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A New Method for Separating Utility and Customer Harmonic Contribution at The Point of Common Coupling

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ABSTRACT

Harmonic disturbances can have significant technical and economic impacts for many different types of facilities equipment and customers' loads. This paper proposes a new method to measure harmonic contributions by utility and customer at the point of common coupling in an industrial distribution system. The new method is based on the sign of the reactive power gradient measured at the point of common coupling (PCC). Simulations were carried out by considering a saturated transformer as harmonic producer at the utility side and an adjustable speed drive as harmonic producer at the customer side. In the proposed method, the reactive power at the point of common coupling which is between utility and customer sides are measured and plotted against time. A least square method is used to perform the line fitting for the reactive power against time of the harmonic distortion to detect harmonic source. A positive gradient indicates that utility is the main contributor of harmonic distortion at PCC and on the other hand, a negative gradient indicates that customer is the main contributor of harmonic distortion at PCC. Results from simulations have verified that the new method is technically sound as it only requires voltage and current measurements at the PCC.

1. INTRODUCTION

Harmonic distortion is not a new phenomenon where concern over harmonic distortion emerged during the early history of ac power system. In the early nineties it has been reported that the main cause of harmonics were then saturated iron in transformer and machines [1]. Later it was found that harmonic may lead to interference in telephone system. The problems of harmonics keep on increasing due to the growth of the modern technology which converts the old bulky power system loads into small size power electronic loads. Presently, the proliferation of power-electronic loads such as adjustable-speed drives (ASD) and switch-mode power supplies have lead to increasing harmonic distortion problems. These loads use diodes, silicon-controlled rectifiers, and power transistors to convert 50/60Hz ac to dc. These efficient and controllable power electronic loads are proliferating and can be found at all power levels. This phenomenon leads to a pertinent issue on who should be responsible for power harmonic distortion. A more technically important issue that has to be encountered before any scheme can be used to penalize the major harmonic contributor at the point of common coupling (PCC), utility or customers.

There are several methods found in the literature that address the issue of harmonic source identification. The real power direction method [2]-[4] is the earliest method proposed in identifying harmonic sources. In fact, some power quality monitors use this method to detect whether the source of harmonic is from the utility side or the customer side. However, the real power direction method has been proven to be only 50 per cent reliable should the customer change loads [5,6]. A better method to clarify interaction between utility and customer harmonic contribution has been used in [7, 8] in which the method is based on Thevenin's Theorem where harmonic at PCC is decomposed into outflow harmonic current (from customer) and inflow harmonic current (from utility). Harmonic measurement instrument has been developed using current injection of inter-harmonic frequency to measure utility and customer harmonic impedances. However, the inter-harmonic current injection is not popular because it is considered as an invasive method [9]. Another method has been proposed in [6] using the superposition-based current and voltage indices to quantify the harmonic sources from a Norton equivalent circuit. In this method, the principle of superposition theorem has been mathematically analyzed and proven to be a good indicator for determining harmonic contributors at the PCC. However, the implementation of superposition theorem will only be possible if utility and customer impedances are known. To measure these impedances, capacitor switching in the distribution system is usually required [9]. Hence, real implementation in locating harmonic source using the superposition theorem is not very practical.

To date, the most recent method used to discriminate harmonic contribution at the PCC is the critical impedance method [10]. In this method, the concept of reactive power is adapted where the reactive power are modified and calculated in terms of impedance between utility and customer. A new index known as critical impedance (CI) is introduced in [10]. However, the critical impedance based method has a limitation because it requires the knowledge of utility impedance value which makes the method impractical for implementation.

This paper presents a new method for discriminating the harmonic contributions between utility and customer based on the reactive power measured at the PCC. The method is based on the energy balance concept at equilibrium [11] in which it considers the polarity of the gradient of the reactive power over time, $\Delta Q/\Delta t$ as an indicator for harmonic contribution from either utility or customer.

