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A New Two Points Method for Identify Dominant Harmonic Disturbance Using Frequency and Phase Spectrogram

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Abstract – *This paper is focused on a practical new method for dominant harmonic disturbance detection implemented using phase and frequency spectrogram based on two-point method. The first measurement point is measured at the incoming of the point of common coupling while the second measurement point at the incoming of the load. After that, the data is processed with phase and frequency spectrogram. By comparing the data, the dominant harmonic disturbance can be identified clearly. The proposed method is compared with power direction method which is the earliest method normally used in commercial product. Then, simulation and experiment are conducted to verify the accuracy of the proposed method. Finally, the results show the proposed method is more accurate than power direction method. Further work is needed to investigate the performance of the proposed method by field measurement.* ***Copyright © 2014 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Harmonic Disturbance, Frequency Spectrogram, Phase Spectrogram*

Nomenclature

PCC	Point of common coupling
PDM	Power direction method
SLQI	Supply load quality index
HGI	Harmonic global index
SM	Superposition method
CIM	Critical impedance method
V_h	Harmonic voltage
I_h	Harmonic current
$cos(\phi)$	Phase shift angle
P_1	Fundamental active power
P	Total active power
m	Harmonic order with negative active power
n	Harmonic order with positive active power
FS	Frequency spectrogram
PS	Phase spectrogram
$STFT$	Short-time Fourier transform
$x(t)$	Input signal
$w(t)$	Observation window
$I_{h(pcc)}$	Summation of $I_{h(load1)}$ and $I_{h(load2)}$
$I_{h(load1)}$	Harmonic current of load 1
$I_{h(load2)}$	Harmonic current of load 2
$V_{h(pcc)}$	Particular order amplitude voltage
V_{pcc}	The summation of $V_{h(pcc)}$ from harmonic order 0 to 50
I_{pcc}	The summation of $I_{h(pcc)}$ from harmonic order 0 to 50
$I_{h(pcc)}$	Particular order amplitude current
$Z_{h(tsi)}$	Total source impedance
$Z_{h(supply\_impedance)}$	Supply impedance
$Z_{h(transmission\_impedance)}$	Transmission impedance
$Z_{h(load\_impedance)}$	Load impedance
P_h	Power for harmonic order

I. Introduction

In recent years, along with continual development of market economy and extension of industrial scale, more and more control equipments based on computer system and electrical equipment are used in many fields in order to improve work productivity and automation level [1].

These equipments have better performance and higher efficiency, but very sensitive response on variation of power supply quality. If the equipments operated with low power supply quality can contribute many economy losses. Moreover, accidents often occur because of low power supply quality, example the temperature of the wire increased when the wire conduct with high frequency current due to skin depth concept. In a nutshell, power quality improvement is the imperative task for power department and electricity consumer. In order to improve the power quality, the limitation of harmonics pollution present at the point of common coupling (PCC) had been control by IEEE Std. 519 [2] which widely accepted in industry. To be precise, the voltage waveform at the PCC is cover by EN 50160 [3]. The IEC 61000 [4], [5] standards mention about the limit of current waveform distortion and methods to measure the harmonic waveform distortion.

Currently, there is no any standards define about the method to identify the dominant harmonic disturbance. Consequently, this paper focus on identified the dominant harmonic disturbance.

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Many methods have been proposed in the previous papers. The power direction method (*PDM*) is the earliest method to detect the dominant harmonic disturbance [6]. The negative active power value means the dominant harmonic disturbance is downstream; otherwise, dominant harmonic disturbance considered upstream. But the PDM is founded theoretically incorrect [7].

Supply load quality index (*SLQI*) [8] is a method to indicate the dominant harmonic disturbance. The SLQI in negative value means downstream as dominant harmonic disturbance and vice versa. The SLQI method cannot measure dominant harmonic disturbance individually and theoretically incorrect because the SLQI method is proposed base on PDM [7], [9]. The harmonic global index (*HGI*) is a method to indicate the dominant harmonic disturbance but theoretically incorrect because the HGI method is proposed base on PDM [7], [9].

