Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 11 (2): 257-265, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.257.265

A Single Point Measurement Method for Evaluating Harmonic Contributions of Utility and Customer in Power Distribution Systems

M. Farhoodnea, A. Mohamed and H. Shareef
Department of Electrical, Electronic and Systems Engineering, University Kebangsaan, Malaysia

Abstract: This study presents a method for determining the contribution of harmonic distortions generated by utility and customer at the Point of Common Coupling (PCC) in power distribution systems. The method is known as the RLC method as the customer load is modeled with RLC components using measured voltage and current at the PCC and the system is represented by a Norton equivalent circuit. The contributions of harmonic voltage and current distortions from utility and customer sides of the system are derived by estimating the customer impedance and then calculating the harmonic currents at customer and utility sides. Several case studies have been made to verify the accuracy of the proposed RLC method in determining the contribution of utility and customer harmonic distortions by making a comparison with the IEEE1459–2000 standard based method. Results showed that the proposed RLC method can accurately determine the harmonic contributions of utility and customer for measurements made at the PCC.

Key words: Harmonic, harmonic distortion, harmonic source location, load modeling, localization of harmonic sources, power quality, sharing harmonic responsibility

INTRODUCTION

In power systems, harmonic currents are injected into the system by nonlinear loads such as power electronic based equipments, arc furnaces, adjustable speed drives and so on. Such equipments have nonlinearity characteristic which can distort fundamental voltage and current waveforms. When such nonlinear loads are supplied from a sinusoidal voltage, their injected harmonic currents are referred to as contributions from the customer. Harmonic currents which flow in any network cause harmonic voltage drops such that the supply voltage at the customer is no longer sinusoidal. Other customers connected to the Point of Common Coupling (PCC) will have harmonic currents injected into them by the distorted network voltage at the PCC and such currents are referred to as supply harmonics. These harmonics have many negative effects on power systems such as power factor distortion and resonance problems. To address the attribution of responsibility between customers and utilities for harmonic distortion in a power system, harmonic source localization approach is usually considered (Ranade and Xu, 1998; Xiaodong and Jackson, 2008).

Methods for determining either harmonic contributions or location of harmonic sources in power systems are normally classified as multiple point and single point measurement strategies. Many of the multiple harmonic sources localization methods are based on Harmonic State Estimation (HSE) (Du *et al*., 1999; D'Antona *et al*., 2009). The problem with HSE based methods is that it depends on complete characteristics of the system and requires several types of measurements such as voltage, real and reactive powers at each harmonic frequency. Generally, such kinds of information are usually unknown or require complicated calculations which are not economical for large systems. Another multiple harmonic sources localization method is based on the independent component analysis (Gursoy, 2007). In this method, the reduced system harmonic impedance matrix is first estimated so as to determine the harmonic currents of the harmonic sources. The minimum electrical distances between the estimated impedance matrix and the actual impedance matrix are then calculated by using the exhaustive search technique. The buses with minimal distances are considered as the location of harmonic sources. This method needs prior knowledge about system parameters and historical load profiles as well as the actual impedance matrix of a system at each harmonic frequency and this makes its implementation impractical and uneconomical. Therefore, to reduce the cost of harmonic measurement and to simplify the calculations, several single point measurement methods have been developed for either identifying the location of harmonic

Corresponding Author: M. Farhoodnea, Department of Electrical, Electronic and Systems Engineering, University Kebangsaan, Malaysia Tel: 0060178798079

sources or determining the harmonic contributions of utility and customer in a power system.

In practical situations, harmonic sources can be located upstream and downstream relative to a monitoring point which is usually at the Point of Common Coupling (PCC). With regards to this, different approaches focusing on single point strategy can be found in the literature, for locating the source of harmonics and determining the share of utility and customer harmonic distortion at the PCC. The side that produces greater harmonic power is responsible for harmonic pollution. The real power direction method (Islam and Samra, 1997) is the earliest method proposed in locating harmonic sources at the PCC. However, the real power direction method has been found to be only 50% reliable should the customer change loads and its disadvantage is that it depends on actual system parameters values for its calculation (Xu *et al*., 2002). Other single point based methods is incentive-based method (Xu and Liu, 1999, 2000). The main weakness of this method is its dependency to actual system parameters values for its calculation. The critical impedance method (Chaoying, *et al*., 2004) and voltage magnitude comparison method (Hamzah *et al*., 2004) are other single point measurement methods. These methods require complete knowledge of system parameters and the criteria of the possible changes of the system impedances in harmonic frequency or implementation of switching tests for determining the values of the harmonic impedances of the system. However, such data are not available in most of the time and implementing switching tests do not allow its application in practical power systems. More recent methods for determining harmonic contributions of utility and customer at the PCC are such as the Total Harmonic Distortion (THD) method (Costa *et al*., 2009) and harmonic vector method (Pfajfar *et al*., 2008) which try to solve the drawbacks of the previous methods. However, these methods still suffer from some problems such as the use of unsuitable index, unpractical harmonic modeling and inability to determine the location of harmonic sources at individual harmonic frequencies. A more recent method for locating the harmonic source is the IEEE1459-2000 standard based method Cataliotti and Cosentino 2010 which is based on the evaluation of three different non active power quantities at the PCC. These three quantities are defined as fundamental reactive power Q_1, Fryze's reactive power Q_F and fictitious reactive power Q_X. Based on this method, Q_1 and Q_F are the minimum and maximum reference values, respectively and Q_X is in between ($Q_1 < Q_X < Q_F$). Hence, when harmonic distortion is due to the utility side, the difference between Q_1 and Q_F is not significant. On the other hand, when harmonic distortion is due to the customer side, the difference between Q_1 and Q_F is significant and Q_X is very close to Q_F.