2. GRADIENT OF PROPOSED REACTIVE POWER METHOD

A method proposed in this paper is based on the reactive power values. However, to use the values of reactive power directly as indicator is not appropriate because it depends on the nature of the harmonic source impedance as to whether it is inductive or capacitive [12]. An intuitive explanation on the reactive power gradient method can be adapted from the energy balance equation given in Eq. (5a). At an equilibrium condition [11]:

$$\begin{matrix} \textit{Rate of change} \\ \textit{of total energy} \end{matrix} = \begin{matrix} \textit{flow of enegy} \\ \textit{into the system} \end{matrix} - \begin{matrix} \textit{flow of energy} \\ \textit{out of the system} \end{matrix} \tag{1a}$$

Applying the concept of energy balance to the reactive power at the PCC, we get

$$\begin{matrix} \textit{Rate of change} \\ \textit{of total Q} \end{matrix} = \begin{matrix} \textit{flow of Q into} \\ \textit{the system} \end{matrix} - \begin{matrix} \textit{flow of Q out} \\ \textit{of the system} \end{matrix} \tag{1b}$$

Eq. (1b) can be rewritten as:

$$\frac{\Delta Q}{\Delta t} = \frac{Qin - Qout}{\Delta t} \tag{1c}$$

At the PCC, $Qout = 0$ and using Eq. (1c) in the proposed method yields,

$$\sum Q_{pcc} = Qin$$

In Fig. 1, it is assumed that the positive direction of reactive power is from utility to customer.

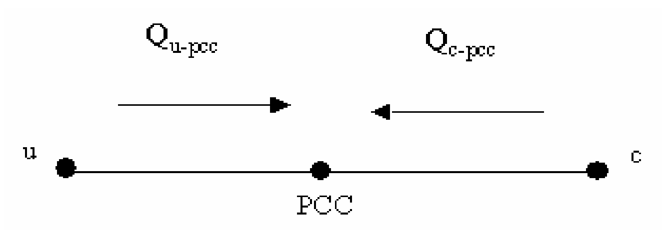


Fig. 1 Positive direction of reactive power

At the PCC, the rate of reactive power is given by,

$$\frac{\Delta Q_{pcc}}{\Delta t} = \frac{(Q_{u-pcc} - Q_{c-pcc})}{\Delta t} \tag{1d}$$

$$\text{If,} \quad Q_{u-pcc} > Q_{c-pcc} \tag{2a}$$

Then the rate of change of reactive power is positive,

$$\Delta Q_{pcc} / \Delta t > 0 \tag{2b}$$

and the utility is the major source of harmonic.

$$\text{If,} \quad Q_{u-pcc} < Q_{c-pcc} \tag{3a}$$

Then the rate of change of reactive power is negative,

$$\Delta Q_{pcc} / \Delta t < 0 \tag{3b}$$

and the customer is the major source of harmonic. Implementation of the proposed can be easily done by calculating the reactive power at PCC using,

$$Q_{pcc} = Im(V_{pcc} . I^{*}_{pcc}) \tag{4}$$

where, V_{pcc} and I_{pcc} are harmonic voltage and current measured at the PCC. The hypothesis for reactive power gradient method can be simplified as follows:

- If $\Delta Q/\Delta t > 0$, utility is the major harmonic source.
- If $\Delta Q/\Delta t < 0$, customer is the major harmonic source.

Procedure of the proposed method

Fig. 2 explains the process taken after each harmonic simulation. After measurement of voltage and current are made for each simulation, a fast fourier analysis (FFT) is performed to identify the harmonic characteristics. A significant harmonic component is then evaluated using the proposed technique.