Superposition method (*SM*) is proposed base on proper modeling with circuit analysis [10]. SM cannot be done accurately without the information for impedance of the entire system. Practically, SM is not a practical method because the impedance for the entire system is hard to be determined. Critical impedance method (*CIM*) is not a practical method because the analysis method is based on harmonic impedance [11]. Where by the harmonic impedance is hard to determine correctly. In order to overcome the shortages of previous method, a practical new method for dominant harmonic disturbance detection is implemented by using phase and frequency spectrogram based on two-point method.

This paper is focused on a practical new method for dominant harmonic disturbance detection is implemented by using phase and frequency spectrogram based on two-point method. The first measurement point is measured at the incoming of the point of common coupling. Then the second measurement point is measured at the incoming of the load. After that, the data is processed with phase and frequency spectrogram. By comparing the data, the dominant harmonic disturbance can be identified clearly.

The proposed new method is compared with power direction method which is the earliest method and it used in commercial product [6]. Then, simulation and experiment are conducted to verify the accuracy of the proposed method. Finally, the results show the proposed method is more accurate than power direction method.

Further work is needed to investigate the performance of the proposed method by field measurement.

II. Previous Technique Used

Method (a) - power direction method (PDM)

The *PDM* is the earliest method to detect the dominant harmonic disturbance [6]. The Eq. (1) shows the formula for PDM. Where by, V_h and I_h is the particular harmonic voltage and current respectively. The *cos*(∅) is the phase shift angle for the particular voltage and current. The positive active power value means the dominant harmonic disturbance is upstream; otherwise, dominant harmonic disturbance considered downstream.

$$P_h = V_h I_h \cos\left(\theta_{Vh} - \theta_{Ih}\right) \tag{1}$$

Method (b) - Supply load quality index (SLQI)

Supply load quality index (*SLQI*) [8] is a method to indicate the dominant harmonic disturbance. The SLQI in negative value means downstream as dominant harmonic disturbance and vice versa. The Eq.2 shows the formula for SLQI. Where by, P_1 and P is the fundamental active power and total active power respectively:

$$SLQI = \frac{P}{P_1} \tag{2}$$

Method (c) - Harmonic global index (HGI)

The harmonic global index (*HGI*) is a method to indicate the dominant harmonic disturbance but theoretically incorrect because the HGI method is proposed base on PDM [7], [9]. The Eq. (3) shows the formula for HGI. Where by, the m and n is the harmonic order with negative and positive active power respectively:

$$HGI = \frac{\sqrt{\sum_{h=m} I_h^{\,2}}}{\sqrt{\sum_{h=n} I_h^{\,2}}} \tag{3}$$

Method (d) - Superposition method (SM) and Critical impedance method (CIM)

Superposition method (*SM*) [10] and Critical impedance method (*CIM*) [11] are proposed base on proper modeling with circuit analysis. Practically, SM and CIM are not a practical method because the harmonic impedance for the entire system is hard to be determined accurately.

III. Proposed Analysis Technique

Time frequency analysis technique is used in this research. In this part, the theory of time-frequency analysis is discussed. The amplitude of the waveform can be computed by frequency spectrogram. However the phase angle of the waveform can be defined by using phase spectrogram.

A. Frequency spectrogram

The spectrogram is categories in to two parts which is frequency spectrogram (FS) and phase spectrogram (PS).

The FS provides a distribution of energy of the signal in a time-frequency plane [2] and is defined in Eq. (4) and Eq. (5):

$$STFT_x\left(\tau, f\right) = \int_{-\infty}^{\infty} x\left(t\right) w\left(\tau - t\right) e^{-j2\pi ft} dt \tag{4}$$

$$S_x\left(\tau, f\right) = \left|STFT_x\left(\tau, f\right)\right|^2 \tag{5}$$

where $x(t)$ is the input signal and $w(t)$ is the observation window which is hanning window. The standard IEC defined that the hanning window can perform better in analyzing harmonic [12]. The parameter instantaneous root means square value is defined by [13].

