A Detection Method for Harmonic Producing Loads

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Abstract

In this paper, with the motivation of using a simple demand meter for the detection of the harmonic producing loads, a harmonic source detection method is proposed by means of the single-point measurements of Scattered Power defined in Czarnecki's power resolution. In addition, the employability of the method is rigorously investigated using the comparative statistical experimental analysis. The obtained results verified that it can effectively be used for the detection of harmonic producing loads in the systems with the reasonable total harmonic distortion (THD_V) values of the point of common coupling (pcc) voltage.

1. Introduction

Harmonic distortion on the voltage and current waveforms significantly concerns present day's power systems due to the large proliferation of the harmonic producing loads. The most important effect of the harmonic distortion can be underlined as the increased losses and decreased life time of the power system equipments. Therefore, the limitation of harmonic pollution has been an imperative issue to decrease the failures depending on harmonic distortion. Accordingly, guidelines, recommended practices and standards have been prepared by several organizations and institutes [1]-[7]. In IEEE std. 519 [1], the total harmonic distortion of voltage and current measured at pcc (point of common coupling) is taken under limitation. In addition, current harmonics are individually limited in IEC 61000-3-2 [2], 3-4 [3] and 3-6 [4] standards, and the restrictions for the wave shape and distortion of the pcc voltage is determined in EN 50160 [5]. On the other hand, in IEC Std. 61000-4-7 [6] and 61000-4-30 [7], the methods are defined to measure harmonic distortion. However, in these standards, there is no method and/or index defined for the detection of dominant harmonic sources. Therefore, in the literature, these standards are accompanied by the research leading to the methods and indices for the detection of the harmonic producing loads and the sharing harmonic contributions between utility and consumer [8]-[20]. The methods and indices for the sharing harmonic responsibility can be classified into two groups according to their measurement strategies, which are single-point and distributed (or multi-point) measurements methods and indices [8]. The multi-point measurements method or index is implemented by using synchronous measurements performed in different metering sections. As a result, the harmonic source detection works based on multi-point measurements strategy are more reliable than the works based on single-point measurements strategy; however, they have higher costs and also are hindered by its requirement for the precise time synchronization.

Following table summarizes the state of the art regarding these methods:

Table I: The state of art regarding the harmonic source detection and sharing harmonic responsibility methods.

Method/Indices	Required Data	Aims
Active Power Direction (APD) [9], [10]	Voltage and current obtained by single-point measurements	Harmonic Source Detection
Supply-Load Quality (SLQ) Index [11]		
Harmonic Global (HG) Index [12]		
Nonactive Powers (NP) Method [13]		
Conformity Current (CC) Method [14]	Voltage and current obtained by single-point measurements	Sharing harmonic responsibility between utility and consumer
Linearity Current (LC) Method [15]		
Superposition and Projection (SP) Method [16]	Norton equivalents of utility and consumer sides	
Critical Impedance (CI) Method [17]	Thevenin equivalents of utility and consumer sides	
Global Power Quality (GPQ) Index [18]	Voltages and currents obtained by multi-point synchronous measurements	Harmonic Source Detection

The works on the methods and indices, given in Table I, can generally be classified to three groups regarding their features;

- First group: APD method, HG and SLQ indices are based on direction of harmonic active power flow.
- Second group: SP and CI methods are based on the circuit analysis with the proper modeling of utility and consumer sides.
- Third group: CC and LC methods measure the harmonic distortion quantity of the consumer according to considered current decomposition.

Furthermore, NP method is based on the comparison of three different definitions of reactive power for harmonic source detection, and GPQ index is calculated by using the combination of HG, SLQ, Total Harmonic Distortions of voltage and current indices. On the other hand, [19] shows that ''toll road'' model, which is defined for the harmonic cost allocation [20], can successfully be used to detect the harmonic sources. The methods used for the detection of harmonic producing loads and sharing harmonic responsibility between utility and consumer are usually a compromise between accuracy required and the cost of the implementation. Therefore, NP method has an important advantage for the cost effective detection of harmonic producing loads due to the fact that the demand meters, which are employed to measure nonactive powers for the energy billing of the consumers, could also be implemented for the detection of the harmonic producing loads in this method. However, it is based on the nonactive powers defined in three different power resolutions. On the other hand, in general, a single power resolution is taken into account in the demand metering strategies due to optimizing computation complexity.