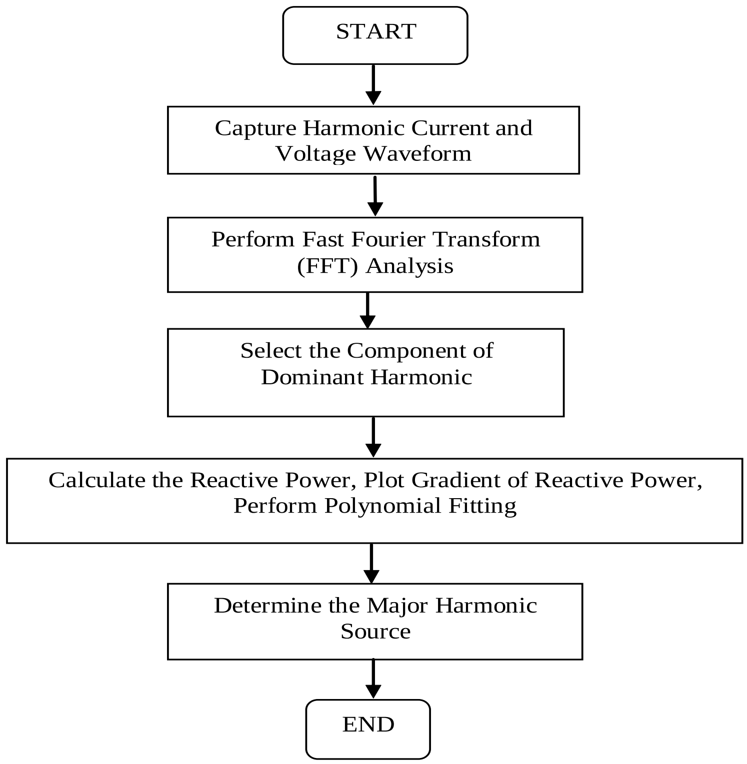


Fig. 2 Simulation Procedure

3. VERIFICATION OF THE PROPOSED METHOD

In the simulation, the modified industrial distribution system [13] is used as a test system where a saturated transformer and an adjustable speed drives are considered as harmonic sources.

3.1 Test System

Fig. 3 represents the test system used for verification of the proposed method. The supply transformer at bus 1 is made saturated to produce harmonic from the utility side for the test system. This model is simulated by using the unified magnetic equivalent circuit transformer model obtained from the EMTDC/PSCAD V4 library of models. A current source model of ASD is injected at bus 2 to generate harmonic from the customer side.

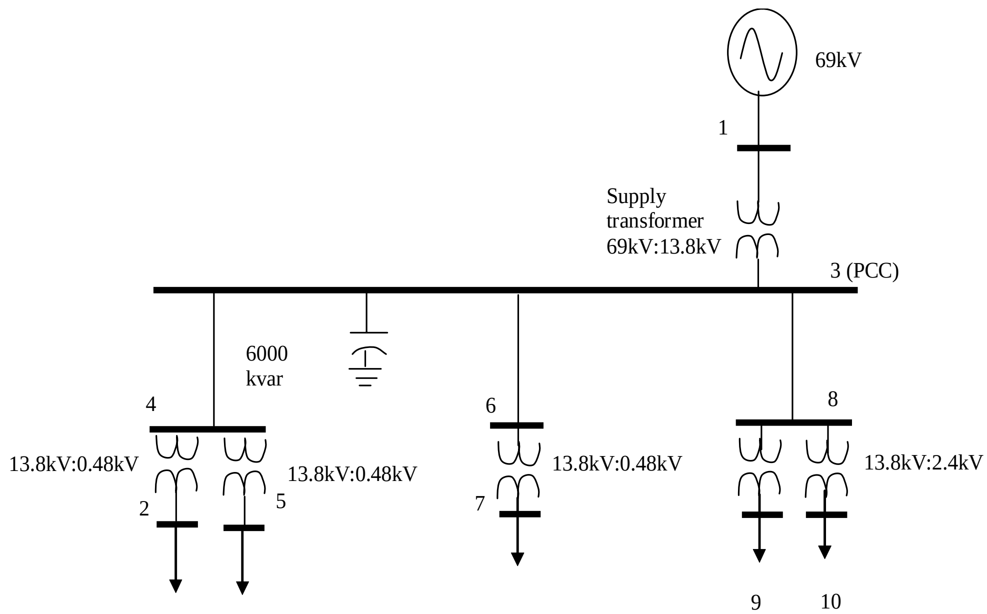


Fig. 3 A Balanced Industrial System

3.2 Simulations Results

The proposed method was verified by simulations using the electromagnetic transient (EMTDC/PSCAD) software and considering two models of harmonic sources. The harmonic data obtained from simulations were then processed by writing MATLAB script files. From the harmonic source models, at significant harmonic frequencies (3^{rd}, 5^{th} , 7^{th} , etc), the sign of the reactive power gradient DQ/Dt is noted so as to distinguish the location of harmonic source.

From the current and voltage values obtained at the PCC, the reactive power gradient is calculated using (4) by writing MATLAB scripts files. A graph of reactive power magnitude against time is first plotted and the least-square based fitting technique is performed for each significant harmonic component. Two major cases are considered in the simulation described as follows:

3.2.1 Harmonic from utility side

A saturated transformer model is used to generate harmonics from the utility side. In saturated transformer, the 3^{rd}, 5^{th} and 7^{th} harmonics are recorded to be significant harmonics at the PCC. Figs. 4(a) and (b) present the current and voltage harmonic components respectively at the PCC obtained from fast fourier transform (FFT) analysis for case A. The most significant voltage and current are observed to occur at the 3^{rd} 5^{th} 7^{th} and 11^{th} harmonic. The reactive power at these harmonics is plotted against time at the PCC for the simulation considering saturated transformer model. A straight line fitting curve for the 3^{rd} 5^{th} 7^{th} and 11^{th} harmonic for saturated transformer are presented in Fig. 5. A positive gradient obtained in Fig. 5 verifies that the major source of harmonics is from the utility side which is due to the saturated transformer.

