Jurnal Teknologi, 43(D) Dis. 2005: 11–32

IDENTIFICATION OF HARMONIC SOURCE AT THE POINT OF COMMON COUPLING BASED ON VOLTAGE INDICES

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Abstract. This paper presents a new method to determine harmonic source either at the utility or the customer based on voltage indices. In the method, both Thevenin and Norton equivalent circuits are first derived for harmonic source identification. Based on these circuits, two cases are analyzed, that is a circuit with a single harmonic source and a circuit with two harmonic sources. In a single harmonic source, harmonic circuit is simplified to a Thevenin equivalent circuit which is used to derive the voltage indices. The voltage measured at the point of common coupling (PCC) is compared with the voltage at the utility sides. In a two harmonic source system, the superposition theorem and Norton equivalent circuits are employed to derive the voltage indices at utility and customer sides based on the voltage and current measurements at the PCC. For both systems, the voltage index based on the higher voltage magnitude is identified as the main harmonic source. Several case studies and a series switching tests are performed in the simulations using the PSCAD/EMTDC program. Comparisons are made with the Critical Impedance (CI) method to verify the accuracy of the proposed method in harmonic source identification. Results proved that the identification of harmonic source at the point of common coupling based on voltage indices is more accurate when compared to the CI method.

Keywords: Harmonic, superposition theorem, harmonic impedance

Abstrak. Kertas kerja ini membentangkan teknik baru untuk mengesan punca gangguan harmonik, samada pembekal atau pengguna. Dalam kaedah ini, litar-litar setara Norton dan Thevenin diperolehi untuk tujuan pengesanan punca gangguan harmonik. Berdasarkan kedua-dua litar setara tersebut, dua kes telah dianalisa iaitu litar yang mempunyai satu punca harmonik dan litar yang mempunyai dua punca harmonik. Di dalam litar yang mempunyai satu punca harmonik, litar setara diringkaskan kepada litar setara Thevenin untuk memperolehi indeks voltan. Voltan yang diperolehi di titik gandingan sepunya (TGS) dibandingkan dengan voltan di pihak pembekal. Di dalam litar yang mempunyai dua punca harmonik, teorem tindihan dan litar setara Norton digunakan untuk menerbitkan indeks voltan daripada bacaan yang diperolehi di titik gandingan sepunya. Beberapa kes dan ujian suis dijalankan menggunakan perisian PSCAD/EMTDC. Perbandingan dilakukan dengan teknik galangan kritikal (GK) untuk membuktikan kesahihan teknik yang dicadangkan dalam pengesanan punca gangguan harmonik. Keputusan yang di perolehi membuktikan teknik pengesanan punca gangguan harmonik berdasarkan indeks voltan lebih baik daripada teknik galangan kritikal (GK).

Kata kunci: Harmonik, teorem tindihan, galangan harmonik

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1.0 INTRODUCTION

Harmonics problem have been a significant issue in three-phase power systems. 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. These loads use diodes, silicon-controlled rectifiers, and power transistors to convert 50/60Hz ac to dc. In Adjustable Speed Drives (ASD), the dc is converted to variable-frequency ac to control a motor speed. 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 system harmonic distortion. To counteract this issue, another more technically important issue has to be solved first, that is, the technique to discriminate utility and customer harmonic contribution at the point of common coupling (PCC).

Harmonic identification at the PCC becomes more complex when the only measurement available are the current and voltage at a single point only. In order to determine the utility and customer harmonic contribution, many methods have been proposed in the literature. The real power direction method [1-3] is the earliest method proposed in identifying harmonic sources. In fact, some power quality monitors use this method to detect the source of harmonic as to whether at the utility side or the customer side. In [4,5], the real power direction method has been found to be only 50 percent reliable should the customer change loads. A better method to clarify interaction between utility and customer harmonic contribution has been used in [6,7]. This 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). References [6,7] developed active harmonic measurement instrument 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 [8]. Reference [5] proposed the superposition-based current and voltage indices to quantify the harmonic sources using a Norton equivalent circuit. In [5], 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 date, the most recent method used to discriminate harmonic contribution at the PCC is the critical impedance method [10]. This method used the critical impedance index to locate the harmonic source. Results based on simulation using the method are presented for comparison in this paper.

This paper presents a method to locate the harmonic source from the measurement at the PCC between utility and customer based on the voltage indices. This principle is similar as the superposition theorem [4,5,9] but to the best of our knowledge, emphasize on voltage indices as harmonic sources location indicator has not been verified in the literature. Two configuration of test system cases are considered in the simulation, which are the system with correction capacitor connected and the system without correction capacitor connected. This paper also employed the single-phase-impedance measurement to obtain the impedance values. The results obtained from simulations are promising for both test configurations using the voltage indices.

2.0 HARMONIC VOLTAGE INDICES AT PCC

For harmonic indices derivation, all values are referred to harmonic component. Harmonic currents at PCC can be from a single source, in which it is from either utility or customer side. On radial utility distribution feeders and industrial plant power systems, the main tendency is for the harmonic currents to flow from the harmonic-producing load to the power system source [11]. Harmonic current at the PCC can also come from both utility and customer sides. Therefore, these two scenarios of harmonic currents flow will be used to derive the harmonic voltage indices at PCC.

2.1 Derivation of Voltage Indices for a Single Source System

The location of harmonic source based on the voltage magnitude considers the equivalent circuit in Figures 1 and 2. In Figure 1, the positive current flow is assumed

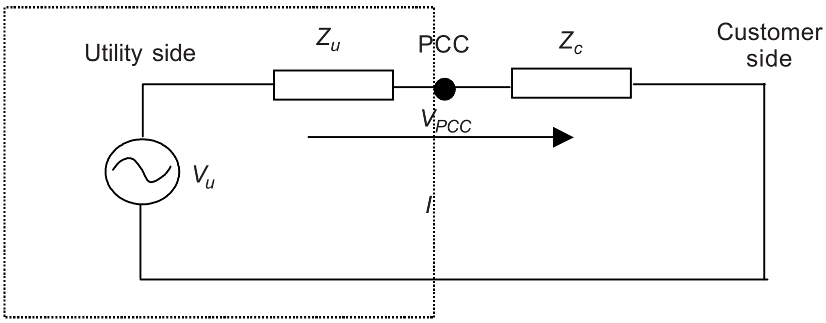

Figure 1 Equivalent circuit for harmonic from utility

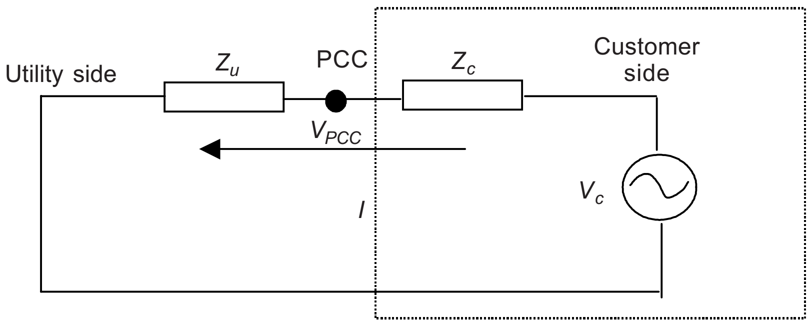

Figure 2 Equivalent circuit for harmonic from customer

from utility to customer. On the other hand, in Figure 2, the positive current flow is assumed from customer to utility.