This study presents an improved single point measurement method for determining the share of utility and customer for harmonic distortions in a power system. The proposed method is known as the RLC method because the measured voltage and current at the PCC are used for obtaining the customer side equivalent impedance which is represented by parallel resistance, inductance and capacitance components. In the RLC method, the utility reference impedance is represented by short circuit impedance of the system. Using the impedance values, the share of customer and utility harmonic voltage and current distortions are determined as a percentage of measured voltage and current harmonics at the PCC for each harmonic frequency. From the contributions of utility and customer harmonic distortions, the location of the harmonic source can be determined based on the dominant harmonic distortions. To prove the accuracy and effectiveness of the RLC method, a comparison is made with the IEEE1459-2000 standard based method Cataliotti and Cosentino 2010.

THEORETICAL BACKGROUND

Generally for simplifying the calculations, it is possible to convert any test system to its Norton equivalent circuit as shown in Fig. 1. In the Fig. 1, the utility side is represented by a current source I_u and an impedance Z_u. Similarly, the customer side is represented by a current source I_c and an impedance Z_c It should be noted that superscript h represents the harmonic frequency and all equations are in the complex form.

Harmonic current sources in the Norton equivalent circuit can be obtained from the measured harmonic voltage V_{pcc} and current I_{pcc} at the PCC by using the following equations (Xu and Liu, 2000):

$$\bar{I}_u^h = \frac{\bar{V}_{pcc}^h}{\bar{Z}_u^h} + \bar{I}_{pcc}^h \tag{1}$$

$$\bar{I}_c^h = \frac{\bar{V}_{pcc}^h}{\bar{Z}_c^h} - \bar{I}_{pcc}^h \tag{2}$$

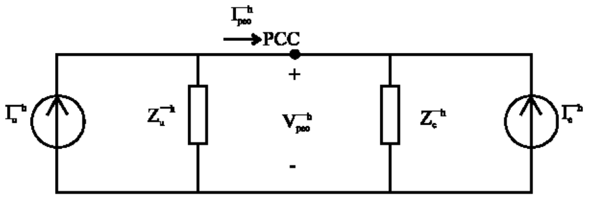

Fig. 1: Norton equivalent circuit

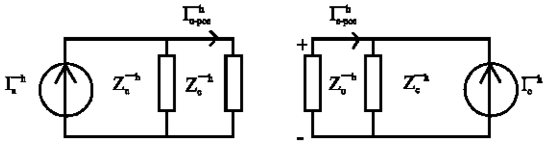

Fig. 2: Decomposed Norton equivalent circuit

By applying the superposition theorem to decompose the system as shown in Fig. 2, the harmonic contributions from the utility and customer can be obtained.

From the Fig. 2, the harmonic current contributions of utility side, $I_{u\text{-}pcc}$ and customer side, $I_{c\text{-}pcc}$ can be derived as:

$$\bar{I}^{h}_{u-pcc} = \frac{\bar{Z}^{h}_{u}}{\bar{Z}^{h}_{u} + \bar{Z}^{h}_{c}} . \bar{I}^{h}_{u} \tag{3}$$

$$\bar{I}^{h}_{c-pcc} = \frac{-\bar{Z}^{h}_{c}}{\bar{Z}^{h}_{u} + \bar{Z}^{h}_{c}} . \bar{I}^{h}_{c} \tag{4}$$

and

$$\bar{I}^{h}_{pcc} = \bar{I}^{h}_{u-pcc} + \bar{I}^{h}_{c-pcc} \tag{5}$$

The values of harmonic current contributions given in Eq. 3 and 4 are in phasor form and therefore it is difficult to compare. Considering the scalar values of Eq. 3 and 4, we obtain the following equations:

$$I^{h}_{scalar-u} = \left|\bar{I}^{h}_{u-pcc}\right| . \cos(\phi^{h}_{u-pcc} - \phi^{h}_{pcc}) \tag{6}$$

$$I^{h}_{scalar-c} = \left|\bar{I}^{h}_{c-pcc}\right| . \cos(\phi^{h}_{c-pcc} - \phi^{h}_{pcc}) \tag{7}$$