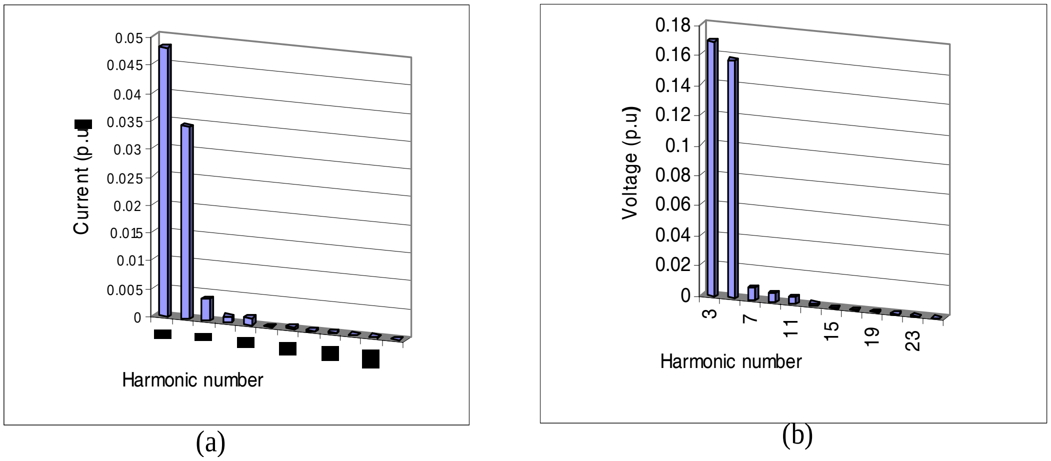


Fig. 4 Harmonic component at the PCC for saturated transformer (a) current (b) voltage