From Figure 1, assuming a loop circuit where Z_u and Z_c can be both inductive. This means that if the impedances are both inductive, the current I is lagging voltage V_u.

From Figure 1, using Kirchoff's Voltage Law (KVL), the voltage equation is:

$$\bar{V}_u - \bar{I}\left(\bar{Z}_u + \bar{Z}_c\right) = 0 \tag{1}$$

The voltage at PCC is given by,

$$\bar{V}_{PCC} = \bar{V}_u - \bar{Z}_u \bar{I} \tag{2}$$

From Equation (2), when current flows from utility to customer, then the voltage at PCC is lower than V_u due to the voltage drop across Z_u. Similarly, voltage at PCC, V_{PCC} is higher than the voltage at customer, V_c, due to the voltage drop across Z_c.

$$\bar{V}_c = \bar{V}_{PCC} - \bar{Z}_c \bar{I} \tag{3}$$

From Equation (2), it is noted that,

$$|V_u| > |V_{PCC}| \tag{4}$$

Based on the fact that $|V_{PCC}| < |V_u|$ from Equation (2), thus,

$$|V_u| > |V_c| \tag{5}$$

Hence, if $|V_u| > |V_{PCC}|$ or $|V_c| < |V_{PCC}|$ the major harmonic source is from the utility.

On the other hand, when the current I flows from customer to utility as shown in Figure 2, the voltage at PCC is lower than V_c due to the voltage drop across Z_c. Similarly, voltage at PCC, V_{PCC} is higher than the voltage at utility, V_u, due to the voltage drop across Z_u. Hence,

$$\bar{V}_u = \bar{V}_{PCC} - \bar{Z}_u \bar{I} \tag{6}$$

From Equation (6) it is noted that,

$$|V_u| < |V_{PCC}| \tag{7}$$

then,

$$|V_u| < |V_c| \tag{8}$$

Hence, if $|V_u| < |V_{PCC}|$ or $|V_c| < |V_{PCC}|$ the major harmonic source is from the customer.

Therefore, the conditions $|V_u| > |V_{PCC}|$ or $|V_c| < |V_{PCC}|$ and $|V_u| < |V_{PCC}|$ or $|V_c| < |V_{PCC}|$ can be used for harmonic source determination in a distribution system provided that the circuit is only a single loop where Z_u and Z_c can be both inductive and $|V_{PCC}| \neq 0$.

2.2 Derivation of Voltage Indices for a Two Sources System

For a two source system and when the impedance, Z_u is inductive and Z_c is capacitive or vice-versa, the conditions $|V_u| > |V_{PCC}|$ or $|V_C| < |V_{PCC}|$ and $|V_u| < |V_{PCC}|$ or $|V_c| < |V_{PCC}|$ are no longer valid. Thus, for a two source system, a new set of conditions will be derived for harmonic source identification. For a two-sources harmonic, the principle of superposition theorem is employed to derive the voltage magnitudes at the utility and customer side. Equations (9) to (10) are adapted from [5]. Figures 3 and 4 explain the concept of superposition theorem and are followed by the equations that are used to determine the harmonic current at the PCC.

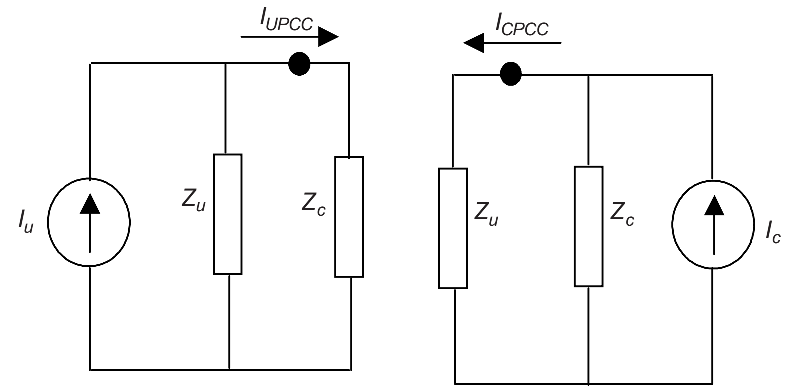

Figure 3 Norton equivalent circuit for utility and customer side

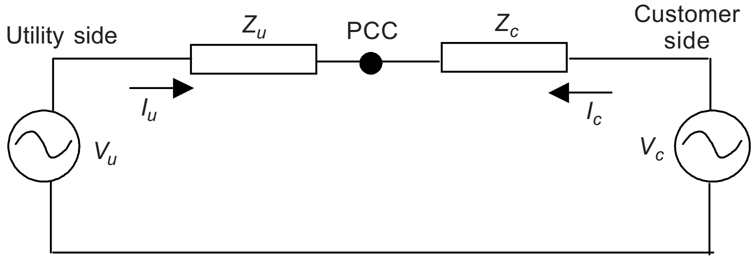

Figure 4 Thevenin equivalent circuit for two-source harmonic

From Figure 3, at the point of common coupling, PCC, the current from the utility can be written as:

$$\bar{I}_{upcc} = \frac{\bar{Z}_u}{\bar{Z}_u + \bar{Z}_c}\bar{I}_u \tag{9}$$

Similarly at the PCC, the current from the customer can be written as:

$$\bar{I}_{cpcc} = \frac{\bar{Z}_c}{\bar{Z}_u + \bar{Z}_c}\bar{I}_c \tag{10}$$

From Figure 3, the voltage at the utility, $|V_u|$ and voltage at the customer, $|V_c|$ is derived as shown in the following equations,

$$|V_u| = |I_u||Z_u| \tag{11}$$

and

$$|V_c| = |I_c||Z_c| \tag{12}$$

These voltages represent the Thevenin voltages for utility and customer respectively and are presented in the Thevenin equivalent circuit of the two-source harmonic in Figure 4. The Thevenin equivalent circuit will be used to generate a new set of conditions for harmonic source identification. Thus, from Figure 4 and by applying Equations (11) and (12), the harmonic contribution by either utility or customer can be obtained by comparing the voltage magnitude due to harmonic at both sides. The conditions for this harmonic source identification can therefore be written as:
If,

$|V_u| > |V_c|$, harmonic source is at the utility side.

