On the Validity of Harmonic Source Detection Methods and Indices

M. Erhan Balci and M. Hakan Hocaoglu

***Abstract*-- In this paper, the validity of the single-point measurements methods and indices, which were proposed for harmonic source detection and sharing harmonic responsibility between utility and consumer, are investigated in a typical distribution system which consists of several critical load cases. A parametrical analysis by means of the variation of the utility side impedance's X/R ratio is also undertaken. The results provide that the conventional methods and indices based on the flow direction of the harmonic active power are still the most effective tools for the harmonic source detection in the typical distribution systems.**

***Index Terms*-- harmonic source detection; sharing harmonic responsibility; harmonic source quantification.**

I. Introduction and Background

PRESENT day power systems invariably have nonlinear loads, which inject harmonics into the system and give rise to non sinusoidal voltages and currents. The most important effect of the harmonic distortion can be underlined as the increased losses and decreased life expectancy of the power system equipment [1]. Thus, the costs associated with harmonic disturbances and any necessary mitigation equipment should be recovered from the consumers that produce harmonic pollution [2]. However, the guidelines and standards on the limitation of harmonic pollution do not provide any tool to detect those consumers [3]-[9]. Therefore, to fulfil this gap, several methods and indices are proposed in the literature.

Active Power Direction (*APD*) method is one of the oldest [10] and probably the most commonly used [11] method today, and based on the sign of the harmonic active power. It defines consumer side as the dominant harmonic source if the respective harmonic active power has a negative sign; otherwise, source side is the dominant for the considered harmonic orders.

In addition to these, two indices were proposed by means of the same way [12], [13]: one is that Supply Load Quality (*SLQ*) index express the harmonic producing quantity of the load as;

$$SLQ = P / P_1 \tag{1}$$

where P and P_1 are the active and fundamental harmonic active powers, respectively [12]. Thus, the load is detected as the dominant source for the harmonic distortion when the value for *SLQ* is smaller than unity; otherwise, supply side is the dominant source for the harmonic distortion.

Second index, Harmonic Global Index, is defined as;

$$HG = \sqrt{\sum_{h \in \ell} I_h^2} \Big/ \sqrt{\sum_{h \in s} I_h^2} \tag{2}$$

where ℓ is the harmonic orders related to the harmonic active powers, which have the negative sign, and s is vice versa [13]. A non-zero value of *HG* index shows that the load causes harmonic distortion.

Linearity Current method [14] defines the harmonic contributions of utility and consumer sides by separating the load current into two components; namely, linear current, which is drawn by the R-L equivalent impedance part of the load, the remaining current when the linear current is subtracted from total current in time domain. The two current components can be expressed as: the linear current;

$$i_\ell(t) = \sum_{h=1} \sqrt{2} \frac{V_h}{Z_h} sin(h\omega_1 t + \theta_h - \phi_h) \tag{3}$$

and the nonlinear current;

$$i_{n\ell}(t) = i(t) - i_\ell(t) \tag{4}$$

Where $\bar{Z}_h = |Z_h| \angle \phi_h$ is the h^{th} harmonic linear load impedance, which is equivalent with the serial connection of the resistance, $R = \mathrm{Re}(V_1\angle\theta_1 / I_1\angle\delta_1)$ and the h^{th} harmonic inductance, $X_h = h \cdot \mathrm{Im}(V_1\angle\theta_1 / I_1\angle\delta_1)$. Therefore, the index that gives the harmonic responsibility of the consumer is expressed as;

$$NLC(\%) = \frac{I_{n\ell}}{I} \cdot 100 \tag{5}$$

Superposition and Projection (*SP*) method, presented in [15], separates harmonic currents into the utility and the customer portions using Norton equivalents of the utility and the consumer sides as illustrated in Fig. 1.

This work was supported in part by Turkish Scientific Council under the project number of 110E113.

M. Erhan Balci is with Balikesir University, Electrical and Electronics Engineering department, Balikesir, Turkey (e-mail: mbalci@balikesir.edu.tr).

M. Hakan Hocaoglu is with Gebze Institute of Technology, Electronics Engineering department, Kocaeli, Turkey (e-mail: hocaoglu@gyte.edu.tr).

978-1-4244-7245-1/10/$26.00 ©2010 IEEE

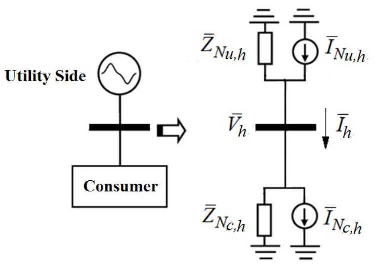

Fig. 1: The system used for the illustration of SP method.

