draft" method was used to identify the harmonic source in the PCC bus. In this method, measurement is performed in PCC bus by using the phase spectrogram (PS) and frequency spectrogram (FS), and based on the "Vector Draft" method, in order to detect the harmonic source [16].

Harmonic Norton model of load is usually used in the papers to model harmonic loads. Regarding that in the harmonic Norton model some cases such as interaction between different harmonic orders of supply voltage, power supply impedance, harmonics generated by other parallel nonlinear loads, and the accidental connection of an active or passive filter are not considered [17]; therefore, the crossed-frequency admittance matrix model [18], which is a more precise model, is used for load in the current paper. In this paper, a new method is proposed to separate the harmonic contribution of the network and load, considering this point that for linear loads, and not for the nonlinear ones, CFAM has a diagonal form.

Using the proposed method, by obtaining the CFAM at an operating point, the harmonic contribution of the network and the load can be calculated in harmonic current changes around the operation point at each harmonic order. In Section 2, the proposed method is expressed in details; then, in Section 3, simulation of the proposed method is performed in three case studies. Finally, in Section 4, a conclusion is presented.

2. Proposed Method

Firstly, before discussing the harmonic contribution method, the harmonic load model used to determine the harmonic contribution is explained. Usually, in the papers that deal with the harmonic contribution, the Norton load model is used. The Norton model does not consider the interaction between harmonic voltages and currents; hence, the CFAM model is used in this paper for the harmonic load model.

Generally, if f, according to (1), is a function of variables $x_1, x_2, ..., x_k, ..., x_K$, f can be linearized in form (2) around the point $X_{ref} = (x_{1_{ref}}, x_{2_{ref}}, ..., x_{K_{ref}})$ and with the value of f_{ref}.

$$f = f(X) = f(x_1, x_2, ..., x_k, ..., x_K) \tag{1}$$

$$\begin{aligned} f = f_{ref} &+ \left.\frac{\partial f}{\partial x_1}\right|_{X=X_{ref}} (x_1 - x_{1_{ref}}) + \left.\frac{\partial f}{\partial x_2}\right|_{X=X_{ref}} (x_2 - x_{2_{ref}}) + ... \\ &+ \left.\frac{\partial f}{\partial x_k}\right|_{X=X_{ref}} (x_k - x_{k_{ref}}) + ... + \left.\frac{\partial f}{\partial x_K}\right|_{X=X_{ref}} (x_K - x_{K_{ref}}) \end{aligned} \tag{2}$$

According to the definition of partial derivative, for calculating $\left.\frac{\partial f}{\partial x_k}\right|_{X=X_{ref}}$, all variables are kept constant at the point X_{ref}, and only the variable x_k changes partially. In this condition, $\frac{\Delta f}{\Delta x_k}$ represents $\left.\frac{\partial f}{\partial x_k}\right|_{X=X_{ref}}$.

Considering the interaction between the voltages and harmonic currents in phasor-mode, the relationship between the k^{th} harmonic current load and the harmonic voltages of the load is as (3). By linearizing (3) around the desired operation point, (4) will be obtained [19]:

$$I_k = f(V_1, V_2, ..., V_k, ..., V_K) \tag{3}$$

$$\underbrace{\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_k \\ \vdots \\ I_K \end{bmatrix}}_{I} = \underbrace{\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1j} & \cdots & y_{1K} \\ y_{21} & y_{22} & \cdots & y_{2j} & \cdots & y_{2K} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{k1} & y_{k2} & \cdots & y_{kj} & \cdots & y_{kK} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{K1} & y_{K2} & \cdots & y_{Kj} & \cdots & y_{KK} \end{bmatrix}}_{Y} \underbrace{\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_j \\ \vdots \\ \Delta V_K \end{bmatrix}}_{\Delta V} + \underbrace{\begin{bmatrix} I_{ref_1} \\ I_{ref_2} \\ \vdots \\ I_{ref_k} \\ \vdots \\ I_{ref_K} \end{bmatrix}}_{I_{ref}} \tag{4}$$

where Y is known as the crossed-frequency admittance matrix (CFAM), ΔV_j is difference between the j^{th} harmonic voltage (V_j) and its value at the operation point ($V_{j_{ref}}$).