B. Phase spectrogram

In order to obtain PS, the signal is processed with short-time Fourier transform (STFT) at first. Where $x(t)$ is the input signal and w(t) is the observation window which is rectangular window. The t (Eq. (6)) is 0.02s (1/fundamental frequency where by the fundamental frequency is 50Hz).

The result of STFT is a complex-valued function allowing the representation of both the phase and magnitude parts of the signal [14]. The phase angle is obtained by apply trigonometry concept on the STFT's result (Eq. (7)). The n (Eq. (9)) is indicated the total number of phase angle of the STFT result. The PS result obtained by average the phase angle of the STFT result.

The PS is taken into accounts and expressed as:

$$STFT_y(\tau,f)=\int_{-\infty}^{\infty}x(t)w(\tau-t)e^{-j2\pi ft}dt \tag{6}$$

$$\phi_{STFT_y}(\tau,f)=Atan\left(\frac{Imag\left(STFT_y(\tau,f)\right)}{Real\left(STFT_y(\tau,f)\right)}\right) \tag{7}$$

$$\theta_y(\tau,f)=\frac{\delta\phi_{STFT_y}(\tau,f)}{dt} \tag{8}$$

$$PS(\tau,f)=\left(\Sigma\theta_y(\tau,f)\right)/n \tag{9}$$

IV. Principle of Proposed Method

The schematic harmonic load is shown in Fig. 1 consists of two harmonic loads. In order to determine the dominant harmonic disturbance, two measurement points are taken. The I_{pcc} and $I_{h(load2)}$ are measured to determine the dominant harmonic disturbance whether the dominant harmonic disturbance is $I_{h(load1)}$ or $I_{h(load2)}$.

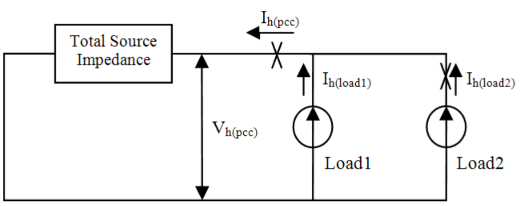

Fig. 1. Schematic for harmonic load

The Eq. (10) until (14) show the equation for schematic harmonic load for Fig. 1. The $V_{h(pcc)}$ (Eq. (10)) is the particular order amplitude voltage in Root Means Square (*RMS*) value. The V_{pcc} (Eq. (10)) is the summation of $V_{h(pcc)}$ from harmonic order 0 to 50 [15]:

$$V_{pcc}=\sum_{h=0,1,2......}^{50}V_{h(pcc)} \tag{10}$$

The $I_{h(pcc)}$ (Eq. (11)) is the particular order amplitude current in RMS value. I_{pcc} (Eq. (11)) is the summation of $I_{h(pcc)}$ from harmonic order 0 to 50 [15]:

$$I_{pcc}=\sum_{h=0,1,2......}^{50}I_{h(pcc)} \tag{11}$$

Eq. (12) shows $I_{h(pcc)}$ is summation of $I_{h(load1)}$ and $I_{h(load2)}$. The Eq. (12) is generated by following Kirchhoff's Current Law where by, the total current flowing to the node is equal with total current flowing out of the node [16]:

$$I_{h(pcc)}\angle\theta_{h(pcc)}=I_{h(load1)}\angle\theta_{h(load1)}+ +I_{h(load2)}\angle\theta_{h(load2)} \tag{12}$$

Eq. (13) shows $Z_{h(tsi)}$ (total source impedance) is addition of supply impedance ($Z_{h(supply\_impedance)}$), transmission impedance ($Z_{h(transmission\_impedance)}$), and load impedance ($Z_{h(load\_impedance)}$) [17]. The $Z_{h(supply\_impedance)}$ is contributed by the transformer impedance. However the $Z_{h(transmission\_impedance)}$ is generated by the distance wire on the transmission line. Lastly, the $Z_{h(load\_impedance)}$ depends on the load:

$$Z_{h(tsi)}=Z_{h(supply\_impedance)}+Z_{h(transmission\_impedance)}+ +Z_{h(load\_impedance)} \tag{13}$$