On the other hand, if

$|V_c| > |V_u|$, harmonic source is at the customer side.

Even though this concept is adapted from the superposition theorem as in [4,5,9], no results from simulations or real measurement based on the voltage magnitude has been found to be analyzed from the literature. To the best of our knowledge, only results which employed current from Equations (9) and (10) are widely used to identify harmonic source as in [6,7]. The current calculation can be more complicated when several values of impedances from several switching exercices are considered because the numerator will have more combination than the number of switching exercise carried out. The harmonic source identification using indices $|V_u|$ and $|V_c|$ is also practical because to determine the impedance values will involve several places of switching as shown in [10]. Thus, a comparison can be made between the range of

$|V_u|$ and $|V_c|$ from several switching exercises. Thus, with more than one values of $|V_u|$ and $|V_c|$ available, the degree of confidence in the harmonic source identification can be increased using the voltage indices.

2.3 Critical Impedance (CI) Indices

The CI indices are presented in this section to be used as comparisons in this paper. Only the CI indices at the utility side are derived based on equations given in [10]. The equations used to calculate the CI indicator, Z_{crVu} is adapted from [10] as follows, when both Z_u and Z_c are inductive impedance,

$$Z_{crVu} = -2\frac{|V_{pcc}|}{|I_{pcc}|}\sin(\theta + \beta) \tag{13}$$

For Z_u inductive and Z_c capacitive, additional equation is derived as follows,

$$Z_{cr-zc} = Z_{crVu} - |Z_u| \tag{14}$$

where, $\theta = \theta_V - \theta_I$, $\beta = 90° - \alpha$ and $\alpha = tg^{-1} Z_u$. The voltage and current magnitude at the PCC are $|V_{PCC}|$ and $|I_{PCC}|$ respectively. The values are referred to the utility side parameters I_u and Z_u. From Equation (13), it is obvious that the impedance angles will influence the value of the CI indices.

3.0 HARMONIC SOURCE IDENTIFICATION IMPLEMENTATION

Harmonic voltage indices are verified using the current and voltage data obtained at the PCC from simulations carried out on a test system. Switching method is employed to obtain the values of utility and customer impedances. Details of the test system used in this simulation, the utility and customer impedances determination and the procedure for implementing harmonic source identification are described as follows.

3.1 Test System

The test system used to verify the proposed method is shown in Figure 5. Harmonics generated from utility and from customer sides are considered in the simulations. The test system is fed from a 13.8 kV, 15 MVA source at 50 Hz frequency. For a harmonic source from utility side, harmonics are generated by simulating personal computers is injected at bus 14. On the other hand, a harmonic source from customer is injected by means of an adjustable speed drive at bus 5. The simulations are carried out using the electromagnetically transient program PSCAD/EMTDC. Fast Fourier Transform (FFT) is performed to discriminate harmonic component at both utility and customer sides. Current and voltage measurements are carried out at the PCC of Figure 5.

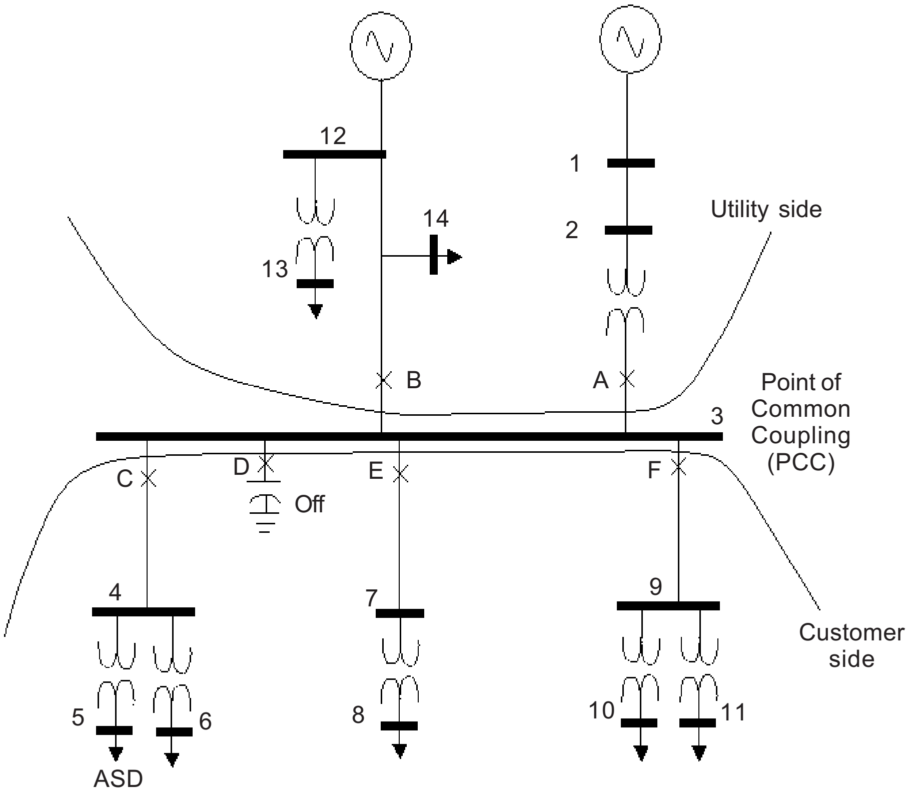

Figure 5 Test system for harmonic source location

3.2 Impedance Determination Using Steady-State Measurements

In this simulation, the values of I_u, Z_u, I_c and Z_c can be obtained by applying the switching method adapted from references [10,12-14]. Details of the switching tests are shown in Table 1 where switching tests at the customer side will provide impedance, Z_u, and current I_u, for the utility whilst switching test at the utility side will provide the impedance, Z_c and current I_c for the customer.