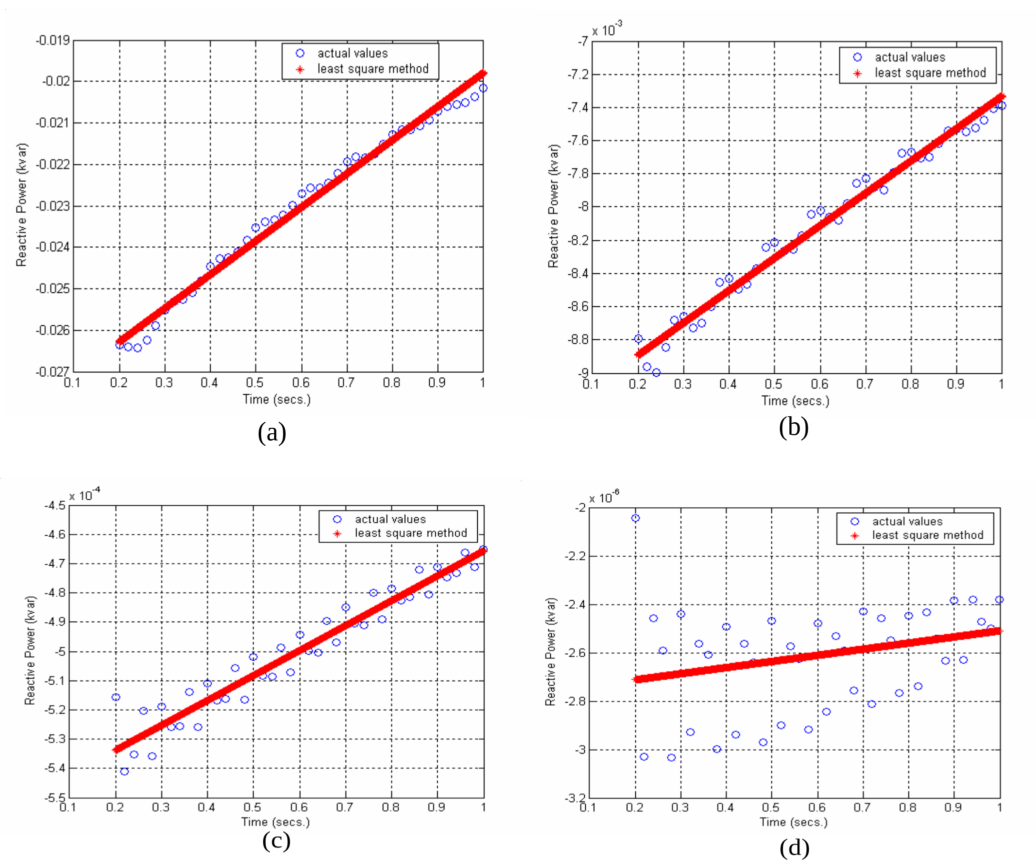


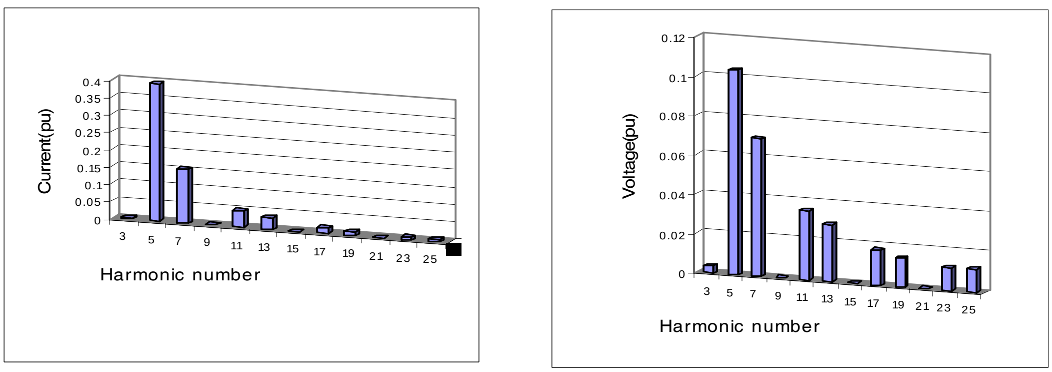
Fig. 5 Gradient for reactive powers at the PCC for the system with saturated transformer: (a) 3^{rd} harmonic (b) 5^{th} harmonic (c) 7^{th} harmonic (d) 11^{th} harmonic

3.2.2 Harmonic from customer side

An adjustable speed drive model [13] is used to produce harmonic from the customer side. In adjustable speed drives, the 5th, 7th, 11th and 13th harmonics are significant.

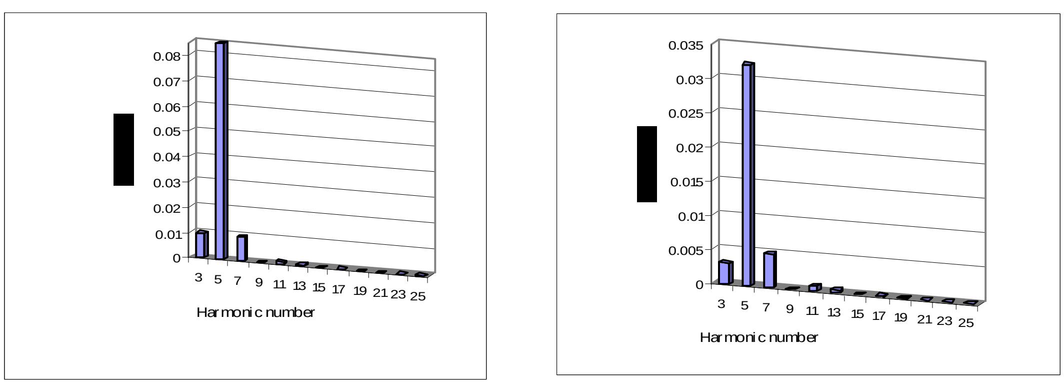
Figs. 6(a) and (b) show the current and voltage harmonic components respectively obtained from the FFT analysis at bus 2. The simulation results from FFT analysis indicate that the significant harmonics are the 5th, 7th, 11th and 13th harmonics. These harmonics are generated by the ASD at bus 2. Figs. 7(a) and (b) provide the current and voltage harmonic at the PCC when the ASD is injected at bus 2. The significant harmonics are the 5th, 7th, 3rd, 11th and 13th. Since only the 5th, 7th, 11th and 13th harmonics are caused by the ASD, the reactive power gradient for these harmonics are plotted and presented in Fig. 8.

The straight line using a least square method in Fig. 8 shows that the reactive power gradients, DQ/Dt are negative. From these results it can be concluded that the major harmonic source is from the customer side which is due to the ASD.