Next, the particular order voltage ($V_{h(pcc)}$) is produced by multiplied $I_{h(pcc)}$ and $Z_{h(tsi)}$ which following ohm's law:

$$V_{h(pcc)}\angle\theta_{h(pcc)}=I_{h(pcc)}\angle\theta_{Ih(pcc)}\times Z_{h(tsi)}\angle\theta_{Zh(tsi)} \tag{14}$$

In this proposed method, the total source impedance is not involved to determine the dominant harmonic disturbance due to the complexity on measuring the total source impedance. Only Kirchhoff's Current Law is used to determine the dominant harmonic source. Eq. (15) and (16) show equation for upstream and downstream respectively:

$$\left|I_{h(pcc)}\angle\theta_{h(pcc)}-I_{h(load2)}\angle\theta_{h(load2)}\right|> \left|I_{h(load2)}\angle\theta_{h(load2)}\right| \tag{15}$$

$$\left|I_{h(pcc)}\angle\theta_{h(pcc)}-I_{h(load2)}\angle\theta_{h(load2)}\right|< \left|I_{h(load2)}\angle\theta_{h(load2)}\right| \tag{16}$$

V. Case Study

In this part, two case studies are discussed.

The first case is about the power direction method.

However the second case is about the proposed method. In the case study, the particular method is analyzed based on its accuracy.

a) Case study for power direction method

The method b and c are generated base on power direction method (method a) [9]. The case study is emphasized on power direction method because the method is been used commercially [6] and it is the basic method for method b and c. Eq. (17) shows the equation for power direction method.

If the P_h in negative value means the harmonic source occurred at the customer side (downstream); otherwise, it is consider as upstream:

$$P_h = V_{h(pcc)} \times I_{h(pcc)} \cos\left(\theta_{Vh} - \theta_{I_h}\right) \tag{17}$$

For the case study for power direction method, the total source impedance is assumed as 0.004+0.25j. Fig. 4 shows the schematic for harmonic load for case study power direction method.

Fig. 2 shows the correlation between power direction method and the current value.

Based on Fig. 4, the amplitude of $I_{h(load1)}$ (5∠0°) always greater than $I_{h(load2)}$ (3∠various from 0° to 360°).

The $I_{h(load2)}$ is various from 0° to 360° because there is no limitation phase shift angle for harmonic current [18].

The actual result is upstream for $I_{h(load2)}$ with any phase angle occurred.