The values of I_u and Z_u for dominant harmonic components at utility side are calculated using the following equations:

$$Z_u = \frac{-\Delta V_h}{\Delta I_h} \tag{15}$$

and

$$I_u = \frac{V_h}{Z_u} + I_h \tag{16}$$

Table 1 Details of switching tests

Test	Operation	Switching at utility side or customer side	Impedance and current to be determined
1	Open line A	Utility	I_c, Z_c
2	Close line A	Utility	I_c, Z_c
3	Open line B	Utility	I_c, Z_c
4	Close line B	Utility	I_c, Z_c
5	Open line C	Customer	I_u, Z_u
6	Close line C	Customer	I_u, Z_u
7	Open line F	Customer	I_u, Z_u
8	Close line F	Customer	I_u, Z_u
9	Switching capacitor in	Customer	I_u, Z_u
10	Switching capacitor out	Customer	I_u, Z_u
11	Open line E	Customer	I_u, Z_u
12	Close line E	Customer	I_u, Z_u

where ΔV_h and ΔI_h are the difference between harmonic voltage and current, respectively for each switching test. On the other hand, the values of I_c and Z_c for dominant harmonic components at customer side are calculated using the following equations:

$$Z_c = \frac{\Delta V_h}{\Delta I_h} \tag{17}$$

and

$$I_c = \frac{V_h}{Z_u} - I_h \tag{18}$$

The harmonic current and voltage data obtained from simulations were then processed by writing MATLAB script files. From Figure 5, switching tests are performed at lines A and B to obtain customer current (I_c) and impedance (Z_c) parameters. Switching tests performed at lines C, D, E and F are for utility side parameters, I_u and Z_u. These multiple switching tests enable the results to be compared and thus can increase the degree of confidence in the harmonic source identification. Figures 6 and 7 present the post disturbance current spectra for sample of switching at the customer side (Test 7) and switching at the utility side (Test 1) respectively. From Figures 6 and 7, it is revealed that there are no significant imbalances among the three phases. Thus, a single-phase-based method for impedance calculation in [14] is acceptable to be used for this simulation.

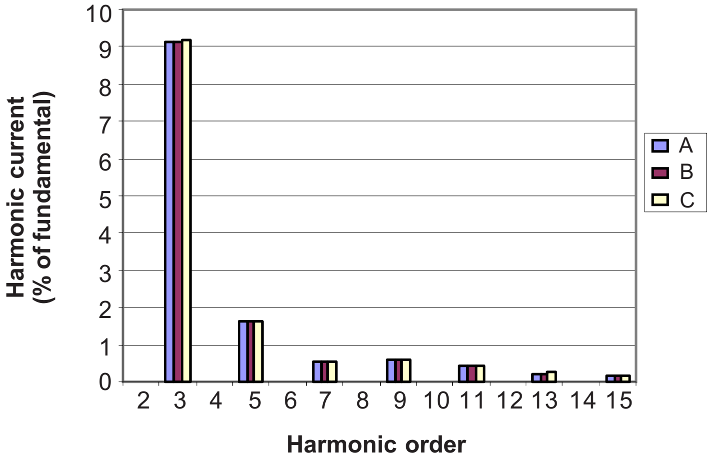

Figure 6 Measured post-disturbance current spectra after switching Test 7

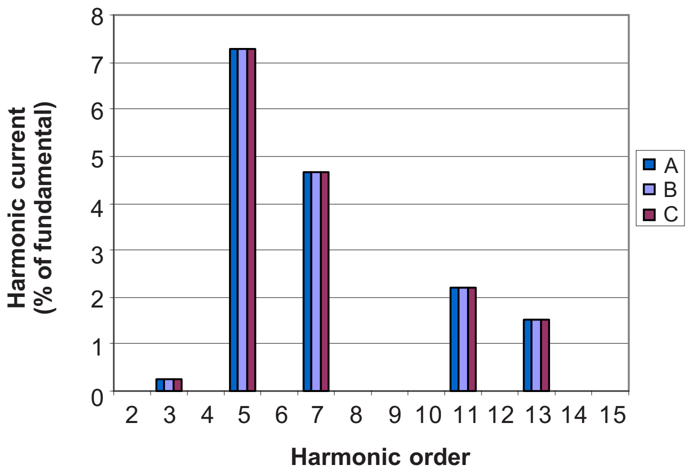

Figure 7 Measured post-disturbance current spectra after switching Test 1

3.3 Implementation of Harmonic Source Identification

The procedures implemented in the proposed method are described as follows:

(i) Measure harmonic voltage and current at PCC. Perform FFT to discriminate the harmonic current component.

(ii) Calculate I_u and Z_u using 15-16 and also I_c and Z_c using 17-18 from harmonic current and voltage data obtained from the switching tests.

(iii) Calculate voltage at the utility side, $|V_u| = |I_u||Z_u|$ or voltage at the customer side, $|V_c| = |I_c||Z_c|$.

(iv) For a single source system without correction capacitor connected, compare the measured harmonic voltage at PCC, $|V_{PCC}|$ and the voltage at the utility, $|V_u|$, or between $|V_{PCC}|$ and the voltage at the customer side $|V_c|$. If $|V_u| > |V_{PCC}|$ or $|V_c| < |V_{PCC}|$, the major harmonic source is from the utility. If $|V_c| > |V_{PCC}|$ or $|V_u| < |V_{PCC}|$, the major harmonic source is from the customer.

(v) For a single source system with correction capacitor connected and a two-source system, compare harmonic voltage at the utility $|V_u|$ and the voltage at the utility the customer side $|V_c|$. If $|V_u| > |V_c|$, the major harmonic source is from the utility. If $|V_c| > |V_u|$ the major harmonic source is from the customer.

4.0 RESULTS

In the following section, results from simulations are presented to verify the theories in section 2. Results based on CI method are also calculated and presented for comparison. Results presented are obtained from simulation of switching tests carried out in the test system. Some switching events do not produce significant change in current and voltage, in which ΔV_h and ΔI_h are zeroes. These conditions do not enable the impedance to be calculated. Therefore, only switching tests, which produce significant change in harmonic voltage and current, are presented in this paper for each case.

4.1 Harmonic from Single Source

In this simulation, the harmonic source is injected at either side of the PCC, utility or customer respectively. Simulations are carried out with and without correction capacitor connected at bus 3 of the system in Figure 5. The objective of implementing these two types of simulations is to find out the effect of correction capacitor on harmonics distortion. Current spectra from FFT will then be used to determine the dominant harmonic component and the most dominant harmonic is selected for harmonic source identification.