In *SP* method, with respect to Superposition theorem, firstly, h^{th} harmonic current is separated into two parts: the first part is the PCC current drawn by the consumer,

$$\bar{I}_{c,h} = \bar{Z}_{Nc,h}\bar{I}_{Nc,h} \big/ \left(\bar{Z}_{Nc,h} + \bar{Z}_{Nu,h}\right) \tag{6}$$

and the rest is the current injected from utility side,

$$\bar{I}_{u,h} = \bar{I}_h - \bar{I}_{c,h} \tag{7}$$

Secondly, the projections of both current portions on the PCC current provide;

$$I_{Pu,h} = \frac{\mathrm{Re}\left(\bar{I}_{u,h}\bar{I}_h^{*}\right)}{I_h} \quad \textit{for utility's harmonic contribution} \tag{8}$$

$$I_{Pc,h} = \frac{\mathrm{Re}\left(\bar{I}_{c,h}\bar{I}_h^{*}\right)}{I_h} \quad \textit{for consumer's harmonic contribution} \tag{9}$$

Note that $I_h = I_{Pu,h} + I_{Pc,h}$. Finally, according to the method, the calculated $I_{Pu,h}$ and $I_{Pc,h}$ values show the harmonic contribution of the utility and consumer sides. In addition, the quantity with negative sign means that the respective side compensates particular harmonic current on the PCC. It is apparent that certain system data is required for the implementation of SP method. These are; the harmonic equivalent impedances of consumer and utility sides and may not be readily available in most cases. The utility side impedance can be assumed as the short circuit impedance of the system. However, it is not easy to estimate the equivalent harmonic impedances for the consumer side. Therefore, different estimation approaches were proposed to overcome this difficulty [16], [17].

In one of the most recent studies [18], a method which is called as Nonactive Power (*NP*) method, is proposed. The method uses various reactive power definitions to detect the dominant harmonic source. These reactive powers are:
Fundamental harmonic reactive power (Q_1);

$$Q_1 = V_1 I_1 sin(\theta_1 - \delta_1) \tag{10}$$

Sharon's reactive power (Q_S) [19];

$$Q_S = \sqrt{\sum_h V_h^2}\sqrt{\sum_h I_h^2 sin^2(\theta_h - \delta_h)} \tag{11}$$

and Fryze's reactive power (Q_F) [19];

$$Q_F = \sqrt{S^2 - P^2} \tag{12}$$

The main idea behind the method is:

- In the case of a non sinusoidal supply voltage and a linear load, Sharon's reactive power should be considerably closer to the fundamental harmonic reactive power than to Fryze's reactive power, which means that $NPM_1(=Q_S-Q_1) << NPM_2(=Q_F-Q_S)$.
- On the contrary, in the case of a sinusoidal supply voltage and a nonlinear load, Sharon's reactive power should be considerably closer to Fryze's reactive power than to the fundamental harmonic reactive power, which means that $NPM_1 >> NPM_2$.
- For the case consists of a non sinusoidal supply voltage and a nonlinear load, Sharon's reactive power can be assumed in the middle of fundamental harmonic reactive power and Fryze's reactive power, which means that $NPM_1 \approx NPM_2 >> 0$.
- When supply voltage is sinusoidal and load is linear, all three reactive powers give the same numerical values, which means that $NPM_1 = NPM_2 = 0$.

In addition to these methods and indices, Conformity Current (*CC*) [20] and Critical Impedance (*CI*) [21] methods are also available in the literature. *CC* method is based on the current decomposition consisting of the part with the same THD level of the supply voltage, conformity current, and the rest, nonconformity current. However, it is well known that the THD levels of the voltage and current are not the same for linear R-L impedances. As a result, *CC* method figures out those loads as the harmonic producer under distorted voltage conditions. Thus; its usage for the detection and quantification of the harmonic producing loads will be problematic. The principle of *CI* method is to compare two magnitudes of harmonic voltage sources in the Thevenin equivalent circuit and choose the larger one as the main harmonic source. This approach gives the same results as SP method for the analysis obtained with the proper modelling of the utility side. However, SP method is much more favourable than CI method in terms of complexity.