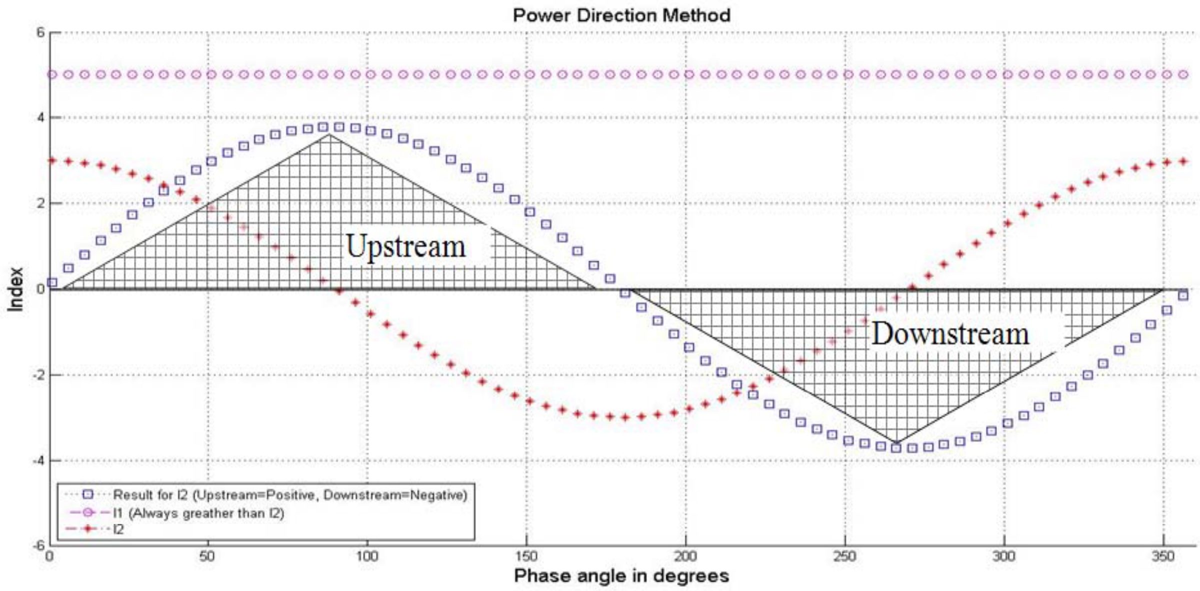

Fig. 2. Correlation between the power direction method and current value

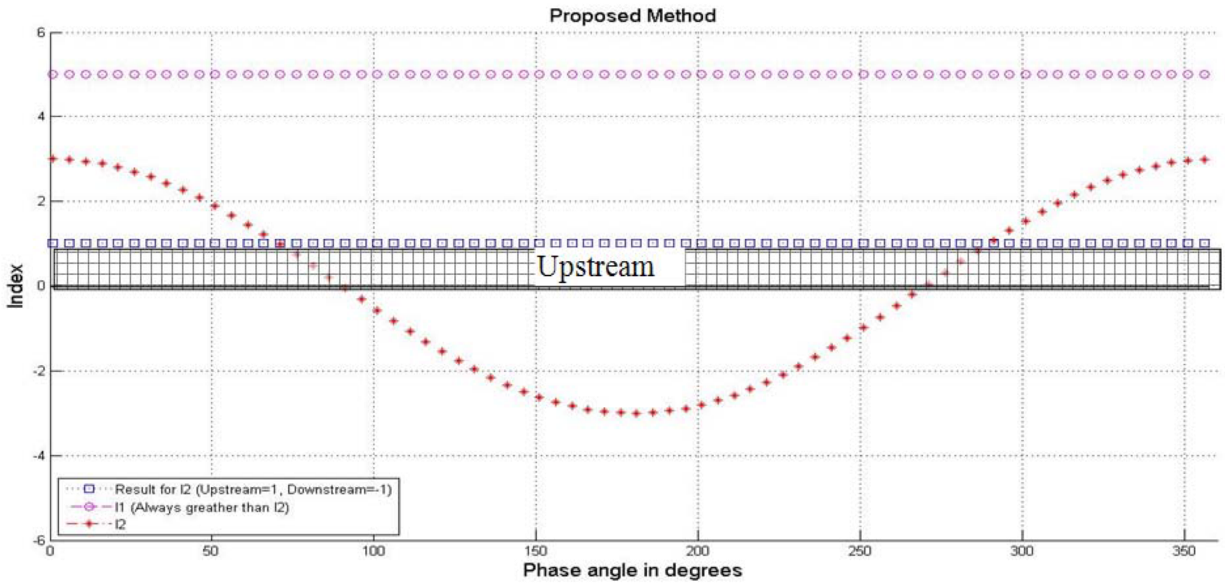

Fig. 3. Correlation between the proposed method and current value

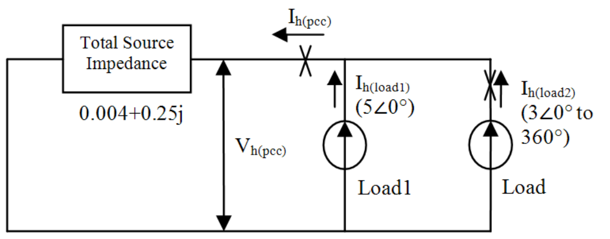

Fig. 4. Schematic for case study

Based on the correlation result in Fig. 2, the power direction's result gives 50 % chance that the contradiction can occur [18] because the result various between upstream and downstream.