By comparing (2) and (4), it can be seen that the elements of each row Y are actually the partial derivatives in (2). Therefore, a partial derivative is used to derive each of the elements. In order to obtain the element y_{kj}, all of the harmonic voltages, except the j^{th} harmonic voltage, are kept constant at the their operation point, and only the j^{th} harmonic voltage is slightly changed. In this case, the ratio of variation which occurs in the k^{th} harmonic current to the j^{th} harmonic voltage changes represents the y_{kj} [19]. So y_{kj} is simply obtained from (5):

$$y_{kj} = \frac{I_k - I_{k_{ref}}}{V_j - V_{j_{ref}}}; \quad where: \begin{cases} \Delta V_1 = 0 \\ \Delta V_2 = 0 \\ \vdots \\ \Delta V_{j-1} = 0 \\ \Delta V_j = \delta_j \\ \Delta V_{j+1} = 0 \\ \vdots \\ \Delta V_K = 0 \end{cases} \tag{5}$$

where δ_j is the amount of partial variation in the magnitude and phase of the j^{th} harmonic voltage at the desired operation point.

The harmonic contribution is determined using the CFAM of load obtained at the desired operating point. Hence, determining the current harmonic contribution is based on this fact that:

- The network is so responsible for PCC harmonic current that the considered load will draw the current if it is linear.

- The nonlinear load is so responsible for PCC harmonic current that transforming the corresponding linear load to this nonlinear load results in drawing the current.

In other words, the important issue is to identify the linear load corresponding to the load (linear or nonlinear).

A linear load has a diagonal CFAM [18]. In a linear load, the k^{th} harmonic current changes are only dependent on the k^{th} harmonic voltage variations of load and voltage changes of the other harmonics do not affect it. Therefore, it can be concluded that if the desired nonlinear load was linear, only the main diagonal of its CFAM would remain, and its other components would be zero. Therefore, it can be said that a term of the k^{th} harmonic current changes of load due to the k^{th} harmonic voltage variations of load is generated even though the load is linear. Therefore, the network, not the load, is responsible in this term of current. The terms of the k^{th} harmonic current changes of load generated by harmonic voltage changes of other orders are actually the terms that are generated due to non-linear nature of the load. In other words, these terms are those a linear load never has. So in these terms, the load, not the network, is responsible. Therefore, the separation of the harmonic contribution of network and load is performed as described. A term of k^{th} harmonic current of load in which the source is responsible ($\Delta I_k^{Utility}$), and a term of k^{th} harmonic current of load in which the load is responsible (ΔI_k^{Load}) are obtained from (6) and (7), respectively:

$$\Delta I_k^{Utility} = y_k \, \Delta V_k \tag{6}$$

$$\Delta I_k^{Load} = \sum_{\substack{j=1 \\ j\neq k}}^{K} y_{kj} \, \Delta v_j = \Delta I_k - y_k \, \Delta v_k \tag{7}$$

The evidence that can greatly proves the accuracy of the proposed method is that in this method, if a linear load is connected to a network with a background harmonic, it will never be recognized as a harmonic responsible because all non-diagonal components of its admittance matrix are zero. Therefore, by using (7), ΔI_k^{Load} will be equal to zero for each harmonic with k^{th} order. This is the result which is expected from determining of the harmonic contribution of a linear load.

Using the "vector projection" method described in [5], the harmonic contribution of network and load in the k^{th} harmonic current changes of PCC ($\lambda_k^{\Delta I,Utility}$ and $\lambda_k^{\Delta I,Load}$) are determined by (8) and (9), respectively:

$$\lambda_k^{\Delta I,Utility}(\%) = \frac{\Delta I_k^{Utility} . \Delta I_k}{|\Delta I_k|^2} \times 100 \tag{8}$$

$$\lambda_k^{\Delta I,Load}(\%) = \frac{\Delta I_k^{Load} . \Delta I_k}{|\Delta I_k|^2} \times 100 \tag{9}$$

In which "." presents the inner product of two vectors.

3. Simulation Results

In this section, the proposed method for determining of the harmonic contribution of current changes between load and network is simulated in MATLAB software. In order to evaluate the accuracy of the proposed method, three cases are investigated. In Case 1, a linear load which is connected to a network that has a background harmonic is investigated. This case is important as the result of determination of the harmonic contribution is already known. It means that if the proposed method is accurate, it should estimate the harmonic contribution of the network in all harmonic orders as 100%, and should assess the harmonic contribution of load as zero.