Similarly, the scalar values for harmonic voltage contributions are determined as follows:

$$V^{h}_{scalar-u} = \left|\bar{V}^{h}_{u-pcc}\right| . \cos(\phi'^{h}_{u-pcc} - \phi'^{h}_{pcc}) \tag{8}$$

$$V^{h}_{scalar-u} = \left|\bar{V}^{h}_{u-pcc}\right| . \cos(\phi'^{h}_{u-pcc} - \phi'^{h}_{pcc}) \tag{9}$$

These scalar values may have either positive or negative signs which means that the values with the same sign add up each other and values with opposite signs cancel out each other as illustrated in Fig. 3.

Considering the effect of utility impedance variation, any deviation from the reference impedance ($Z_{u\text{-}old}$) can be represented by a new harmonic current source ($I_{u\text{-}new}$) at the utility side by using:

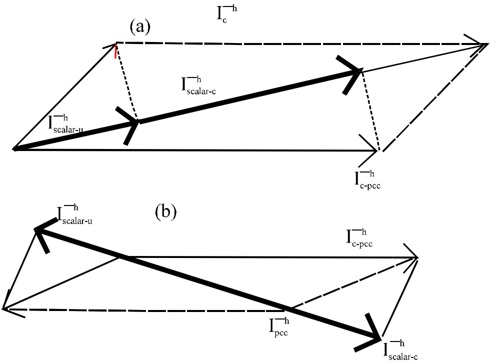

Fig. 3: Scalar contribution of harmonic vector, (a) add up condition and (b) cancel out condition

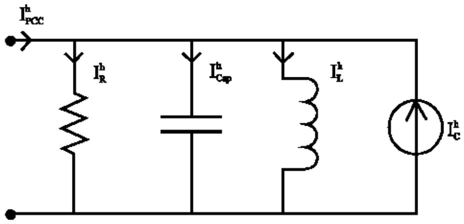

Fig. 4: Customer equivalent circuit

$$\bar{I}^{h}_{u-new} = \frac{\bar{V}^{h}_{pcc-new}}{\bar{Z}^{h}_{u-old}} + \bar{I}^{h}_{pcc-new} \tag{10}$$

In this method, the customer load is modeled in terms of a parallel combination of resistance (R), inductance (L) and capacitance (C) load model (Varadan and Makram, 1993; El-Arini, 1998). Figure 4 depicts the equivalent circuit of the customer side with the customer load represented by resistance, inductance and capacitance.

Using the measured voltage and current at the PCC, the RLC parameters of the customer load can be calculated using,

$$R_c = \frac{\sum_{h=1}^{H} \left(V^{h}_{PCC}\right)^2}{\sum_{h=1}^{H} V^{h}_{PCC} . I^{h}_{PCC} . \cos(\phi_h)} \qquad \text{For } R_c > 0 \tag{11}$$

$$C_c = \frac{\sum_{h=1}^{H} h . V^{h}_{PCC} . I^{h}_{CLI} . \sin(-\phi_h)}{\omega \sum_{h=1}^{H} \left(V^{h}_{PCC}\right)^2 h^2} \qquad \text{For } C_c > 0 \tag{12}$$

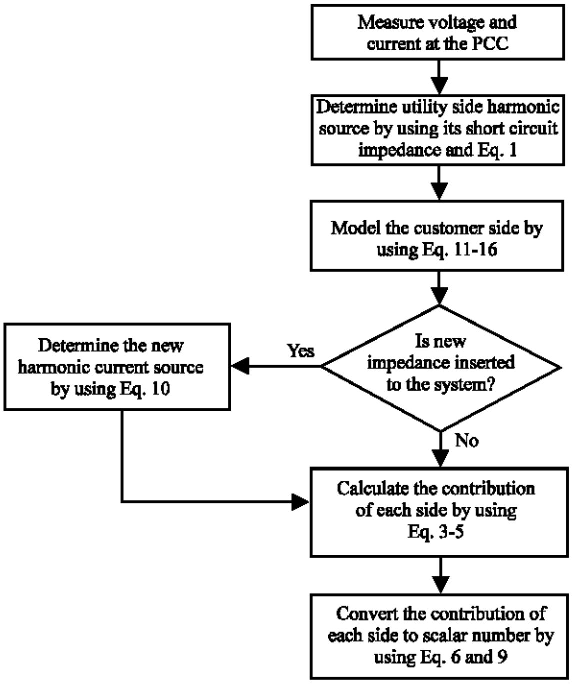

Fig. 5: Implementation procedure of the RLC method

$$L_c = \frac{\sum_{h=1}^{H} \left(V_{PCC}^h\right)^2 / h^2}{\omega . \sum_{h=1}^{H} V_{PCC}^h . I_{LI}^h . \sin(\phi_h) / h} \qquad \text{For } L_c > 0 \qquad (13)$$