b) Case study for proposed method

For the case study for proposed method, the value for total source impedance, $I_{h(load1)}$, $I_{h(load2)}$ and schematic (see Fig. 4) are similar with the case study for power direction method. Fig. 3 shows the correlation between the proposed method and current value. As usual, the amplitude of $I_{h(load1)}$ ($5\angle0°$) always greater than $I_{h(load2)}$ ($3\angle$various from 0° to 360°). The actual result is upstream for $I_{h(load2)}$ with any phase angle occurred. The proposed method can provided a constant upstream result with any phase angle occurred at the $I_{h(load2)}$. Based on the correlation result in Fig. 2 correlation between the power direction method and current value, Fig. 3, the proposed method's result gives 100 % accuracy.

VI. Simulation Result and Analysis

In this research, the simulation is done by PSCAD. Fig. 5 shows PSCAD simulation schematic circuit. The simulation consists of two harmonic loads. The total source impedance is assumed as 0.004+0.25j.

The measurement point a and b is used to measure load 1 and load 2 respectively. However the measurement point c is used to measure the total load of the simulation. In the simulation, the power supplied with pure 240Vrms, 50Hz.

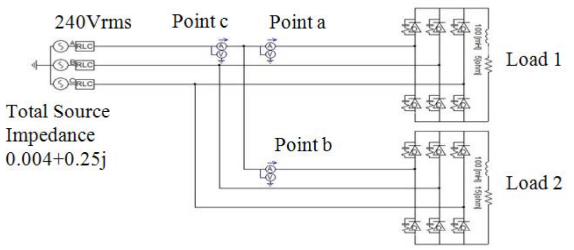

Fig. 5. PSCAD simulation schematic

Table I shows the PSCAD simulation result. The actual harmonic source is on load 1 because the load 1 (Measurement point a) is generated more harmonic current than load 2 (Measurement point b). The result for power direction method via Eq. (17) is not similar with the actual harmonic source.

But the proposed method shows the same result with the actual harmonic source.

The proposed method can be computed via Eq. (15) and (16). For 5th and 7th order harmonic, the calculation for proposed method is shown Eq. (18) and (19) respectively.

In the nutshell, the simulation result shows that the proposed method more accurate than the power direction method:

$$\left|14\angle10° - 5\angle4°\right| > \left|5\angle4°\right| \tag{18}$$

$$\left|10\angle-40° - 3\angle-32°\right| > \left|3\angle-32°\right| \tag{19}$$

TABLE I
PSCAD SIMULATION RESULT

Measurement point	Order	Voltage	Current	Actual Harmonic Source	Power Direction Method	Proposed Method
a ($I_{load\ 1}$)	1	232∠-95°	62∠-105°			
	5	20∠-87°	9∠13°			
	7	16∠-120°	7∠-42°			
b ($I_{load\ 2}$)	1	232∠-95°	27∠-107°			
	5	20∠-87°	5∠4°	Up	Down	Up
	7	16∠-120°	3∠-32°	Up	Up	Up
C (I_{pcc})	1	232∠-95°	88∠-105°			
	5	20∠-87°	14∠10°			
	7	16∠-120°	10∠-40°			

VII. Experiment Result and Analysis

In this research, the experiment is done by harmonic generator (see Fig. 6) and the connection similar with PSCAD. The harmonic generator can variable the harmonic load level between 1kW to 5kW. In this experiment, the load 1 and load 2 are defined as 1kW and 5kW respectively. The experiment (see Fig. 7) is supplied with pure 240 Vrms, 50 Hz and the source impedance is unknown practically. Two measurement points are conducted in this experiment to identify the dominant harmonic disturbance.

I_{pcc} is the first measurement point to identify the total harmonic generated by the system. However, I_{load2} is the second measurement point to identify the harmonic generated by the particular load. With the information of I_{pcc} and I_{load2} the dominant harmonic disturbance can be identified by equation (Eq. (18) and (19)) weather is load 1 or load 2.