In this paper, with the motivation of using classical demand meters, which are employed for the energy billing of the consumers, for the detection of the harmonic producing loads, a harmonic source detection method is proposed by means of the single-point measurements of Scattered Power defined in Czarnecki's power resolution [21]. The usefulness of the proposed method is demonstrated using comparative statistical experimental analysis. The obtained results clearly show that it can effectively be used for the detection of harmonic producing loads in the systems with the reasonable THD_V values of the pcc voltage.

2. The Proposed Method

The proposed method is based on the single-point measurements of Scattered Power, which is defined in Czarnecki's power resolution, for each one of the consumers connected to a pcc. For nonsinusoidal single-phase system, this power resolution can briefly be summarized as below:

The equivalent conductance of the load is defined firstly;

$$G_e = \frac{P}{V^2} \tag{1}$$

and n^{th} harmonic admittance of the load,

$$Y_n = G_n + jB_n = \frac{P_n}{V_n^2} + j\frac{Q_n}{V_n^2} \tag{2}$$

where n^{th} harmonic active (P_n) and reactive (Q_n) powers are calculated as $P_n = V_n I_n \cos(\theta_n)$ and $Q_n = V_n I_n \sin(\theta_n)$.

Accordingly, the load current is divided into four orthogonal components: these current components are;

Active,

$$I_a = \frac{P}{V} \tag{3}$$

Reactive,

$$I_x = \sqrt{\sum_{n\in m} B_n^2 V_n^2} \tag{4}$$

Scattered,

$$I_s = \sqrt{\sum_{n\in m} (G_n - G_e)^2 V_n^2} \tag{5}$$

and Generated Harmonic Currents,

$$I_h = \sqrt{\sum_{n\in k} I_n^2} \tag{6}$$

where k represents current harmonic numbers do not present in the set of voltage harmonic numbers, m denotes that voltage harmonic numbers, and active power is calculated as;

$$P = \sum_{n\in m} P_n \tag{7}$$

Therefore, the load current has the decomposition given in (8):

$$I^2 = I_a{}^2 + I_x{}^2 + I_s{}^2 + I_h{}^2 \tag{8}$$

Thus, the power components can be calculated with the product of the rms values of voltage and these current components:

Active,

$$P = VI_a \tag{9}$$

Reactive,

$$Q_x = VI_x \tag{10}$$

Scattered,

$$D_s = VI_s \tag{11}$$

and Generated Harmonic powers,

$$D_h = VI_h \tag{12}$$

giving the Apparent Power;

$$S = \sqrt{P^2 + Q_x^2 + D_s^2 + D_h^2} \tag{13}$$

From the outlines of Czarnecki's power resolution given above, it can qualitatively be concluded that two power components could be used to detect the harmonic producing loads: These are; Scattered Power, which occurs by the difference between n^{th} harmonic conductance and equivalent conductance, and Generated Harmonic Power, which occurs due to current harmonic numbers do not present in the set of voltage harmonic numbers. However, in the practical systems, Generated Harmonic Power is zero due to the fact that voltage and current have the same order of harmonic numbers. On the other hand, the values of D_s for possible supply voltage and load cases are given in Table II.

Table II: Ds values for various supply voltage and load cases.