On the other hand, in the literature, there are several papers investigating the validity of the harmonic source detection and harmonic responsibility sharing methods. The most important conclusions of these studies can be listed below;

- In [22], it is concluded that the performance of *APD* method depends on the utility side's X/R ratio and the metering point or the relative size of the impedances of the utility and consumer sides
- In [23], it is found that the linear loads with compensation capacitor may be penalized where the capacitors dramatically amplify the already existing distortion produced by neighbouring nonlinear loads.

Therefore, it can be concluded that the accuracy of the methods implemented with the single-point measurements strategy depends on the topologies of the load and utility sides.

In this paper, the validity of the harmonic source detection and harmonic responsibility sharing methods and indices based on single-point measurements are investigated in a typical distribution system, which consists of some critical load cases, by taking into account the effect of the utility side impedance's X/R ratio.

II. ANALYSIS

In this section, the validity of the summarized methods and indices are parametrically analyzed in a test system given in Fig. 2. The main characteristics of the system loads are given below:

- An impedance compensated with a capacitor (Load 1),
- Different impedances in parallel (Load 2),
- A load with an active compensator that filters all current components except the active portion of the fundamental harmonic (Load 3),
- An impedance with a phase control circuit (Harmonic Producing Load, Load 4),
- And an R-L impedance (Load 5).

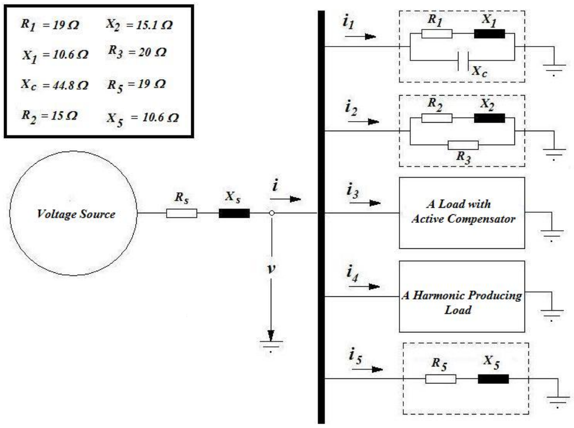

Fig. 2: A typical distribution system.

In the analysis, the harmonic producing load is simulated using Norton Model, which is obtained from the results of an experimental analysis given in [24]. The h^{th} harmonic impedances and current sources of the model and the h^{th} harmonic currents of the load measured for sinusoidal voltage source and X/R=0.1 are plotted as the percentage of fundamental harmonic in Fig. 3.

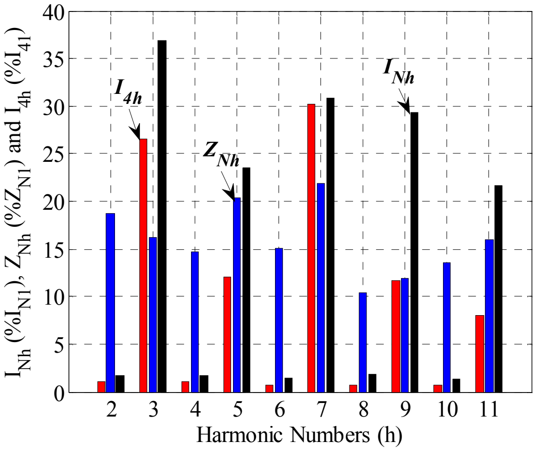

Fig. 3: The h^{th} harmonic impedances and current sources of the model and the h^{th} harmonic currents of the load measured for sinusoidal voltage source and X/R=0.1.

It is seen from Fig. 3 that the harmonic producing load (Load 4) draws a highly distorted current, which has THD_I measured as 47 %. In the system, when X/R ratio of the utility impedance is changed from 0.1 to 100, the measured THD values for the pcc voltage and the currents of the loads apart from Load 3 are plotted in Fig. 4.

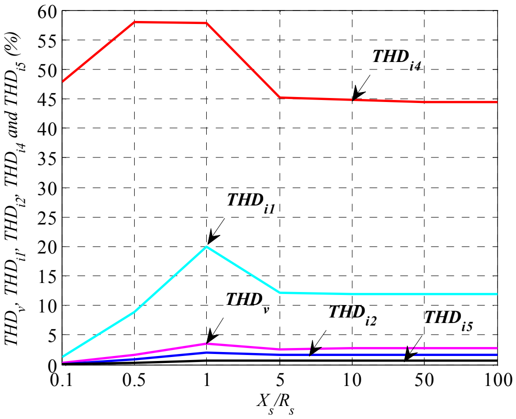

Fig. 4: THD values for the pcc voltage and the currents of the loads a part from Load 3 in the interval of Xs/Rs between 0.1 and 100.