4.1.1 Harmonic Source without Capacitor Connected

Simulations are first carried out without connecting correction capacitor at bus 3. The results are shown to illustrate the dominant harmonic, which can be either from the utility or customer side. Figures 8 and 9 show the harmonic current waveform and harmonic current spectrum for harmonics injected at the utility side, respectively. Figures 10 and 11 show the harmonic current waveform and harmonic current spectrum for harmonics injected at the customer side, respectively. The THD_I of harmonic sources from utility and customer sides are presented in Table 2. From the table it is noted that the THD_I to be 9.31% and 9.47% at the PCC for the utility and customer respectively, without the correction capacitor connected. These values are above the limit

Table 2 THD_I without correction capacitor connected

Harmonic source	**THD_I(%)**
From utility	9.31
From customer	9.47

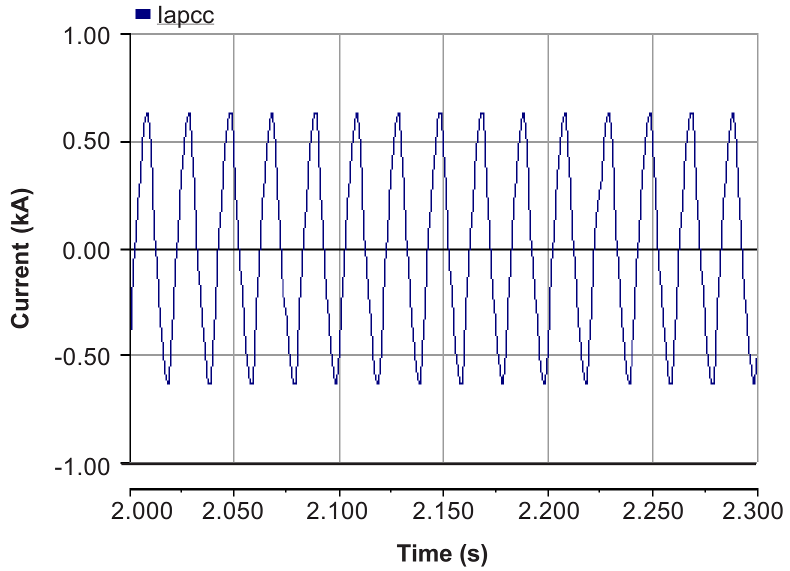

Figure 8 Harmonic current waveform PCC for harmonic injected at the utility side

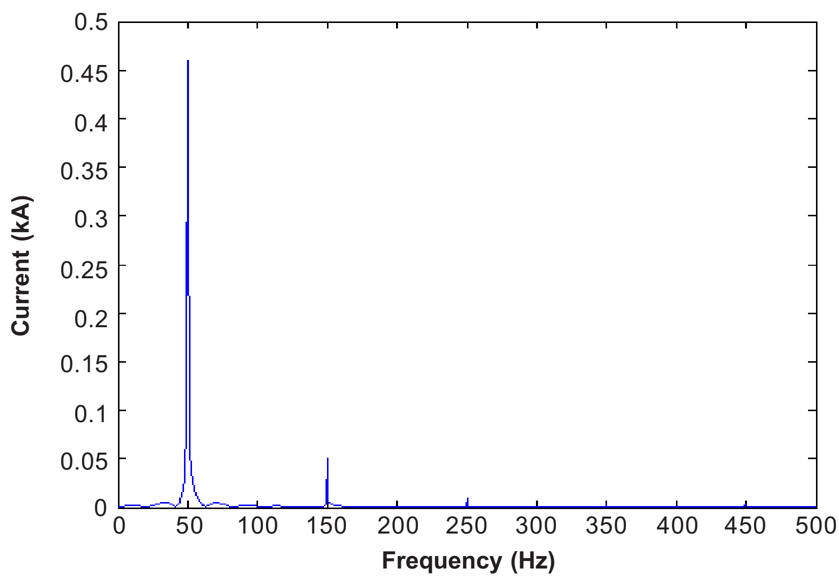

Figure 9 Harmonic spectrum at PCC for harmonic injected at the utility side

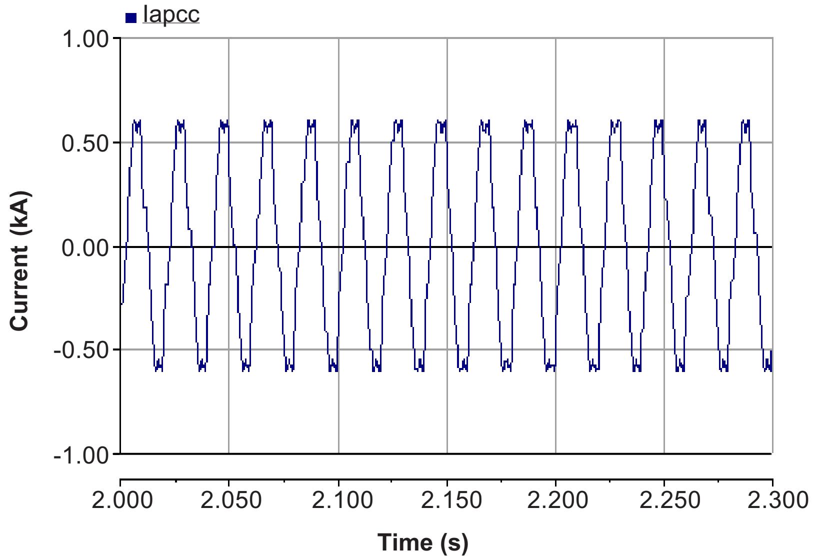

Figure 10 Harmonic current waveform at PCC for harmonic injected at the customer side

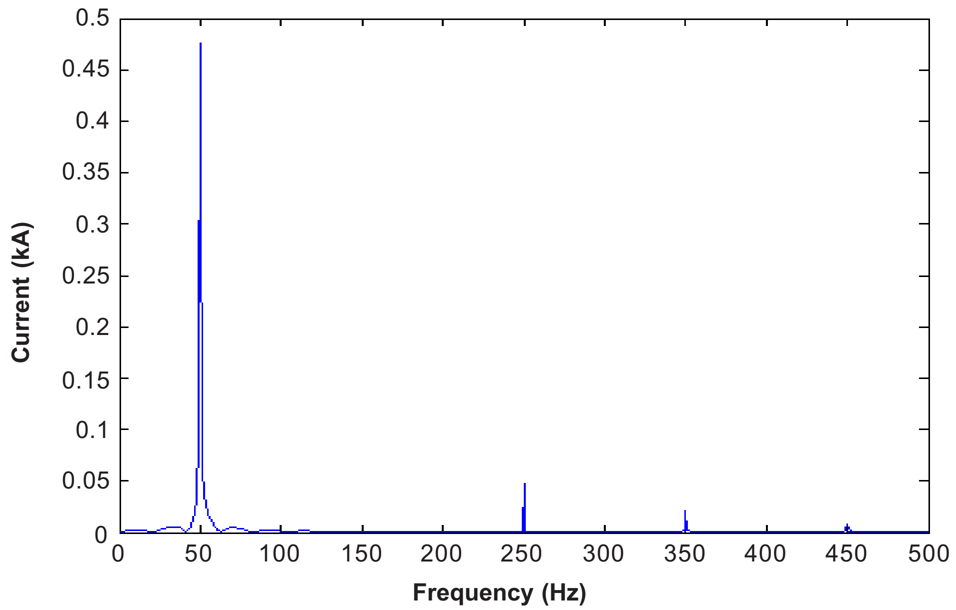

Figure 11 Harmonic current spectrum at PCC for harmonic injected at the customer side

recommended by the IEEE Std. 519-1992, which is 8% for the ratio of the short circuit current to the maximum load current below 50 and voltage below 69 kV. From Figure 9, it is shown that the dominant harmonic component from the utility is the third harmonic. On the other hand, Figure 11 shows that the dominant harmonic component from the customer is the fifth harmonic.