where:

$$I_{CLI}^h = I_{PCC}^h - \frac{V_{PCC}^h}{R_c} \qquad (14)$$

$$I_{LI}^h = I_{CLI}^h - \frac{V_{PCC}^h}{Z_{cap}} \qquad (15)$$

$$I_{I}^h = I_{LI}^h - \frac{V_{PCC}^h}{Z_L} \qquad (16)$$

and φ_h is the phase angle difference between related voltage and current.

I_I in Eq. 16 represents the current source related to nonlinear components at the customer side and is considered as the customer harmonic current source, I_c in Fig. 1. It should be noted that Eq. 12 and 13 are derived from non-active current from time domain computation which satisfies the Fryze's power theory. The theory is based on Fryze's reactive power in non sinusoidal situations where the time domain supply current is decomposed into its active and reactive currents (Czarnecki, 1997).

The procedure in implementing the RLC method for estimating contributions of utility and customer harmonic distortions in a power distribution system is described in Fig. 5.

TEST SYSTEMS AND SIMULATION

To validate the performance and accuracy of the RLC method, a simple and a 10 bus test systems are considered. For all cases, the results of the RLC method are compared with the results obtained by using actual or known customer impedance value of the system to show the validity and accuracy of the method. In the RLC method, the customer impedance value in terms of the R, L and C parameters are estimated by using Eq. 11-13. The results of the RLC method is also compared with the results of the IEEE1459-2000 standard based method (Cataliotti and Cosentino, 2010). In the simulations, harmonic sources are placed at both utility and customer sides in terms of harmonic voltage and current sources, respectively, with harmonic spectrums of the 5th, 7th and 11th harmonic orders. Four scenarios are considered in the simulations as follows:

- Harmonic source at utility side
- Harmonic source at customer side
- Harmonic sources at both utility and customer sides
- Harmonic sources at both utility and customer sides with capacitor bank C_1 switched on at the customer side

Simulations were carried out using the Matlab program and calculations were computed for the utility and customer harmonic current and voltage contributions using Eq. 6-9.

A simple test system shown in Fig. 6 is considered for illustrating the RLC method at various operating conditions of the non linear loads and harmonic sources. In the figure, a supply voltage $V_1 = 230$V at a fundamental frequency of 50 Hz and phase angle $\alpha_1 = 0°$, utility impedance $Z_u = 0.15+j0.1319\Omega$, customer impedance $Z_c = 34.14+j30.25\Omega$ and a switchable capacitor bank $C_1 = 343$ Var is placed at the customer side for improving the load power factor from 0.75 to 0.9. Harmonic sources with harmonic spectrums of the 5th, 7th and 11th harmonic orders are assumed to exist at both the utility and customer sides.

A 10 bus test system shown in Fig. 7 is also considered to verify the proposed RLC method. The test system data is shown in Table 1. In the simulation,

Table 1: 10 Bus test system data

Components	Parameters	Value	Components	Parameters	Value
G_1	VN (Ph-Ph rms) $S1''_k$ X/R	33 kV 100 MVA 10	T_1	V_N (Ph-Ph rms) S_N Z%	33/11 kV 7.5 MVA 0.97+j4.69 p.u
T_2, T_4, T_5	VN (Ph-Ph rms) S_N Z%	11/0.415 kV 1 MVA 1+j5 p.u	T_3, T_6	V_N (Ph-Ph rms) S_N Z%	11/0.415 kV 2.5 MVA 1+j5 p.u
L_1	Active power (P) P.F	600 kW 0.8	L_2, L_3	Active power (P) P.F	1440 kW 0.8
L_4	Active power (P) P.F	398.4 kW 0.8	L_5	Active power (P) P.F	1284 kW 0.8
C_1	Reactive power (Q_c)	0.24 MVAr			