	Liner Load	Nonlinear (or Harmonic Producing) Load
Sinusoidal Voltage (or Voltage with Negligible THD_V)	D_s has a negligible value.	D_s has a considerable value.
Nonsinusoidal Voltage (with the reasonable THD_V value)		

Table II shows that Scattered Power component (D_s) of the resolution has the cases underlined below;

- *Sinusoidal Voltage (or Voltage with Negligible THD_V):* For a linear load, one can see that apparent power is very close to the fundamental harmonic apparent power due to the fact that the voltage and current harmonics are negligible. As a result, in sinusoidal voltage and linear load case, Scattered Power has negligible value. On the other hand, for a nonlinear (or harmonic producing) load, the n^{th} harmonic load conductances a part from fundamental harmonic have the considerable values due to the fact that the load injects current harmonics, which is extremely higher than the respective voltage harmonics. Therefore, in the case of sinusoidal voltage and harmonic producing load case, Scattered Current, which is drawn due to the differences between n^{th} harmonic conductance and equivalent conductance, has a considerable value. Accordingly, Scattered Power, which is the product of the rms values of the voltage and Scattered Current, has the same case.
- *Nonsinusoidal Voltage (with the reasonable THD_V value):* In IEEE std. 519 [1], the limit of THD_V is determined as 5% at the bus voltages lower than 69 kV, 2.5% at the bus voltages between 69 kV and 161 kV and 1.5% at the bus voltages higher than 161 kV. On the other hand, in IEC 61000-3-6 [4], it is determined as 8% at LV, 6.5% at MV and 3% at HV. However, [22] shows that 5% is the caution level of THD_V for the consumers. Thus, the maximum reasonable THD_V of the pcc voltage can be taken as 5%. As a result, for a linear load supplied with the

nonsinusoidal voltage having the reasonable THD_V, the n^{th} harmonic load conductance a part from fundamental harmonic have the small values due to the fact that the current harmonics, which is lower than the respective voltage harmonics. Therefore, in the case of nonsinusoidal voltage and a linear load, Scattered Current and Scattered Power have negligible values. On the other hand, for nonsinusoidal voltage and a harmonic producing load case, D_s has a considerable value like in the case of sinusoidal voltage and a harmonic producing load case.

According to the cases mentioned above, it can be concluded whether the load has a non-harmonic producing characteristic or not.

3. Evaluation of the Proposed Method

In this section, the proposed method is evaluated using the statistical experimental analysis. In the analysis, the results of the proposed method and Harmonic Global (HG) index, given in (14), are compared for various linear and harmonic producing loads under a sinusoidal and one hundred nonsinusoidal voltages:

$$HG = \sqrt{\sum_{n\in \ell} I_n^2} \Big/ \sqrt{\sum_{n\in s} I_n^2} \qquad (14)$$

In (14), ℓ and s are the harmonic numbers related to the harmonic active powers, which have negative sign, and the harmonic active powers, which have positive sign, respectively. According to HG index, load is a harmonic producer when it is different from zero.

The schematic of the system used for the evaluation of proposed method on the detection of harmonic producing loads is depicted in Fig. 1.

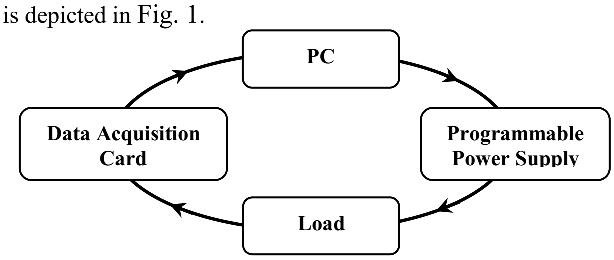

***Fig. 1:** The schematic of the test system.*

In the schematic, presented in Fig. 1, PC processes voltage and current data, and controls the programmable power supply. The loads used in the test system are R-L impedance with R/Z=0.89, a dimmer controlled R-L impedance (R/Z=0.89 and with the triac conduction angles: 90^o-270^o), a number of computers, which have voltage and current pairs plotted in Fig. 2 (a), (b) and (c) for sinusoidal excitation.

It is shown from Fig. 2 (a) that the currents measured for sinusoidal supply voltage and a R-L impedance is sinusoidal. On the other hand, the currents of the dimmer controlled R-L impedance and computers of which THD_I are measured as 50% and 185%, respectively, are seen as highly distorted from Fig. 2 (b) and (c).