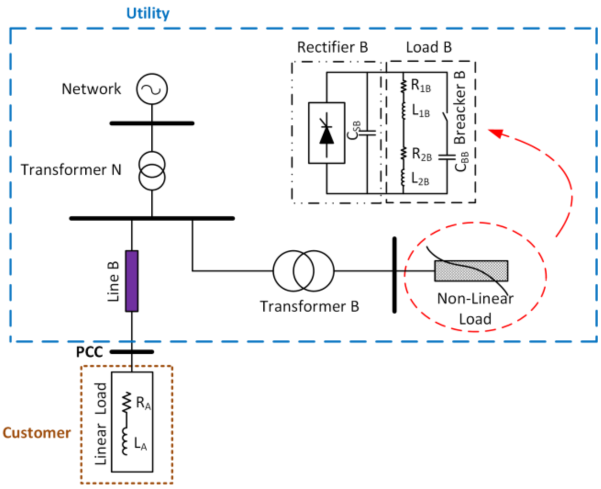

Fig. 1. A connection of a linear load and a network with background harmonic, at the PCC bus.

In Case 2, a nonlinear case is connected to a clean network without a background harmonic. In this case, the proposed method is expected to estimate the harmonic contribution of load as 100% at all harmonic orders and to estimate the harmonic contribution of the network as zero. In Case 3, a nonlinear non-linear connected to a network that has a background harmonic is investigated. The result of this case is expected to be between that of first and second cases, and for each harmonic order, the network and the load have a certain contribution.

3-1-Case 1: The linear load connected to a network with background harmonic

In this case, as shown in Fig. 1, a linear R-L load ($Load_A$) is connected to the network ($Line_B$) by a line ($Network_B$). To generate a background harmonic for the network, a rectifier ($Rectifier_B$) which is feeding its load ($Load_B$) is connected to a network by a transformer ($Transformer_B$). The harmonic generated by the rectifier causes the network to be harmonic from point of investigated linear load. Information of parameters in the investigated system is given in Table 1.

The aim is determining the harmonic contribution of current changes due to the network and load at the PCC bus. First, at the operating point of system, i.e. before t = 0.6s (at t = 0.6s variations are considered), the voltage and current of each harmonic order is obtained at the PCC bus, using the FFT transformation and taking into account 20 frequencies (including the DC component, the fundamental component and 18 harmonic orders). To get the CFAM elements at this operating point, $Load_A$ is disconnected and then is connected to a controlled voltage source.