In the interval of the X/R between 0.1 and 100, the 3rd harmonic active powers, calculated as the percentage of fundamental harmonic active power, are given for each load in Table I.

TABLE I: P3 (% P1) OF THE LOADS CALCULATED FOR THE INTERVAL OF THE X/R BETWEEN 0.1 AND 100.

X_s/R_s / Load Number	1	2	3	4	5
0.1	0.00	0.00	0.00	-0.04	0.00
0.5	0.00	0.00	0.00	-0.05	0.00
1	0.00	0.00	0.00	-0.05	0.00
5	0.00	0.00	0.00	-0.03	0.00
10	0.00	0.00	0.00	-0.03	0.00
50	0.00	0.00	0.00	-0.02	0.00
100	0.00	0.00	0.00	-0.02	0.00

Table I shows that only Load 4 has negative P_3 values. Thus, it can be concluded using APD method successfully indicates that Load 4 is the dominant harmonic source for the 3rd harmonic current.

For the same interval of the X/R, SLQ indices of the loads are given in Table II.

TABLE II: SLQ INDICES OF THE LOADS CALCULATED FOR THE INTERVAL OF THE X/R BETWEEN 0.1 AND 100.

Xs/Rs / Load Number	1	2	3	4	5
0.1	1.00	1.00	1.00	0.99	1.00
0.5	1.00	1.00	1.00	0.99	1.00
1	1.00	1.00	1.00	0.98	1.00
5	1.00	1.00	1.00	0.99	1.00
10	1.00	1.00	1.00	0.99	1.00
50	1.00	1.00	1.00	0.99	1.00
100	1.00	1.00	1.00	0.99	1.00

Table II shows that SLQ values are smaller than unity for Load 4. And accordingly, it can be concluded that using SLQ indices Load 4 is again successfully found as a harmonic producing load.

For the same interval of the X/R ratios, *HG* indices of the loads are given in Table III.

TABLE III: HG INDICES OF THE LOADS CALCULATED FOR THE INTERVAL OF THE X/R BETWEEN 0.1 AND 100.

X_s/R_s / Load Number	1	2	3	4	5
0.1	0.00	0.00	0.00	0.48	0.00
0.5	0.00	0.00	0.00	0.58	0.00
1	0.00	0.00	0.00	0.58	0.00
5	0.00	0.00	0.00	0.45	0.00
10	0.00	0.00	0.00	0.45	0.00
50	0.00	0.00	0.00	0.44	0.00
100	0.00	0.00	0.00	0.44	0.00

It is seen from Table III that Load 4 has non zero HG values. Thus, it can be also successfully pointed out that Load 4 is a harmonic producing load.

For all X/R ratios, NLC (%) indices of the loads are given in Table IV. Table IV shows that loads apart from Load 5 are wrongly detected as the harmonic producing loads.

TABLE IV: NLC(%) INDICES OF THE LOADS CALCULATED FOR THE INTERVAL OF THE X/R BETWEEN 0.1 AND 100.

Xs/Rs / Load Number	1	2	3	4	5
0.1	1.18	0.14	0.28	43.23	0.00
0.5	9.04	0.88	1.65	50.41	0.00
1	19.83	1.93	3.63	50.32	0.00
5	12.26	1.39	2.67	41.55	0.00
10	12.18	1.39	2.68	41.20	0.00
50	12.17	1.40	2.69	40.93	0.00
100	12.17	1.40	2.70	40.89	0.00

For the X/R ratios, $I_{Pc,3}$ and $I_{Pu,3}$ values, which are calculated using the determination of load side's Norton Impedance presented in [17], of the loads are given in Table V. From Table V, $I_{Pc,3} > I_{Pu,3}$ relation is observed for only Load 1 and Load 4. Thus, it can be concluded using *SP* method that Load 1 and Load 4 are the dominant harmonic sources for 3rd harmonic current. However, Load 1 is mislabelled as a harmonic source.

For all of the X/R ratios, NPM_1 and NPM_2 values, which are calculated using normalized values of the Q_1, Q_S and Q_F powers as described in NP method are given in Table VI.

From Table VI, $NPM_1 >> NPM_2$ and $NPM_1 \approx NPM_2 >> 0$ relations are observed for only Load 1 and Load 4. According to this result, it can be concluded using NP method Load 1 and Load 4 are labelled as the harmonic producing loads. Once again Load 1 is mislabelled as a harmonic source.