(a) Harmonic source from utility side

Harmonics generated from personal computer models are injected at bus 14 of the test system to simulate harmonics from the utility. The average values of the third harmonic impedance calculated from the switching tests is $Z_c = 14.2879 + j32.1050\Omega$ for the customer side and $Z_u = -0.3632 + j1.8328\Omega$ for the utility side. Both impedances, Z_u and Z_c are inductive. Therefore, the voltage indices at the utility, $|V_u|$ and at the PCC, $|V_{PCC}|$ are used to determine the harmonic source location. Results calculated for voltage magnitudes, $|V_u|$ and $|V_{PCC}|$ for the third harmonic are listed in Table 3. The table also presents the results obtained using the CI method based on Equation (13) for a case when both impedances, Z_u and Z_c are inductive.

From Table 3, it is shown that the current from utility, $|I_u|$ is within the range of 0.48 – 0.74 kA. From the table, the harmonic impedance at the utility side is within 1.88 – 2.98Ω and the harmonic voltage at the utility side, $|V_u|$ is within 1.40 – 1.44 kV. These values are higher than the values of harmonic voltage measured at the PCC, $|V_{PCC}|$ which is 1.33 kV, thus satisfying the condition $|V_u| > |V_{PCC}|$, and therefore indicating that harmonic current is from the utility side. In Table 3, The CI indices are calculated based on the measurement at the utility side. The CI method reveals that for Test 5-7, $|Z_u| > Z_{crVu}$ in which according to the method [10], this statement satisfies the condition that harmonic is from the opposite site of the measuring point, which is the customer which contradict to the actual case. Thus, from the table, only result from Test 8 correctly locate the harmonic source that is at the utility side, when $|Z_u| < Z_{crVu}$ with the CI method. Therefore, results obtained from the Voltage Indices method are a better indicator than the Critical Impedance method.

Table 3 Results of voltage indices and critical impedance indicators for harmonic from utility

			Voltage indices method			**Critical impedance method**	
Test	**$\|I_u\|$ (kA)**	**$\|Z_u\|$ (Ω)**	**$\|V_u\|$ (kV)**	**$\|V_{PCC}\|$ (kV)**	**Voltage index**	**Z_{crVu}**	**CI indicator**
5	0.64	2.22	1.42	1.33	$\|V_u\|>\|V_{PCC}\|$	-70.42	$\|Z_u\|>Z_{crVu}$
6	0.48	2.98	1.44	1.33	$\|V_u\|>\|V_{PCC}\|$	-62.38	$\|Z_u\|>Z_{crVu}$
7	0.74	1.88	1.40	1.33	$\|V_u\|>\|V_{PCC}\|$	-50.11	$\|Z_u\|>Z_{crVu}$
8	0.56	2.49	1.41	1.33	$\|V_u\|>\|V_{PCC}\|$	67.54	$\|Z_u\|<Z_{crVu}$

(b) Harmonic source from customer side

Harmonic generated from ASD models are injected at bus 5 of the test system to simulate harmonics from the customer side. The average values of the fifth harmonic impedance calculated from the switching tests when no correction capacitor connected is Z_u = 1.9846 + j2.8995Ω for the utility side and Z_c = 14.7926 + j52.8502Ω for the customer side. Both Z_u and Z_c are inductive. Results calculated for voltage magnitude V_u for the fifth harmonic are listed in Table 4. Table 4 also present the results obtained using the CI method based on Equation (13) for a case when both impedances, Z_u and Z_c are inductive.

From Table 4, it is obviously shown that the current from utility, $|I_u|$ is within the range of 0.0006 – 0.0098 kA and the harmonic impedance at the utility side is within 2.35 – 3.8Ω. In the table, the harmonic voltage at the utility side, $|V_u|$ is within 0.0002 – 0.037 kV. These values are lower than the voltage measured at the PCC, $|V_{PCC}|$ which is 0.091 kV, thus satisfying the condition that $|V_u| < |V_{PCC}|$, which indicate that harmonic current is from the customer side. The CI method reveals that for Test 5-8, $|Z_u| > Z_{crVu}$ in which according to method [10], this statement satisfies the condition that harmonic is from the opposite side, which is the customer.

Table 4 Results of voltage indices and critical impedance indicators for harmonic from customer

			Voltage indices method			**Critical impedance method**	
Test	$\|I_u\|$ **(kA)**	$\|Z_u\|$ **(Ω)**	$\|V_u\|$ **(kV)**	$\|V_{PCC}\|$ **(kV)**	**Voltage index**	Z_{crVu}	**CI indicator**
5	0.0098	3.8	0.037	0.091	$\|V_u\|<\|V_{PCC}\|$	-5.30	$\|Z_u\|>Z_{crVu}$
6	0.0098	2.35	0.023	0.091	$\|V_u\|<\|V_{PCC}\|$	-4.86	$\|Z_u\|>Z_{crVu}$
7	0.0006	2.76	0.0002	0.091	$\|V_u\|<\|V_{PCC}\|$	-3.00	$\|Z_u\|>Z_{crVu}$
8	0.0006	2.76	0.0002	0.091	$\|V_u\|<\|V_{PCC}\|$	-3.05	$\|Z_u\|>Z_{crVu}$

4.1.2 Harmonic Source with Correction Capacitor Connected

In this section, simulations results are presented when a correction capacitor is connected at bus 3 of the test system. The THD_I when the correction capacitor is present in the circuit is shown in Table 5. From the table, the THD_I at the utility and customer are noted to be 111% and 35%, respectively. These values are higher compared

Table 5 THD_I with correction capacitor connected

Harmonic source	THD_I **(%)**
From utility	111
From customer	35

to the THD_I with no correction capacitor placed in the circuit in Table 2 because the parallel and series resonance exist between capacitor reactance and the network inductance. These resonance will cause an amplified current to oscillate between energy storage in the inductance and the energy storage in the capacitance.

(a) Harmonic source from utility side

The average values of the third harmonic impedance calculated from the switching tests when correction capacitor is connected is Z_u = -0.4917 + j2.4777Ω for the utility side and Z_c = 2.4647 – j14.03Ω for the customer side. Hence, it is shown that Z_u is inductive whilst Z_c is capacitive, thus the condition used to compare $|V_{PCC}|$ and $|V_u|$ cannot be used because it is only valid when both impedances are inductive. The customer impedance is capacitive due to the effect of the correction capacitor connected at the customer side. Hence, to determine the source of harmonic in this case requires the knowledge of both parameters at the utility and customer sides and by using these parameters, both $|V_u|$ and $|V_c|$ are calculated and listed in Table 6.