According to the explanation given in Section 2, minor

Table 1. Information of parameters in the simulated system in each case study

	Case 1 & Case 2	*Case 3*
Load$_A$	$\begin{cases} R_A = 600\Omega \\ L_A = 0.1H \end{cases}$	$\begin{cases} R_{1A} = 540\Omega \\ L_{1A} = 20H \end{cases}$ $\begin{cases} R_{2A} = 540\Omega \\ L_{2A} = 20H \end{cases}$ $\{C_{3A} = 100F$
Breaker$_A$	-----------	$\begin{cases} open & t < 0.6s \\ close & t \geq 0.6s \end{cases}$
Rectifier$_A$	-----------	type : 12 - pulse $\text{firing angle} = \begin{cases} 27^\circ & t < 0.6s \\ 50^\circ & t \geq 0.6s \end{cases}$ $C_{SA} = 0.05mF$
Transformer$_A$	-----------	$\begin{cases} S_N = 250MVA \\ V_{1N} = 11kV \\ V_{2N} = 6.3kV \\ V_{3N} = 6.3kV \\ r_{\text{Primary}} = r_{\text{Secondary}} = r_{\text{Tertiary}} = 0.002pu \\ l_{\text{Primary}} = l_{\text{Secondary}} = l_{\text{Tertiary}} = 0.08pu \end{cases}$
Line$_B$	$\begin{cases} R_{Line_B} = 1\Omega \\ L_{Line_B} = 10^{-3}H \end{cases}$	$\begin{cases} R_{Line_B} = 1\Omega \\ L_{Line_B} = 10^{-3}H \end{cases}$
Network	$\begin{cases} V_N = 11kV \\ f = 50Hz \\ S_{SC} = 100MVA \\ \frac{X}{R} = 7 \end{cases}$	$\begin{cases} V_N = 11kV \\ f = 50Hz \\ S_{SC} = 100MVA \\ \frac{X}{R} = 7 \end{cases}$
Load$_B$	$\begin{cases} R_{1B} = 540\Omega \\ L_{1B} = 20H \end{cases}$ $\begin{cases} R_{2B} = 540\Omega \\ L_{2B} = 20H \end{cases}$ $\{C_{3B} = 100F$	$\begin{cases} R_{1B} = 540\Omega \\ L_{1B} = 20H \end{cases}$ $\begin{cases} R_{2B} = 540\Omega \\ L_{2B} = 20H \end{cases}$ $\{C_{3B} = 100F$
Breaker$_B$	$\begin{cases} open & t < 0.6s \\ close & t \geq 0.6s \end{cases}$	$\begin{cases} open & t < 0.6s \\ close & t \geq 0.6s \end{cases}$
Rectifier$_B$	type : 6 - pulse $\text{firing angle} = \begin{cases} 5^\circ & t < 0.6s \\ 42^\circ & t \geq 0.6s \end{cases}$ $C_{SB} = 0.1mF$	type : 6 - pulse $\text{firing angle} = \begin{cases} 5^\circ & t < 0.6s \\ 42^\circ & t \geq 0.6s \end{cases}$ $C_{SB} = 0.1mF$
Transformer$_B$	$\begin{cases} S_N = 250MVA \\ V_{1N} = 11kV \\ V_{2N} = 6.3kV \\ r_{\text{Primary}} = r_{\text{Secondary}} = 0.002pu \\ l_{\text{Primary}} = l_{\text{Secondary}} = 0.08pu \end{cases}$	$\begin{cases} S_N = 250MVA \\ V_{1N} = 11kV \\ V_{2N} = 6.3kV \\ r_{\text{Primary}} = r_{\text{Secondary}} = 0.002pu \\ l_{\text{Primary}} = l_{\text{Secondary}} = 0.08pu \end{cases}$

changes at each harmonic order of the reference voltage (operating point voltage) occurs after each other, and is applied to this $Load_A$ by this controlled voltage source. The minor change in the magnitude and phase of the reference voltage at each harmonic order is considered to be 5%. Using (5), each of the CFAM elements is obtained. Then, to change the harmonic values of voltage and current at PCC bus in the system (Fig. 1), at t = 0.6s, the firing angle of $Rectifier_B$ changes from 5° to 42°, and in addition $Breaker_B$ is closed. The generated changes in the voltage and current waveform are shown in Fig. 2.