Using the test system, the normalized values (N) of the power components of Czarnecki's power resolution and HG index, which are measured for the R-L impedance, the dimmer controlled R-L impedance and the computers under sinusoidal supply voltage, are given in Fig. 2 (d), (e) and (f), respectively.

In addition to that, the histograms of these quantities, which are measured for the R-L impedance, the dimmer controlled R-L impedance and the computers under one hundred distorted voltages with 5% value of THD_V, are given in Fig. 2 (g), (h) and (i), respectively.

Fig. 2 (d) shows that the R-L impedance draws active (P), reactive (Q_x) and scattered (D_s) powers measured as 0.89, 0.44, 0.0001, respectively. Fig. 2 (g) also shows that these powers measured under the distorted test voltages are around the measured values under sinusoidal supply voltage. For a sinusoidal and hundred distorted test voltages, HG is measured as almost zero.

It is seen from Fig. 2 (e) that the P, Q_x and D_s of the R-L impedance controlled with a dimming circuit are 0.65, 0.66 and 0.38 for sinusoidal supply voltage. The histogram of P, plotted in Fig. 2 (h), shows that this power measured under the distorted test voltages are very close to the measured values under sinusoidal voltage. However, for the distorted test voltages, Q_x and D_s vary in the intervals from 0.6 to 0.7 and from 0.3 to 0.4, respectively. For this load, HG is measured as 0.2 in sinusoidal voltage case and has the values between 0.1 and 0.2 for the distorted test voltages.

It is observed from Fig. 2 (f) that the P, Q_x and D_s of the computers are 0.45, 0.71 and 0.53 for sinusoidal supply voltage. From the histograms, plotted in Fig. 2 (i), it is seen for the computers supplied with the distorted test voltages that P, Q_x and D_s vary in the intervals from 0.4 to 0.6, from 0.1 to 0.7 and from 0.5 to 0.9, respectively. In addition, HG is measured as 1.1 in sinusoidal voltage case and has the values between 0.8 and 1.2 for the distorted test voltage cases.The results of the statistical analysis are summarized in Table III.

Table III: The results of the proposed method and HG index.

	Proposed method based on Ds	HG Index
R-L impedance	Normalized D_s is almost zero. It means that load is a linear load.	HG is almost zero. It means that load is a linear load.
R-L impedance controlled with a dimming circuit	Normalized D_s is considerably large. It means that load is a harmonic producing load.	HG is considerably larger than zero. It means that load is a harmonic producing load.
Computers		