Table 6 Results of voltage indices for harmonic from utility

Test	$\|I_c\|$ (kA)	$\|Z_c\|$ (Ω)	$\|V_c\|$ (kV)	Test	$\|I_u\|$ (kA)	$\|Z_u\|$ (Ω)	$\|V_u\|$ (kV)
1	0.00094	14.37	0.014	5	0.456	2.58	1.18
2	0.00096	14.37	0.014	6	0.484	2.47	1.19
3	0.0013	14.12	0.018	7	0.456	2.58	1.18
4	0.0013	14.12	0.018	8	0.484	2.47	1.19

From Table 6, it is shown that the current from customer, $|I_c|$, is within the range of 0.00094 – 0.0013 kA and the values of the current from utility, $|I_u|$ is within the range of 0.456 – 0.484 kA. From the table, the harmonic impedance at the customer side is within a small range of 14.12 – 14.37Ω and the harmonic impedance at the utility side are within 2.47 – 2.58Ω. In Table 6, the harmonic voltage at the customer side, $|V_c|$ is within 0.014 – 0.018 kV and the values of harmonic voltage at the utility side, $|V_u|$ is within the range of 1.18 – 1.19 kV, thus satisfying the condition $|V_u| > |V_c|$. Thus, this indicates that harmonic is from the utility side.

The harmonic source location is also determined using the CI method. For a case when Z_u and Z_c are inductive and capacitive respectively, Equation (14) is employed to calculate the CI index. Since the equation employs the value of utility impedance, Z_u only, Tests 5-8 are used in the CI method. The results for CI method are listed in Table 7. From the table, it is obvious that only results from Tests 5 and 8 satisfy the condition that harmonic source is at the utility side. Therefore, it is shown that the CI method does not 100% correctly locate the harmonic source from the switching tests available.

Table 7 Results of critical impedance indices s for harmonic from utility

Test	$\lvert Z_{cr\text{-}zc} \rvert$	$\lvert Z_u \rvert$	$\lvert Z_c \rvert$	CI indicator
5	29.53	2.59	14.25	$\lvert Z_u\rvert<\lvert Z_c<\lvert Z_{cr\text{-}zc}\rvert$
6	6.17	4.38	14.25	$\lvert Z_u\rvert<\lvert Z_c\rvert$
7	8.42	2.56	14.25	$\lvert Z_u\rvert<\lvert Z_c\rvert$
8	25.16	2.47	14.25	$\lvert Z_u\rvert<\lvert Z_c<\lvert Z_{cr\text{-}zc}\rvert$

(b) Harmonic source from customer side

Harmonic is also injected at the customer side by injecting ASD current model at bus 5 and the average values of the fifth harmonic impedance calculated from the switching tests when correction capacitor is connected is $Z_u = 0.465 + j3.639\Omega$ for the utility side and $Z_c = 0.304 - j7.253\Omega$ for the customer side. Hence, it is shown that Z_u is inductive whilst Z_c is capacitive. Thus condition for using a single source harmonic location cannot be used. The customer impedance is capacitive and it is due to the effect of the correction capacitor connected at the customer side. Hence, to determine the source of harmonic source, both parameters at the utility and customer sides have to be known. Thus, $\lvert V_u\rvert$ and $\lvert V_c \rvert$ are calculated and the results are listed in Table 8.

Table 8 Results of voltage indices for harmonic from customer

Test	$\lvert I_c\rvert$ (kA)	$\lvert Z_c\rvert$ (Ω)	$\lvert V_c\rvert$ (kV)	Test	$\lvert I_u\rvert$ (kA)	$\lvert Z_u\rvert$ (Ω)	$\lvert V_u\rvert$ (kV)
1	0.039	7.13	0.278	5	0.026	4.86	0.125
2	0.039	7.21	0.283	6	0.024	4.38	0.107
3	0.036	7.35	0.260	7	*	*	*
4	0.036	7.35	0.260	8	*	*	*

* value is too small

From Table 8, it is shown that the current from customer, $\lvert I_c\rvert$, is within the range of 0.036 – 0.039 kA and the value of the current from utility, $\lvert I_u\rvert$ is within the range of 0.024 – 0.026 kA. From the table, the harmonic impedance at the customer side is within a small range of 7.13 - 7.35Ω and the harmonic impedance at the utility side is within the range of 4.38 – 4.86Ω. In Table 8, the harmonic voltage at the customer side, $\lvert V_c\rvert$ is within 0.260 – 0.283 kV whilst the values of harmonic voltage at the utility side are within the range of 0.107 – 0.125 kV. These results satisfy the condition $\lvert V_c\rvert > \lvert V_u\rvert$, which correctly indicate harmonic is from the customer side.

The harmonic source location is also determined using the CI method. For a case when Z_u and Z_c are inductive and capacitive respectively, Equation (14) is employed to calculate the CI index. Since the equation employs the value of utility impedance only, Tests 5-6 are used for the CI indicator. The results for CI method are listed in Table 9. From the table, it is shown that both results from Tests 5 and 6 satisfy the condition that harmonic source is at the opposite side, which is the customer.

Table 9 Results of critical impedance indices for harmonic from customer

Test	$\lvert Z_{cr\text{-}zc}\rvert$	$\lvert Z_u\rvert$	$\lvert Z_c\rvert$	CI indicator
5	10.21	4.86	7.26	$\lvert Z_u\rvert<\lvert Z_c\rvert$
6	7.96	4.38	7.26	$\lvert Z_u\rvert<\lvert Z_c\rvert$

4.2 Harmonics From Two Sources

Harmonic are also injected at both utility and customer sides by connecting PC models at bus 14 and ASD models at bus 5. Figure 12 shows the harmonic current spectra when harmonics are injected at both utility and customer sides. From the figure, it is shown that the third harmonic is the most dominant and is followed by the seventh harmonic. Thus, the third harmonic is considered to be analyzed in locating the harmonic source.

From the switching tests carried out at both sides, the average values of the third harmonic impedance is Z_u = -1.333 +j3.735Ω for the utility side and Z_c = 2.28 + j29.77Ω for the customer side. Both Z_u and Z_c are inductive. For a two sources system, both parameters at the utility and customer sides have to be known for harmonic source location. The voltages at both utility, $\lvert V_u\rvert$ and customer $\lvert V_c\rvert$ are calculated and the results are listed in Table 10.