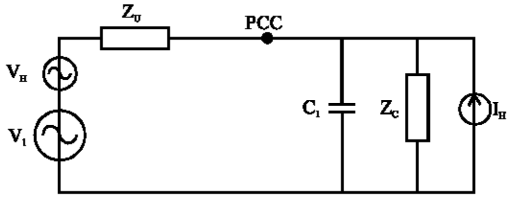

Fig. 6: Simple test system

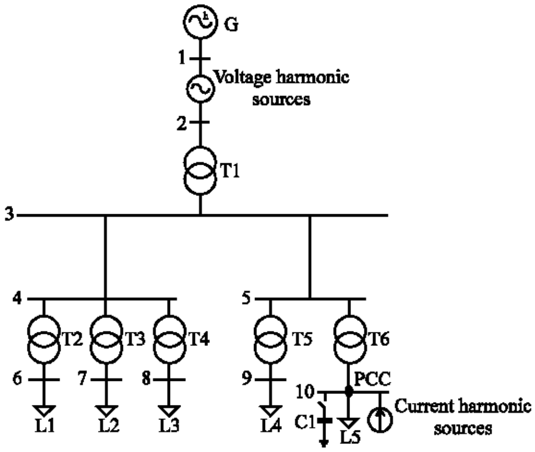

Fig. 7: One-line diagram of the 10 bus test system

harmonic sources are assumed to exist at both the utility side (bus 2) and customer side (bus 10). All the loads are assumed to operate at full load condition with a power factor of 0.80. The capacitor bank C_1 at bus 10 is used to improve the power factor of load 5 from 0.80 to 0.9.

TEST RESULTS

Results of a simple test system: Table 2 shows a comparison of the actual and estimated customer R, L and C components values. The estimated R, L and C values are calculated based on the measured harmonic voltages and currents at the PCC using Eq. 11-13. From the table, it is clear that the estimated R, L and C values are close to the actual values and therefore the proposed RLC method can be considered accurate.

Table 3 to 6 show the results of simulation of the simple system for each of the above mentioned scenarios in terms of the utility and customer harmonic current contributions calculated by using Eq. 6-7 and the utility and customer harmonic voltage contributions calculated using Eq. 8-9. The results are compared with the harmonic contributions calculated from using the actual R, L and C values. From the results shown in Table 3, the utility voltage and current harmonic distortions at all harmonic frequencies are 100% and this proves that the harmonic source is from the utility side. As for the results shown in Table 4, the customer voltage and current harmonic distortions at all harmonic frequencies are 100% and therefore the harmonic source is from the customer side. For the case with harmonic sources placed at utility and customer sides, the results in Table 5 show that the utility gives greater voltage and current distortions compared to the customer harmonic contributions. The negative harmonic voltage distortions at the customer side implies that the harmonic source at the customer side acts like a harmonic filter which then mitigates the effect of voltage harmonics caused by utility. Table 6 shows the results for the case of harmonic sources at both utility and customer sides and with a capacitor bank switched on at the customer side. The results show that the share of customer voltage and current harmonic distortions are increased due to the parallel resonance phenomenon occurring in the vicinity of the 5th, 7th and 11th harmonic frequencies as shown in impedance-frequency curve of Fig. 8.

Table 2: Actual and estimated values of RLC components

Comparison	R_c Ω	L_c (H)	C_c (F)
Actual value	60.90	0.219	0
Estimated value	58.91	0.217	0

Comparing the results of the proposed RLC method with that of using the actual R, L and C parameters, the harmonic distortion values are very close to the actual values and this proves the accuracy of the RLC method. Table 7 shows the results of the IEEE1459-2000 standard based method Cataliotti and Cosentino 2010 and the results are compared to the results of the proposed RLC method in terms of harmonic localization. In Table 7, Q_1, Q_x and N indicate the fundamental reactive power, fictitious reactive power and non active power, respectively. The results show that the IEEE1459-2000 standard based method is not able to fully determine correct location of the harmonic source. The reason for incorrect harmonic source location is that the harmonic source at the customer side produces current harmonics with low magnitudes while the harmonic source at the

Table 3: Utility and customer harmonic contributions with harmonic source at utility side

Harmonic order	5th		7th		11th	
PCC voltage (V)	41.45<-81.36		27.97<-7.05		14.35<-35.48	
PCC current (A)	0.69<-91.40		0.45<-14.85		0.24<-40.18	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	0	0	0	0	0	0
Customer harmonic current contribution (%)	0	0	0	0	0	0
Utility harmonic voltage contribution (%)	100	100	100	100	100	100
Utility harmonic current contribution (%)	100	100	100	100	100	100

Table 4: Utility and customer harmonic contributions with harmonic source at customer side

Harmonic order	5th		7th		11th	
PCC voltage (V)	5.13<131.25		2.49<-139.26		1.98<-142.42	
PCC current (A)	0.33<-138.20		0.11<-48.86		0.06<-52.17	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	100	100	100	100	100	100
Customer harmonic current contribution (%)	100	100	100	100	100	100
Utility harmonic voltage contribution (%)	0	0	0	0	0	0
Utility harmonic current contribution (%)	0	0	0	0	0	0