(a)

Fig. 6 Harmonic characteristics at bus 2 for ASD: (a) current (b) voltage



(a)

Fig. 7 Harmonic component at the PCC for ASD: (a) current (b) voltage

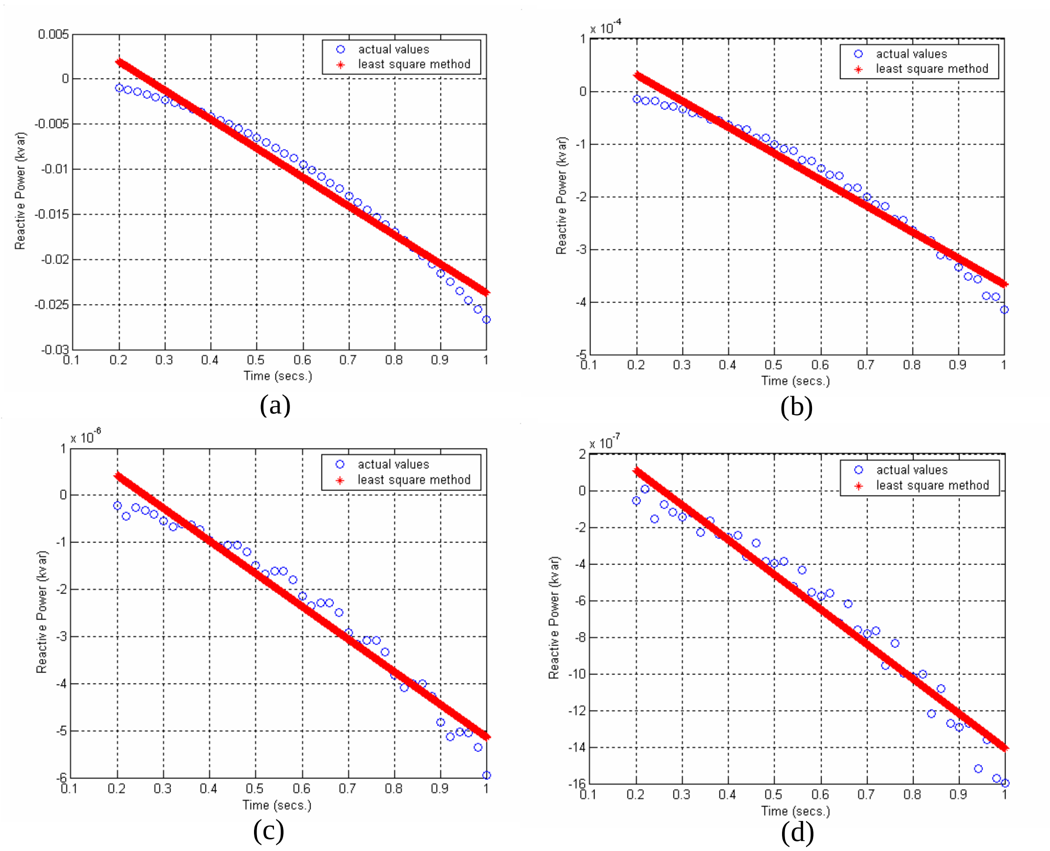


Fig. 8 Gradient for reactive powers at the PCC for the system with an adjustable speed drive: (a) 5th harmonic (b) 7th harmonic (c)11th harmonic (d)13th harmonic

From the simulations carried out, it has been verified that the reactive power gradient results agree with the hypothesis of reactive power gradient method mentioned in section 3.

4. CONCLUSIONS

This paper presents a new method based on the reactive power gradient for locating the harmonics source contributions at the PCC in an industrial distribution system. The hypothesis of the reactive power gradient method is that if the sign of the gradient is positive, the major harmonic source is from the utility side whereas if the sign of the gradient is negative, the major harmonic source is from the customer side. The proposed method was tested via simulations by considering saturated transformer as utility side harmonic sources and adjustable speed drive as load side harmonic sources. Simulation results have verified the accuracy of the proposed method. The main advantages of the proposed method can be described as follows:

- The voltage and current measurements at a single point are sufficient to determine the location of harmonic sources using the proposed method.
- The method does not require customer and utility impedances in the reactive power gradient calculation.
- The method has shown that only a single index is sufficient to locate the harmonic source at the pcc.

- The proposed method utilizes least-square based curve fitting technique, hence it does not rely on one point measurement which make the result reliable and robust.

Thus, the method is considered as technically sound and practical and has a good potential for a practical application.

5. ACKNOWLEDGEMENTS

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