III. CONCLUSIONS

In this study, the validities of the APD, SLQ, HG, LC, SP and NP methods & indices are investigated for three critical load cases;

- A R-L impedance load compensated with passive capacitor (Load 1),
- A group of the impedances, which do not have identical power factors (Load 2),
- And a load with an active compensator that works based on the compensation strategy with respect to IEEE std. 1459-2000 power resolution [25], which filters the current apart from active portion of the fundamental component (Load 3).

Main findings of the investigation are summarized as follows:

- Using NLC indices all critical load cases namely Load 1, 2 and 3 are wrongly detected as harmonic producing load,
- Using SP and NP methods the first critical case (Load 1) is detected as harmonic producing load,
- However, using APD method, SLQ and HG indices all critical load cases are, correctly, identified as non harmonic producer or linear load.

One can understand that NLC provides erroneous detection for third case (Load 3) due to the fact that the load draws sinusoidal current. On the other hand, for the first and second cases, it should be reminded that these load cases draws the sinusoidal current under sinusoidal excitation. Therefore, they should be labeled as linear loads. Thus, the APD method, SLQ and HG indices give much accurate results than SP and NP methods.

Consequently, this paper reports that the conventional methods & indices, APD, SLQ and HG, are still the most effective harmonic source detection tools for the typical distribution systems.

TABLE V: $I_{Pc,3}$ AND $I_{Pu,3}$ VALUES, WHICH ARE DEFINED IN SP METHOD, OF THE LOADS FOR THE INTERVAL OF THE X/R BETWEEN 0.1 AND 100.

X_S/R_S \Load Number	1		2		3		4		5	
	$I_{Pc,3}$	$I_{Pu,3}$	$I_{Pc,3}$	$I_{Pu,3}$	$I_{Pc,3}$	$I_{Pu,3}$	$I_{Pc,3}$	$I_{Pu,3}$	$I_{Pc,3}$	$I_{Pu,3}$
0.1	0.01	0.00	0.00	0.02	-0.01	0.01	0.48	0.00	0.00	0.01
0.5	0.01	0.00	-0.01	0.03	-0.01	0.01	0.50	0.00	0.00	0.01
1	0.02	0.01	-0.01	0.05	-0.01	0.01	0.52	0.00	0.00	0.01
5	0.03	0.01	-0.02	0.07	-0.01	0.01	0.55	0.00	0.00	0.02
10	0.03	0.01	-0.02	0.07	-0.01	0.01	0.55	0.00	0.00	0.02
50	0.03	0.01	-0.02	0.07	-0.01	0.01	0.55	0.00	0.00	0.02
100	0.03	0.01	-0.02	0.07	-0.01	0.01	0.55	0.00	0.00	0.02

TABLE VI: NPM_1 AND NPM_2 VALUES, WHICH ARE CALCULATED FOR NP METHOD, OF THE LOADS FOR THE INTERVAL OF THE X/R BETWEEN 0.1 AND 100.

X_S/R_S \Load Number	1		2		3		4		5	
	NPM_1	NPM_2	NPM_1	NPM_2	NPM_1	NPM_2	NPM_1	NPM_2	NPM_1	NPM_2
0.1	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.10	0.00	0.00
0.5	0.09	0.00	0.00	0.00	0.00	0.02	0.13	0.05	0.00	0.00
1	0.20	0.00	0.00	0.00	0.00	0.04	0.12	0.06	0.00	0.00
5	0.12	0.00	0.00	0.00	0.00	0.03	0.10	0.02	0.00	0.00
10	0.12	0.00	0.00	0.00	0.00	0.03	0.10	0.02	0.00	0.00
50	0.12	0.00	0.00	0.00	0.00	0.03	0.10	0.02	0.00	0.00
100	0.12	0.00	0.00	0.00	0.00	0.03	0.10	0.02	0.00	0.00

IV. REFERENCES

[1] V. E. Wanger, “Effects of Harmonics on Equipment”, IEEE Trans. on Power Del., Vol. 8, No. 2, pp. 672– 680, 1993.

[2] E. J. Davis, A. E. Emanuel, D. J. Pileggi, “Evaluation of Single-point Measurement Method for Harmonic Pollution Cost Allocation”, IEEE Trans. Power Delivery, vol. 15, no. 1, pp. 14-18, 2000.

[3] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE 519, 1992.

[4] Limitation of Emission of Harmonic Currents in Low-Voltage Power Supply Systems for Equipment with Rated Current Less Than 16A, IEC 61000-3-2, 2000.