Table 5: Utility and customer harmonic contributions with harmonic source at both utility and customer sides

Harmonic order	5th		7th		11th	
PCC voltage (V)	37.16<-85.86		25.56<-11.24		14.18<-43.23	
PCC current (A)	0.94<-106.16		0.55<-21.05		0.30<-42.45	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	-10.70	-10.81	-5.79	-5.94	-1.88	-2.16
Customer harmonic current contribution (%)	26.72	27.83	16.40	17.43	17.63	18.39
Utility harmonic voltage contribution (%)	110.7	110.81	105.79	105.94	101.88	102.16
Utility harmonic current contribution (%)	73.28	72.16	83.59	82.56	82.37	81.60

Table 6: Utility and customer harmonic contributions with harmonic source at both utility and customer sides and capacitor bank C_1 switched on

Harmonic order	5th		7th		11th	
PCC voltage (V)	66.91<-98		76.36<-74.50		11.05<-172.6	
PCC current (A)	2.30<-45.90		3.65<-6.08		0.82<-91.26	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	38.7	40.72	86.31	86.34	194.5	197.35
Customer harmonic current contribution (%)	79.90	79.31	87.97	87.92	81.85	80.99
Utility harmonic voltage contribution (%)	59.60	59.29	14.04	13.66	-95.15	-96.90
Utility harmonic current contribution (%)	22.05	20.95	12.45	12.20	19.12	18.77

Table 7: Results using the IEEE1459–2000 standard based method

Condition	Q_1	Q_x	N	Decision (location of the dominate harmonic source)	Accuracy of decision
Harmonic source at utility side	698.54	717.69	740.80	Utility	True
Harmonic source at customer side	698.54	699.09	702.86	Utility	Wrong
Harmonic source at both utility and customer side	698.54	720.94	757.09	Utility	True
Harmonic source at both utility and customer side with capacitor bank C_1	403.14	413.96	449.47	Utility	Wrong

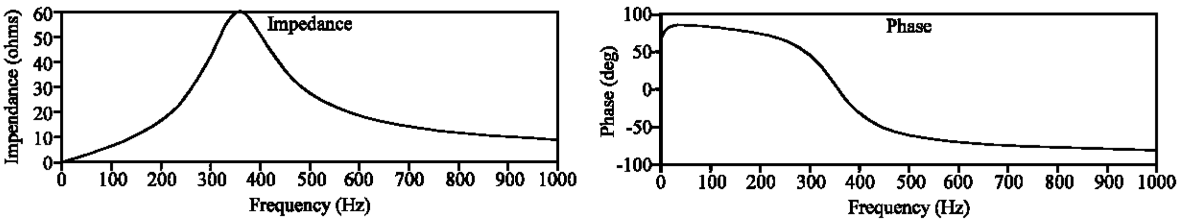

Fig. 8: Impedance vs. frequency characteristic of the system in presence of capacitor bank C_1 at customer side

utility side produces voltage harmonics with high magnitudes. Therefore, the calculated harmonic powers at the customer side are negligible compared to the utility side and this is the main reason for the incorrect customer harmonic source location by the IEEE1459-2000 standard based method. In comparison, the results of the RLC method give correct harmonic source location based on the dominant harmonic contributions of the utility and customer sides.

Results of the 10 bus test system: Table 8 shows the calculated R, L and C parameters for the customer side calculated by using the RLC method and the parameters are compared with the known actual impedance values. The comparing of results prove that the RLC method is able to accurately model the customer load in terms of its parallel R, L and C components.

Table 9 shows the harmonic contribution results for the case where the harmonic source is placed at the utility side which at bus 2 of the 10 bus system. The results show that with the 100% voltage and current harmonic distortions at the utility side and 0% voltage and current harmonic distortions at the customer side, the source of harmonic is from the utility side. In the case for the harmonic source placed at the customer side, the results of Table 10 show that the voltage and current harmonic distortions at the customer side are 100%. Table 11 shows the results for the case where harmonic sources are placed at both utility and customer sides. The results show that the utility has greater voltage and current harmonic distortions compared to that at the customer side and therefore this means that the utility is responsible for generating harmonic distortions. By inserting the capacitor bank C_1 at bus 10, parallel resonance phenomenon is said to occur as shown in Fig. 9. From the figure, it is shown that parallel resonance is visible in the vicinity of the 5th, 7th and 11th harmonic orders. The results for the case with a capacitor bank inserted in the system are shown in Table 12. From the table, it is shown that the voltage and current harmonic distortions of the 7th and 11th harmonic orders at the customer side are much greater than that at the utility side and therefore the customer is responsible for harmonic distortions.