The result of determining the harmonic contribution of

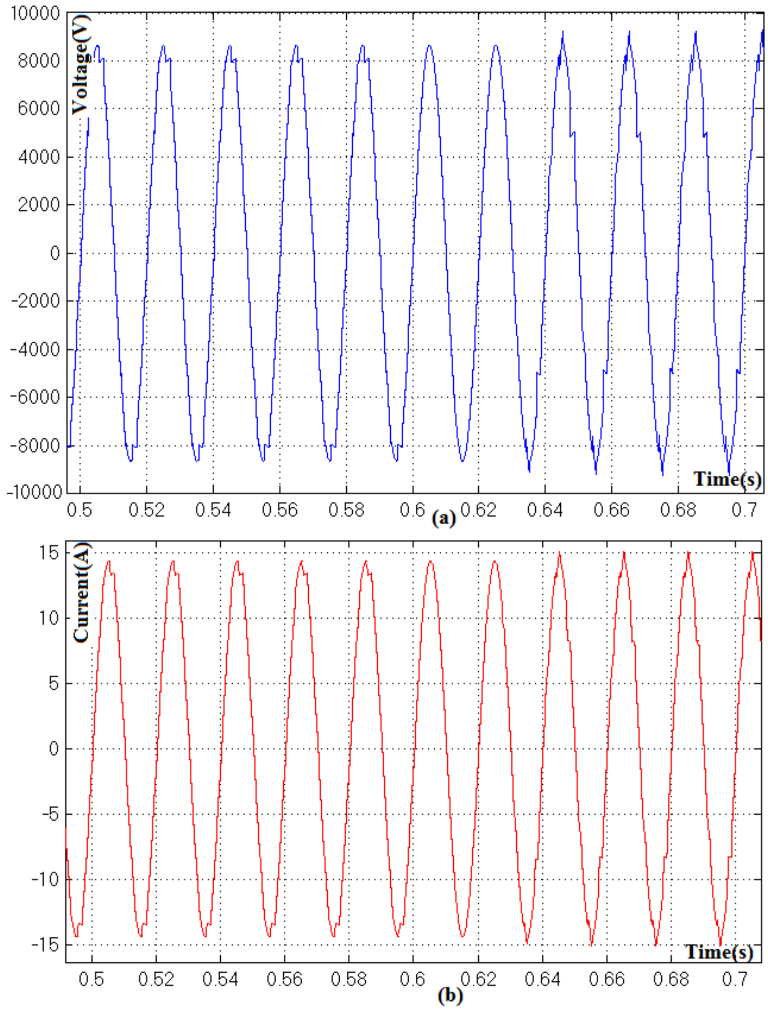

Fig. 2. Voltage and current waveform at PCC bus before and after considering the change in t = 0.6s at Case 1. (a) Line-to-ground voltage, phase A (b) Current of phase A

Table 2. The results of determining the harmonic contribution of the change occurring in the PCC current in each of the harmonic orders for Case 1

Harmonic order	5	7	11	13	17	19
$\lambda_k^{\Delta I,Utility}(\%)$	100	100	100	100	100	100
$\lambda_k^{\Delta I,Load}(\%)$	0	0	0	0	0	0

the $Load$ and the $Utility$ at the system shown in Fig. 1, in the harmonic current changes generated in the PCC, is given in Table 2 for each of the harmonic orders using (8) and (9).

According to Table 2, the load harmonic contribution in the harmonic current changes generated at the PCC bus, for all harmonic orders, is detected as zero and its value is detected for the network as 100%. This is the result that is expected in determining the harmonic contribution of a linear load connected to a network with background harmonic. It should be noted that due to the nature of nonlinear load, there are only 6k±1 harmonic orders in the system and the other harmonics are zero. Therefore, they are not included in the Table.

3-2-Case 2: Nonlinear load connected to a network without background harmonics

In this case, the desired network and its parameters are chosen as the network Case 1, but in this case it is assumed that the studied customer, according to Fig. 3, is a nonlinear load connected by $Transformer_B$. By changing the angle of fire of $Rectifier_B$ from 5° to 42° and closure of $Breaker_B$, changes are made in the current and voltage of the PCC, as shown in Fig. 4.

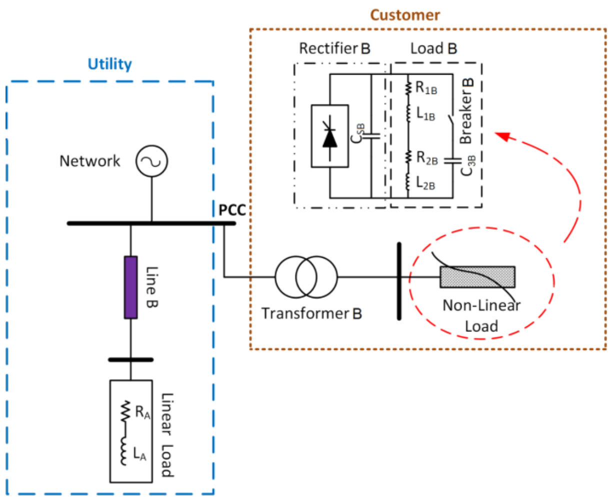

Fig. 3. Connecting a nonlinear load and a network without background harmonic, in the PCC bus.