Table II shows the practical experiment result. The load 1 and load 2 are connected with 1kW and 5kW harmonic generator respectively. Obviously, load 2 is downstream as dominant harmonic disturbance. so the actual result shows load 2 as downstream. Eq. (20) and (21) show the equation for power direction method for 5th n 7th harmonic order.

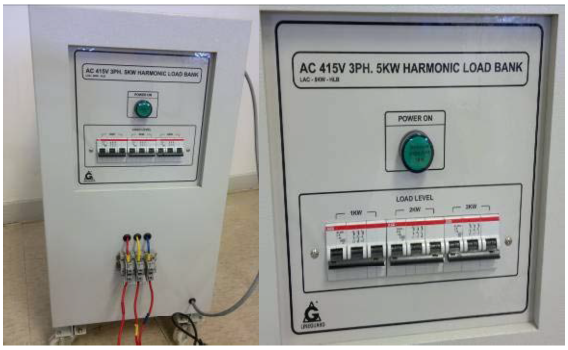

Fig. 6. Variable harmonic load bank

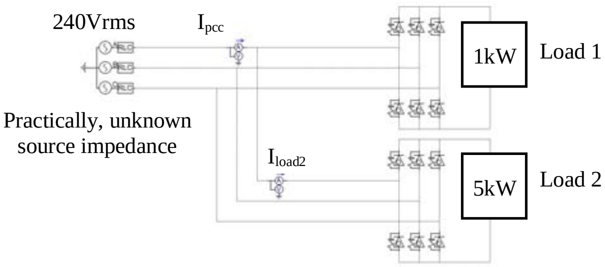

Fig. 7. Experiment schematic

However, Eq. (22) and (23) show the method for the proposed method. The result show the proposed method are similar with actual result. Finally, the experiment result show the proposed method is more accurate than power direction method:

$$P_5 = 1.70 \cdot 1.56 \cdot cos\left(-133-168\right) = \\ = 137\text{W}\left(upstream\right) \tag{20}$$

$$P_7 = 1.60 \cdot 0.70 \cdot cos\left(-42-168\right) = \\ = -0.97\text{W}\left(downstream\right) \tag{21}$$

$$\left|1.90\angle 168° - 1.56\angle 168°\right| < \left|1.56\angle 168°\right| \tag{22}$$

$$\left|0.86\angle 161° - 0.70\angle 161°\right| < \left|0.70\angle 161°\right| \tag{23}$$

TABLE II
PRACTICAL EXPERIMENT RESULT

Measurement point	Order	Voltage	Current	Actual Harmonic Source	Power Direction Method	Proposed Method
($I_{load\,2}$)	1	239.40∠0°	6.68∠0°			
	5	1.70∠-133°	1.56∠168°	Down	Up	Down
	7	1.60∠-42°	0.70∠161°	Down	Down	Down
(I_{pcc})	1	239.40∠0°	8.18∠0°			
	5	1.70∠-133°	1.90∠168°			
	7	1.60∠-42°	0.86∠161°			

VIII. Conclusion

In this paper, a new two point method is proposed for identify the dominant harmonic disturbance at the PCC.

Based on the analysis of the method, the proposed new method is performed 100% (see Fig. 3) accuracy while the power direction is performed accuracy with 50% (see Fig. 2). Moreover, the result in Tables I and II show the proposed new method is more accurate than the power direction method. The proposed new method does not require any data other than the voltage and current waveforms at the measuring point. But the cost of instrument setup required for proposed new method is more than power direction method because the proposed new method needs to take two measurement points at the PCC while power direction only take one measurement point. Taking into account on the advantages and accuracy, the proposed method can be considered as practical, easy to implement and compatible. The proposed method was tested via simulations and experiment. Simulation and experiment results have verified the accuracy of the proposed method. However, further work is needed to investigate the performance of the proposed method by field measurement.

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