Table 8: Load parameters

Comparison	R_c (Ω)	L_c (H)	C_c (F)
Actual value	0.1322	58.52e-5	0
Estimated value	0.1320	58.49e-5	0

Table 9: Utility and customer harmonic contributions with harmonic source at utility side

Harmonic order	5th		7th		11th	
PCC voltage (V)	60.49<-98.05		36.47<-26.90		16.91<-58.19	
PCC current (A)	455.72<-106.34		273.39<-32.85		126.36<-61.98	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	0	0	0	0	0	0
Customer harmonic current contribution (%)	0	0	0	0	0	0
Utility harmonic voltage contribution (%)	100	100	100	100	100	100
Utility harmonic current contribution (%)	100	100	100	100	100	100

Table 10: Utility and customer harmonic contributions with harmonic source at customer side

Harmonic order	5th		7th		11th	
PCC voltage (V)	12.25<119.62		5.67<-152.74		4.10<-157.82	
PCC current (A)	199.85<-146.87		66.50<-59.71		30.95<-65.38	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	100	100	100	100	100	100
Customer harmonic current contribution (%)	100	100	100	100	100	100
Utility harmonic voltage contribution (%)	0	0	0	0	0	0
Utility harmonic current contribution (%)	0	0	0	0	0	0

Table 11: Utility and customer harmonic contributions with harmonic source at both utility and customer sides

Harmonic order	5th		7th		11th	
PCC voltage (V)	51.34<-106.43		33.47<-34.79		16.72<-72.19	
PCC current (A)	621.41<-118.40		334.06<-38.01		157.27<-62.65	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	-15.78	-15.82	-6.60	-7.27	2.94	2.71
Customer harmonic current contribution (%)	27.68	27.73	17.61	17.84	19.27	19.29
Utility harmonic voltage contribution (%)	115.78	115.83	106.6	107.27	97.05	97.28
Utility harmonic current contribution (%)	72.31	72.26	82.38	82.15	80.72	80.70

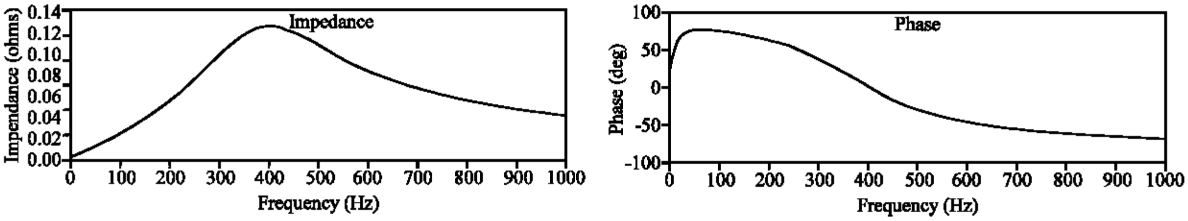

Fig. 9: Impedance vs. frequency characteristic of the system in presence of capacitor bank C_1 at customer side

Table 12: Utility and customer harmonic contributions with harmonic source at both utility and customer sides and switched on capacitor bank C_1

Harmonic order	5th		7th		11th	
PCC voltage (V)	74.16<-119.30		58.64<-72.81		17.66<-160.90	
PCC current (A)	885.86<-91.45		764.42<-23.26		307.33<-89.48	
Localization method	RLC method	Actual value	RLC method	Actual value	RLC method	Actual value
Customer harmonic voltage contribution (%)	23.39	23.71	54.92	56.30	121.48	120.37
Customer harmonic current contribution (%)	46.86	47.75	64.58	64.83	63.74	63.35
Utility harmonic voltage contribution (%)	76.64	76.02	45.11	43.27	-21.35	-21.86
Utility harmonic current contribution (%)	53.19	52.71	34.45	35.26	36.19	36.46

Table 13: Obtained results using IEEE1459–2000 standard based method

Scenario	Q_1 (MVAr)	Q_x (MVAr)	N (MVAr)	Decision (location of the dominate harmonic source)	Accuracy of decision
harmonic source at utility side	0.7262	0.7405	0.7408	Utility	True
harmonic source at customer side	0.7262	0.7308	0.7321	Utility	Wrong
harmonic source at both utility and customer side	0.7262	0. 7481	0.7550	Utility	True
harmonic source at both utility and customer side with capacitor bank C_1	0.5572	0.6374	0.6473	Customer	True

From the results shown in Table 9-12, it is clear that the estimated harmonic contributions values are very close to that calculated from using the actual impedance values and this proves the accuracy of the RLC method. To further validate the accuracy of the RLC method, it is compared with the IEEE1459-2000 standard based method. Table 13 shows the results of the IEEE1459-2000 standard based method for the four scenarios in the placement of utility and customer harmonic sources. The results show that the IEEE1459-2000 standard based method cannot accurately determine the location of harmonic sources for all the scenarios. In addition, it is also unable to determine the share of harmonic distortions of individual harmonic orders at the customer and utility sides.