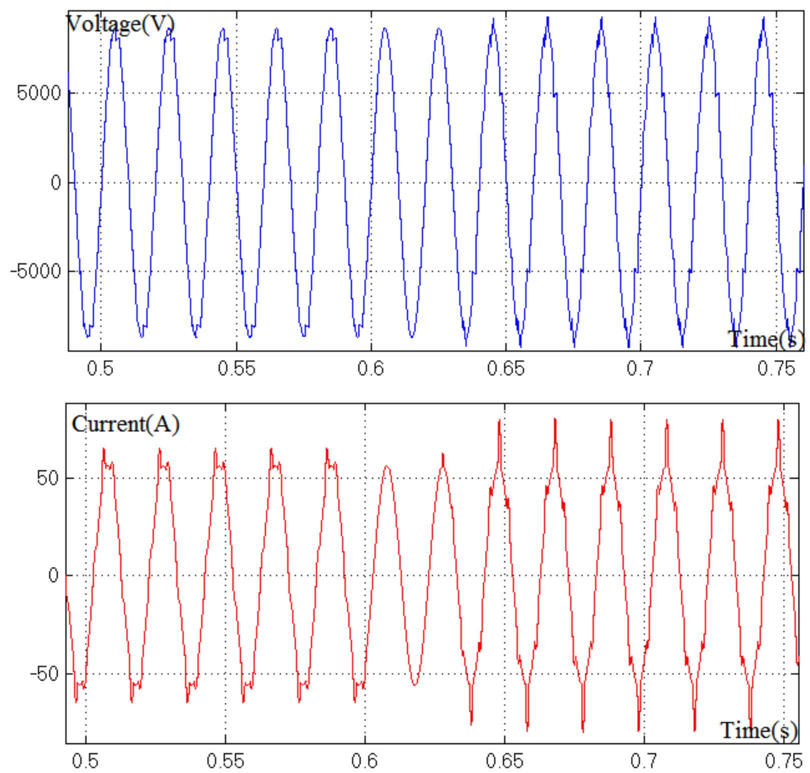

Fig. 4. Waveform of voltage and current at PCC bus before and after applying the changes at the instant t = 0.6s in Case 2.
(a) Line-to-ground voltage of phase A (b) Current of phase A

Table 3. The results of determining the harmonic contribution due to change the PCC current in each of the harmonic orders for Case 2

Harmonic order	5	7	11	13	17	19
$\lambda_k^{\Delta I,Utility}(\%)$	0.02	0.44	0.34	0.27	0.13	0.39
$\lambda_k^{\Delta I,Load}(\%)$	99.98	99.56	99.66	99.73	99.87	99.61

The result of determining the harmonic contribution of *Load* and *Utility* of the system shown in Fig.3 in the harmonic current changes generated in the PCC for each of the harmonic orders using (8) and (9) is given in Table 3.

According to Table 3, in this case, as expected, the harmonic load contribution of all harmonics is much more than the estimated network contribution and is estimated to be relatively close to 100% with a good precision. Given that in this case the network is completely homogeneous and all the harmonics are due to the load, the results of the Table are reasonable. However, it is observed that in some harmonics, as compared to other harmonics, the expected result for determining the harmonic contribution of the load and the network (100% and 0% respectively) is not estimated. The reason of this seems to be that the harmonic amplitude of these harmonics is low and thus the accuracy of computations is reduced. This point should also be noted that in any case, with the first glance to the Table, one can find that the harmonic responsible is the load, not the network. Like case 1, since the harmonic orders other than 6k±1 are zero, they are not included in the Table

3-3-Case 3: Nonlinear load connected to a network with background harmonic

In this case, according to Fig. 5, the nonlinear load connected to the PCC is similar to the nonlinearity load in Case 2; and the network with the background harmonic connected to the PCC is in accordance with the network with background harmonic of the Case 1. Information about the system parameters is given in Table 1. The operating point and CFAM are obtained similar to the previous two cases. At t = 0.6s both $Breaker_A$ and $Breaker_B$ are closed; in addition, the $Rectifier_A$ fire angle changes from 27° to 50° and the $Rectifier_B$ fire angle changes from 5° to 42°. The changes occurred in the current and voltage of the *PCC* are shown in Fig. 6.

The result of the harmonic contribution of $Load$ and $Utility$ of the system shown in Fig. 5 in the harmonic current changes generated in the PCC for each harmonic order using (8) and (9) is given in Table 4.

According to Table 4, in each of the harmonic orders, different contributions are estimated for each of the sides; in some harmonic orders, *Customer* is detected as responsible, and in some other, *Utility* is responsible. In the system under consideration, due to the presence of 6-pulse rectifier at the load side, it is expected that the harmonic orders 6k±1 generated in the system are due to the load. Using the proposed method, according to result obtained in Table 4, the harmonic contribution of load for orders 5, 7, 17 and 19 is estimated at almost 100%, and the harmonic contribution of utility is estimated to be zero. The harmonic orders obtained from 12-pulse rectifier are 12k±1. Harmonic orders 11 and 13 in the examined system originate from 6 and 12 pulse rectifiers. The main responsible of 11^{th} harmonic flowing in PCC is utility with sharing 65.84%. Also, the main responsible of 13^{th} harmonic flowing in PCC is customer with sharing 57.61%

4. Conclusion

In this paper, a new method is proposed by using a CFAM model of load to determine the harmonic contribution of current changes around an operating point, in the PCC bus. The contribution separating equations, which are based on the diagonal CFAM for linear loads, are expressed, and then presented as indicators using the “vector projection” method.