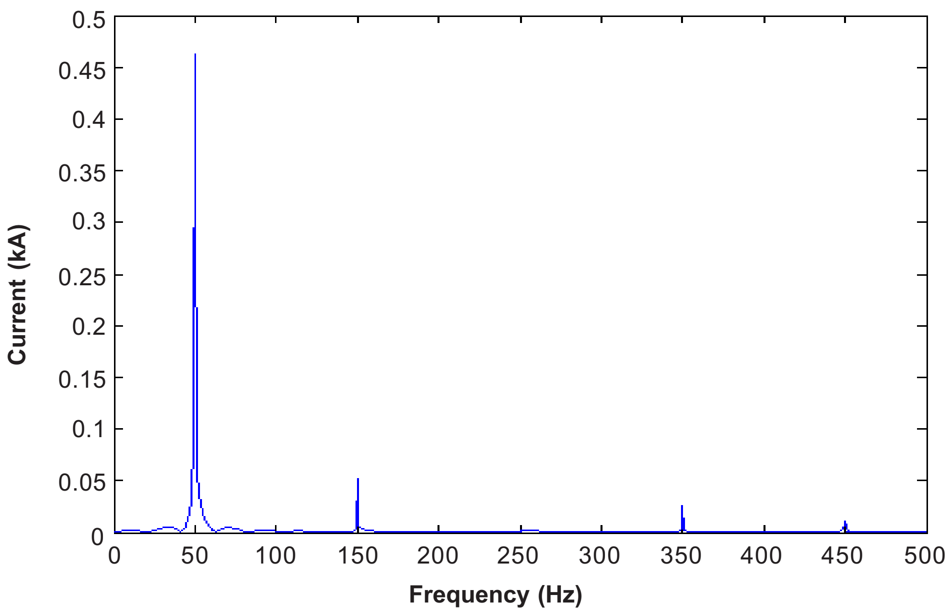

Figure 12 Harmonic current spectrum at PCC for harmonic injected at both utility and customer side

Table 10 Results of voltage indices for harmonic from both sides

Test	$\lvert I_c \rvert$ (kA)	$\lvert Z_c \rvert$ (Ω)	$\lvert V_c \rvert$ (kV)
1	0.0028	32.18	0.09
2	0.0028	32.22	0.09
Test	$\lvert I_u \rvert$ (kA)	$\lvert Z_u \rvert$ (Ω)	$\lvert V_u \rvert$ (kV)
5	0.4493	3.206	1.44
6	0.4479	2.990	1.43
7	0.2827	5.15	1.46
8	0.2827	5.10	1.44
11	0.5594	2.53	1.42
12	0.5779	2.44	1.41

From Table 10, it is shown that the current from customer, $\lvert I_c \rvert$, is 0.0028 kA and the value of the current from utility, $\lvert I_u \rvert$ is within the range of 0.2827 – 0.5779 kA. From the table, the harmonic impedance at the customer side is 32.18 – 32.22Ω whilst the harmonic impedance at the utility side is within 2.99 – 5.10Ω. In Table 10, the harmonic voltage at the customer side, $\lvert V_c \rvert$ is 0.09 kV and the values of harmonic voltage at the utility side is within the range of 1.43 – 1.46 kV, thus satisfying the condition $\lvert V_u \rvert > \lvert V_c \rvert$. This indicates harmonic is from utility. Harmonic spectra from Figure 6 shows that the main third harmonic component is from utility. Thus, the results in Table 10 satisfy this condition. Since both impedances are inductive, thus for CI method, Equation (13) is employed to calculate the critical impedance in this situation. The results for CI method are listed in Table 11 and it is shown that only results from Tests 5,7,8 and 11 satisfy the condition, $\lvert Z_u \rvert < Z_{crVu}$ in which harmonic source is at the utility side. On the contrary, Tests 6 and 12 satisfy the condition $\lvert Z_u \rvert > Z_{crVu}$ which indicates the harmonic source is from the customer. Therefore, from this two test system, the CI method has been found does not 100% locate the harmonic source correctly.

Table 11 Results of critical impedance indices for harmonic from both sides

Test	Z_{crVu}	$\lvert Z_u \rvert$	CI indicator
5	57.18	3.21	$\lvert Z_u \rvert < Z_{crVu}$
6	-26.40	2.99	$\lvert Z_u \rvert > Z_{crVu}$
7	20.13	5.15	$\lvert Z_u \rvert < Z_{crVu}$
8	58.10	5.10	$\lvert Z_u \rvert < Z_{crVu}$
11	13.78	2.53	$\lvert Z_u \rvert < Z_{crVu}$
12	-69.85	2.44	$\lvert Z_u \rvert > Z_{crVu}$

4.3 Comparison of Harmonic Source Using Critical Impedance Method and Voltage Magnitude Method

From the results presented, comparisons can be made between the Voltage Indices Method and the Critical Impedance Method. Comparisons between these methods are presented in Table 12.

Table 12 Comparison of harmonic source location using Critical Impedance Method (CIM) and Voltage Magnitude Method (VOM)

Method	Critical Impedance Method	Voltage Indices (VI) Method
1	The CI method is very sensitive to voltage, current and impedance angles. A slight error in these angles will effect the harmonic source detection.	The VI method depends on magnitude of harmonic current and impedance rather than the angle.
2	Two different indices are required for inductive and capacitive impedances, thus require the knowledge of the nature of the circuit, inductive or capacitive.	Require both values of impedances to determine harmonic source location in a two-source system. Similar indices, V_u and V_c can be used in all cases.
3	More complicated and need more computational process.	Less complicated and need less computational process.

5.0 CONCLUSIONS

This paper has presented a new method based on the voltage indices to locate the harmonic source with a constraint that the measuring point is at the PCC only. The results obtained using Voltage Indices compared with the Critical Impedance method reveal that the former is superior to the latter. The error in CI method is most likely due to its dependency on the angle measurement used in the calculation. Other findings of this paper are listed as follows:

(1) Capacitor connected in the circuit influences the nature of the circuit, in which the impedance, Z_c is found to be capacitive.
(2) Voltage indices between $|V_u|$ and $|V_{PCC}|$ can be used if both impedances are inductive in a single harmonic system.
(3) Voltage indices between $|V_u|$ and $|V_c|$ can be used irrespective to the nature of the circuit impedance, when one of them is inductive or capacitive and also when both are inductive.
(4) Critical Impedance method cannot be used straightforward if the nature of circuit, either it is inductive or capacitive is not known.

(5) A single-phase-based method for impedance calculation in [14] has been proven to be acceptable to be used when no significant imbalanced is found among the three phases.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Universiti Teknologi MARA for the financial support in terms of scholarship and Universiti Kebangsaan Malaysia (IRPA code 02-02-0014-EA188) for the financial support on the project.

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