[5] Limitation of Emission of Harmonic Currents in Low-Voltage Power Supply Systems for Equipment with Rated Current Greater Than 16A, IEC 61000-3-4, 1998.

[6] Assessment of Emission Limits for Distorting Loads in MV and HV Power Systems, IEC 61000-3-6, 1996.

[7] Voltage characteristics of the electricity supplied by public distribution systems, EN 50160, 1994.

[8] General Guide on Harmonics and Inter harmonics Measurement and Instrumentation for Power Supply Systems and Equipment Connected Thereto, IEC 61000-4-7, 2002.

[9] Power Quality Measurement Methods, IEC 61000-4-30, 2003.

[10] L. Cristaldi, A. Ferrero, ‘‘Harmonic Power Flow Analysis for the Measurement of the Electric Power Quality’’, IEEE Trans. on Instrumentation and Measurement, vol. 44, no. 3, p.p. 683–685, 1995.

[11] M. Aiello, A. Cataliotti, V. Cosentino, S. Nuccio, ‘‘A Self-Synchronizing Instrument for Harmonic Source Detection in Power Systems’’, IEEE Trans. on Instrumentation and Measurement, vol. 54, no. 1, pp. 15–23, 2005.

[12] A. Ferrero, A. Menchetti, R. Sasdelli, ‘‘Measurement of the Electric Power Quality and Related Problems’’, ETEP, vol. 6, no. 6, pp. 401–406, 1996.

[13] C. Muscas, ‘‘Assessment of Electric Power Quality: Indices for Identifying Disturbing Loads’’, ETEP, vol. 8, no. 4, p.p. 287–292, 1998.

[14] A. Dellapos Aquila, M. Marinelli, V. G. Monopoli, P. Zanchetta, ‘‘New Power-Quality Assessment Criteria for Supply Systems under Unbalanced and Non sinusoidal Conditions’’, IEEE Trans. on Power Delivery, vol. 19, no.3, p.p. 1284-1290, 2004.

[15] W. Xu, Y. Liu, ‘‘A Method for Determining Customer and Utility Harmonic Contributions at the Point of Common Coupling’’, IEEE Trans. on Power Delivery, vol. 15, no. 2, p.p. 804–811, 2000.

[16] 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’’, EPSR, vol. 78, pp. 1959-1968, 2008.

[17] T. Pfajfar, B. Blaz□ic□, I. Papic□, ‘‘Harmonic Contributions Evaluation with the Harmonic Current Vector Method’’, IEEE Trans. on Power Del., vol. 23, no. 1, pp. 425-433, 2008.

[18] P. V. Barbaro, A. Cataliotti, V. Cosentino, S. Nucci, ‘‘A Novel Approach Based on Nonactive Power for the Identification of Disturbing Loads in Power Systems’’, IEEE Trans. on Power Delivery, vol. 22, no. 3, p.p. 1782-1789, 2007.

[19] M. E. Balci, M. H. Hocaoglu, “Quantitative Comparison of Power Decompositions”, EPSR, vol. 78, no. 3, pp. 318 – 329, 2008

[20] K. Srinivasan, R. Jutras, “Conforming and Nonconforming Current for Attributing Steady State Power Quality Problems”, IEEE Trans. On Power Delivery, vol. 13, no.1, pp. 212-217, 1998.

[21] C. Chaoying, L. Xiuling, D. Koval, W. Xu and T. Tayjasanant, ‘‘Critical Impedance Method - a New Detecting Harmonic Sources Method in Distribution Systems’’, IEEE Trans. on Power Delivery, vol. 19, no. 1, p.p. 288- 297, 2004.

[22] W. Xu, X. Liu, Y. Liu, ‘‘An Investigation on the Validity of Power-Direction Method for Harmonic Source Determination’’, IEEE Trans. on Power Del., vol. 18, no. 1, pp. 214-219, 2003.

[23] N. Locci, C. Muscas, S. Sulis, ‘‘On the Measurement of Power-Quality Indexes for Harmonic Distortion in the Presence of Capacitors’’, IEEE Trans. on Instrum. and Meas., vol. 56, no. 5, pp. 1871-1876, 2007.

[24] M. E. Balci, O. Karacasu, S. D. Ozturk, M. H. Hocaoglu, ‘‘A New Model for Harmonic Producing Loads’’, ELECO’08, Bursa, Turkey, 2008 (in Turkish).

[25] IEEE Standard Definitions for the Measurement of Electric Power Quantities under Sinusoidal Non-sinusoidal, Balanced or Unbalanced Conditions, IEEE Std. 1459-2000, 2002.