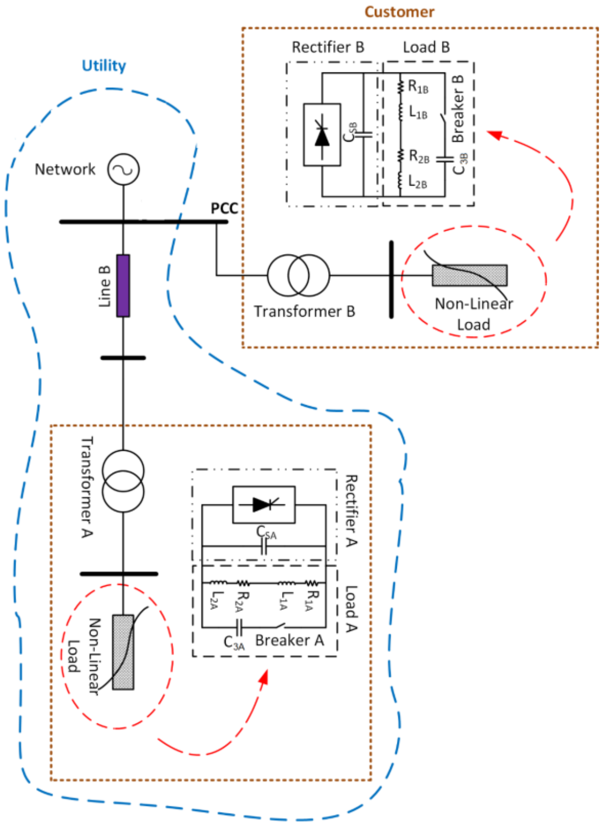

Fig. 5. The connection of a nonlinear load and a network with background harmonic, in the PCC bus.

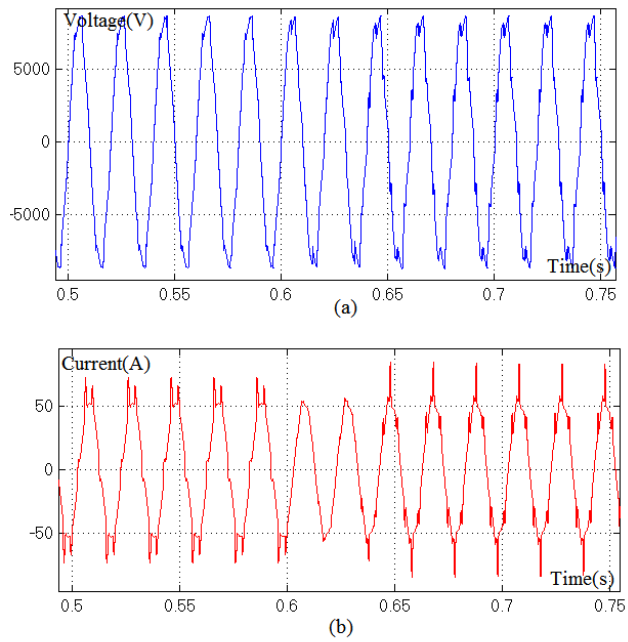

Fig. 6. Waveform of voltage and current at PCC bus before and after applying the changes at the instant t = 0.6s in Case 3. (a) Line-to-ground voltage of phase A (b) Current of phase A

Table 4. The results of determining the harmonic contribution due to change the PCC current in each of the harmonic orders for Case 3

Harmonic order	5	7	11	13	17	19
$\lambda_k^{\Delta I,Utility}(\%)$	0.07	0.09	65.84	41.39	0.04	0.02
$\lambda_k^{\Delta I,Load}(\%)$	99.93	99.91	34.16	58.61	99.96	99.98

To evaluate the proposed method, simulation was performed in three case studies using MATLAB software. In all three case studies, the results were close to the expected results.