CONCLUSION

A new method for determining the contribution of harmonic distortions at the PCC has been presented. In the method, the utility harmonic source is represented by its short circuit impedance and a current source whereas the customer impedance is modeled in terms of its parallel R, L and C components. The proposed method which is known as the RLC method has been validated on a simple 2 bus and a 10 bus test systems. Four simulation cases were reported showing the application of the RLC method in determining the contribution of harmonic distortions at the PCC and at the same time determining the harmonic source location. Comparing the results of the RLC method with the results obtained from using the actual impedance values and the IEEE1459-2000 standard based method, it is proven that the RLC method can accurately determine the voltage and current harmonic distortions at the utility and customer sides and locate the harmonic sources even at resonance situations.

ACKNOWLEDGMENTS

This research has been done at University Kebangsaan Malaysia under grant number UKM-OUP-TK-15-68/2010 during 2009-2010.

REFERENCES

Cataliotti, A. and V. Cosentino, 2010. A new measurement method for the detection of harmonic sources in power systems based on the approach of the IEEE Std. 1459-2000. IEEE Trans. Power Delivery, 25: 332-340.

Chaoying, C., X. Liu, D. Koval, W. Xu and T. Tayjasanant, 2004. Critical impedance method: A new detecting harmonic sources method in distribution systems. IEEE Trans. Power Delivery, 19: 288-297.

Costa, F.H., I.N. Santos, S.F.P. Silva and J.C. de Oliveira, 2009. A case study of sharing the harmonic voltage distortion responsibility between the utility and the consumer. Proceedings of the International Conference on Renewable Energies and Power Quality, April 15-17, Spain, pp: 1-6.

Czarnecki, L., 1997. Budeanu and fryze: Two frameworks for interpreting power properties of circuits with nonsinusoidal voltages and currents. Electrical Eng., 80: 359-367.

D'Antona, G., C. Muscas and S. Sulis, 2009. State estimation for the localization of harmonic sources in electric distribution systems. IEEE Trans. Instr. Measur., 58: 1462-1470.

Du, Z.P., J. Arrillaga, N.R. Watson and S. Chen, 1999. Identification of harmonic sources of power systems using state estimation. IEE Proc. Generation Transmission Distrib., 146: 7-12.

El-Arini, M.M.M., 1998. A time domain load modelling technique and harmonics analysis. Proceedings of the 8th International Conference on Harmonics and Quality of Power, Oct. 14-18, Greece, pp: 930-938.

Gursoy, E., 2007. Independent component analysis for harmonic source identification in electric power systems. http://idea.library.drexel.edu/bitstream/1860/1781/1/Gursoy_Ekrem.pdf.

Hamzah, N., A. Mohamed and A. Hussain, 2004. Harmonic source location at the point of common coupling based on voltage magnitude. Proc. IEEE Region Conf. TENCON, 3: 220-223.

Islam, K.M.S. and A.H. Samra, 1997. Identification of harmonic sources in power distribution systems. Proceedings of the IEEE Southeastcon'97 Engineering new New Century, April 12-14, Blacksburg, VA , USA., pp: 301-303.

Pfajfar, T., B. Blazic and I. Papic, 2008. Harmonic contributions evaluation with the harmonic current vector method. IEEE Trans. Power Delivery, 23: 425-433.

Ranade, S. and W. Xu, 1998. An overview of harmonics modeling and simulation. Proceedings of Tutorial Harmonics Model Simulation, (THMS'98), IEEE Power Engineering Society, pp: 1-5.

Varadan, S. and E.B. Makram, 1993. Generalized load modeling in the presence of harmonics and distortion. Proceedings of the 25th Southeastern Symposium on System Theory, Mar. 7-9, USA., pp: 124-128.

Xiaodong, L. and W. Jackson, 2008. Investigation of non-linear devices modeled as a harmonic current source. Proceedings of Industrial and Commercial Power Systems Technical Conference, May 4-8, Clearwater Beachm pp: 1-7.

Xu, W. and Y. Liu, 1999. A method to determine customer harmonic contributions for incentive-based harmonic control applications. Proceedings of the IEEE Power Engineering Society Summer Meeting, Jul. 18-22, Canada, pp: 361-366.

Xu, W. and Y. Liu, 2000. A method for determining customer and utility harmonic contributions at the point of common coupling. IEEE Trans. Power Delivery, 15: 804-811.

Xu, W., X. Liu and Y. Liu, 2002. An investigation on the validity of power direction method for harmonic source determination. IEEE Power Eng. Rev., 22: 62-62.