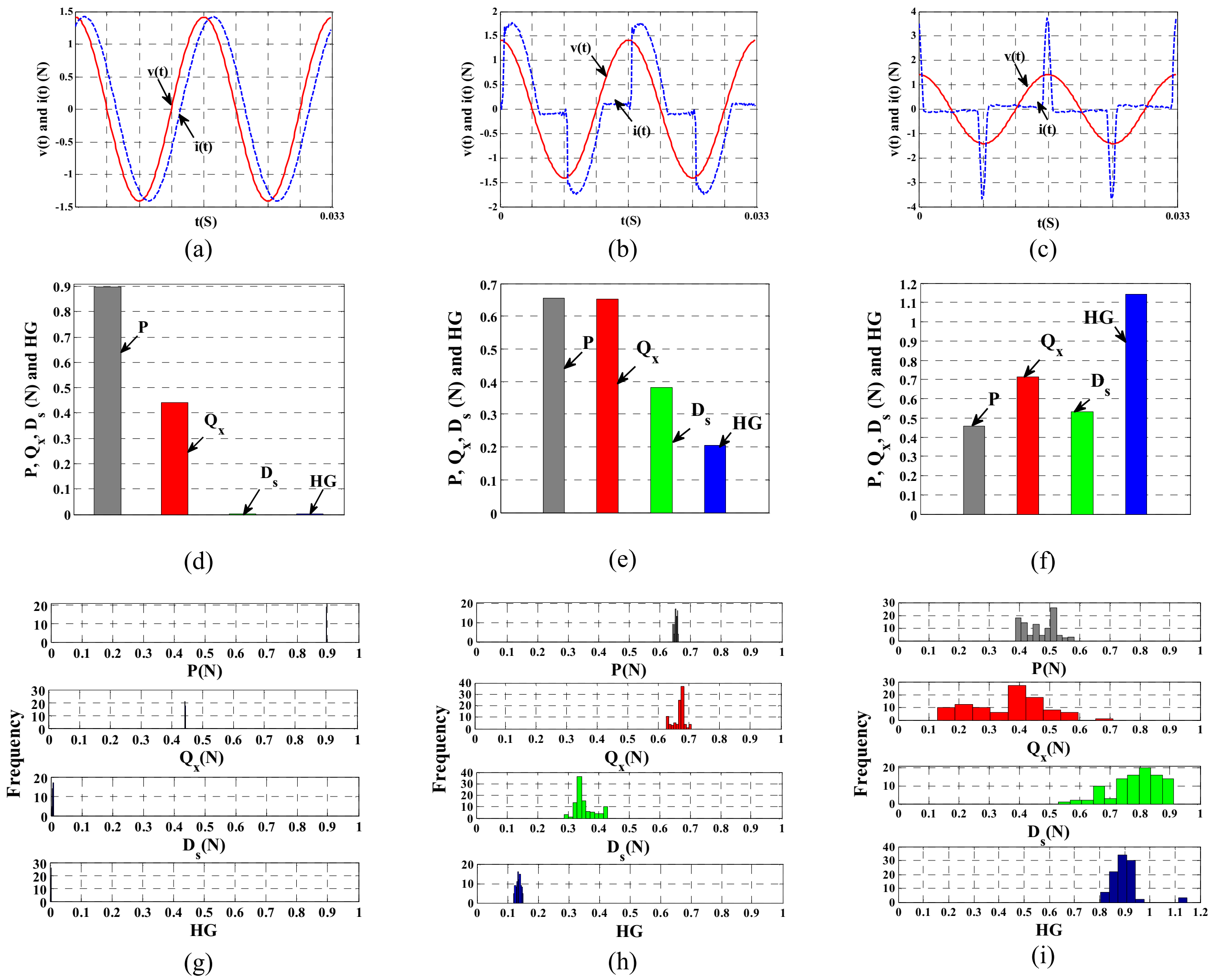

Fig. 2: (a), (b) (c): *The voltage and current pairs of the R-L impedance under sinusoidal excitation, the R-L impedance controlled with a dimming circuit and a number of computers, respectively,* ***(d), (e), (f):*** *The normalized values of P, Q_x and D_s and HG values measured for the voltage and current pairs plotted in (a), (b), (c), respectively,* ***(g), (h), (i):*** *The histograms of these quantities measured under the nonsinusoidal test voltages for the R-L impedance, the R-L impedance controlled with a dimming circuit and a number of computers, respectively.*

It is shown from the table that the proposed method and HG index points out that R-L impedance is linear load, and the R-L impedance controlled with a dimming circuit and computers are the harmonic producing loads. Thus, it can be concluded that the proposed method is in agreement with HG index. Furthermore, it should be underlined that new detection method can cost effectively be implemented by using specially designed demand meter, which is built by using Czarnecki's power resolution. The same meter can also be used for the energy billing of the consumer.

4. Conclusions

In this paper, a new single-point method is proposed for the detection of the harmonic producing loads. It is based on the Scattered Power, which is defined in the power resolution of Czarnecki. According to the proposed method, it can be concluded that load is not harmonic producing load if Scattered Power has negligible value. Otherwise, it is a harmonic producing load. The advantage of the proposed method is that it can be implemented using a simple demand meter, which is used for the energy billing of the consumer. The results of the experimental analysis for various types of loads show that the proposed single-point approach concurs with HG index in the systems with the reasonable THD_V values of the pcc voltage.

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