5. References

[1] D. Salles, C. Jiang, W. Xu, W. Freitas, H.E. Mazin, Assessing the collective harmonic impact of modern residential loads—Part I: Methodology, IEEE transactions on power delivery, 27(4) (2012) 1937-1946.

[2] I. Santiago, M. López-Rodríguez, A. Gil-de-Castro, A. Moreno-Munoz, J. Luna-Rodríguez, Energy consumption of audiovisual devices in the residential sector: Economic impact of harmonic losses, Energy 60, 292-301 (2013).

[3] K.M. Islam, A.H. Samra, Identification of harmonic sources in power distribution systems, in: Proceedings IEEE SOUTHEASTCON'97.'Engineering the New Century', IEEE, 1997, pp. 301-303.

[4] W. Xu, X. Liu, Y. Liu, An investigation on the validity of power-direction method for harmonic source determination, IEEE transactions on power delivery, 18(1) (2003) 214-219.

[5] W. Xu, Y. Liu, A method for determining customer and utility harmonic contributions at the point of common coupling, IEEE Transactions on Power Delivery, 15(2) (2000) 804-811.

[6] N. Hamzah, A. Mohamed, A. Hussain, Harmonic source location at the point of common coupling based on voltage magnitude, in: 2004 IEEE Region 10 Conference TENCON 2004., IEEE, 2004, pp. 220-223.

[7] C. Chen, X. Liu, D. Koval, W. Xu, T. Tayjasanant, Critical impedance method-a new detecting harmonic sources method in distribution systems, IEEE Transactions on Power Delivery, 19(1) (2004) 288-297.

[8] S.F. de Paula Silva, J.C. de Oliveira, The sharing of responsibility between the supplier and the consumer for harmonic voltage distortion: A case study, Electric Power Systems Research, 78(11) (2008) 1959-1964.

[9] M. Farhoodnea, A. Mohamed, H. Shareef, H. Zayandehroodi, An enhanced method for contribution assessment of utility and customer harmonic distortions in radial and weakly meshed distribution systems, International Journal of Electrical Power & Energy Systems, 43(1) (2012) 222-229.

[10] H. Hua, X. Jia, D. Cao, C. Zhao, Practical method to determine the harmonic contribution of a specific harmonic load, in: 2012 IEEE 15th International Conference on Harmonics and Quality of Power, IEEE, 2012, pp. 769-773.

[11] Z.P. Du, J. Arrillaga, N. Watson, S. Chen, Identification of harmonic sources of power systems using state estimation, IEE Proceedings-Generation, Transmission and Distribution, 146(1) (1999) 7-12.

[12] G. D'Antona, C. Muscas, S. Sulis, State estimation for the localization of harmonic sources in electric distribution systems, IEEE Transactions on instrumentation and measurement, 58(5) (2009) 1462-1470.

[13] E. Gursoy, D. Niebur, Harmonic load identification using complex independent component analysis, IEEE Transactions on power delivery, 24(1) (2008) 285-292.

[14] K. Pulimera, P.K. Rajan, Independent component analysis for harmonic source estimation from piecewise constant parameter mixed measurements, in: 2011 IEEE 43rd Southeastern Symposium on System Theory, IEEE, 2011, pp. 81-86.

[15] A. Kumar, B. Das, J. Sharma, Determination of location of multiple harmonic sources in a power system, International journal of electrical power & energy systems, 26(1) (2004) 73-78.

[16] A. Abdullah, G. Peng, S. Ghani, M. Jopri, A new vector draft method for harmonic source detection at point of common coupling, in: 2014 IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014), IEEE, 2014, pp. 110-114.

[17] M. Lamich, J. Balcells, M. Corbalán, E. Griful, Nonlinear loads model for harmonics flow prediction, using multivariate regression, IEEE Transactions on Industrial Electronics, 64(6) (2017) 4820-4827.

[18] M. Fauri, Harmonic modelling of non-linear load by means of crossed frequency admittance matrix, IEEE transactions on Power systems, 12(4) (1997) 1632-1638.

[19] J. Caicedo, A. Romero, H. Zini, Frequency domain modeling of nonlinear loads, considering harmonic interaction, in: 2017 IEEE workshop on power electronics and power quality applications (PEPQA), IEEE, 2017, pp. 1-6.

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