

Accurate harmonic source identification using S-transform

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ABSTRACT

This paper introduces the accurate identification of harmonic sources in the power distribution system using time-frequency distribution (TFD) analysis, which is S-transform. The S-transform is a very applicable method to represent signals parameters in time-frequency representation (TFR) such as TFR impedance (Z_{TFR}) and the main advantages of S-transform it can provide better frequency resolution for low frequency components and also offers better time resolution for high-frequency components. The identification of multiple harmonic sources are based on the significant relationship of spectral impedances (Z_S) that extracted from the Z_{TFR} , consist of the fundamental impedance (Z_l) and harmonic impedance (Z_h). To verify the accuracy of the proposed method, MATLAB simulations carried out several unique cases on IEEE 4-bus test feeder cases. It is proven that the proposed method is superior, with 100% correct identification of harmonic source location. It is proven that the method is accurate, fast and cost-efficient to localize harmonic sources in the power distribution system.

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1. INTRODUCTION

As the power quality (PQ) issues caused mainly by harmonics directly affect the overall continuation of electric transmission and distribution network, the uninterrupted monitoring of electric power systems (EPSs) has become highly necessary for the utility industry [1, 2]. The harmonic distortion causes several adverse effects such as overheating of rotational machines, static machines, and current-carrying conductors. Furthermore, it causes premature breakdown or action of protecting appliances and harmonic resonance situations on the customers' EPS and metering imprecisions [2, 3].

In EPS, multiple harmonic sources can be found at the utility side, which known as upstream and downstream when harmonic sources located at the customer side with respect to a measurement point of point of common coupling (PCC) [4, 5]. Previously, numerous of harmonic source identification can be found in many kinds of literature. The earliest technique to localize the harmonic sources is utilizing power direction technique. However, this method used limited harmonic power-based indices, whereas mathematical analysis has shown the power direction method is not suitable for harmonic source detection [6, 7]. Furthermore, a state

estimation method is presented with the accomplishment of least square and Kirchhoff current law [8]. Yet, a study from [9], explained that the state estimation technique requires numerous measurement devices and unreasonable setup cost for the large power system. Thus, to overcome the previous constraint, the critical impedance method is introduced [10, 11]. The main disadvantage of this method is to know the value of source internal impedances of customer and utility, whereas it is difficult to obtain these parameters without switching tests [12, 13]. Consequently, a harmonic current vector method is introduced due to solving the previous method drawback. However, the measurement long-drawn-out and hard to analyze harmonic impedances at the customer side [14-16].

In the previous studies [17-20], the harmonic source estimation is discussed by applying the Bayesian estimation and harmonic state estimation (HSE). Unfortunately, this technique involves high computational complexity and the set-up cost of the distributed measurement system station is very expensive [5, 21, 22]. In real-time, accuracy, fast analysis and low cost are essential. Therefore, the limitation of previous analysis techniques can be solved by using signal processing techniques such as fast fourier transform (FFT), spectrogram and S-transform [2].

A harmonic source identification using FFT is introduced to provide fast analysis in determining the location of harmonic sources in the EPS. The significant relationship of spectral impedance, which are fundamental and harmonic impedance are used due to identify the harmonic location of the harmonic source [23, 24]. However, the drawback of the FFT technique, such as the signal information, for instance, amplitude frequencies and phases, cannot be acquired correctly. This is because of the leakage, aliasing effects, and picket fence formed by the FFT [25-27]. As a result of the FFT limitation, the spectrogram is presented to identify the harmonic source location [28]. Conversely, the spectrogram has two main disadvantages. First, its time-frequency resolution is limited by Heisenberg's Uncertainty Principle. Secondly, both its energy location in the time-frequency representation and its resolution can vary with the window selected [29-32].

The S-transform is the advancement of wavelet transform (WT) and short-time fourier transform (STFT) by its variable window and phase correction, respectively. Similar to WT, it offers an improved time and frequency representation of a signal. Additionally, the scalable and movable Gaussian window properties of the ST can be utilized for superior recognition of any power quality events [2, 33-35]. Due to the excellent features of the S-transform in power quality analysis, it is a necessity to perform an analysis of identifying the location of the harmonic sources using this technique. In this paper, the S-transform is proposed to identify the location of the harmonic source in the distribution system with a single-point measurement approach at the point of common coupling (PCC). S-transform is a technique that uses time-frequency analysis to distinguish the signals in time and frequency representation (TFR) [36, 37]. The S-transform is proposed because it is able to provide provides better frequency resolution for low-frequency components and also offers better time resolution for high-frequency components.

2. PROPOSED METHOD

Harmonic current source type-load is selected as a frequent and widely use of harmonic producing loads in industrial [38, 39]. A time-frequency analysis which is used in this research is the S-transform. Three steps are proposed in this method. Firstly, measurement of voltage and current at the PCC. Secondly, these signals are analyzed using S-transform due to obtain the signal parameters in time-frequency representation (TFR) plane. Thirdly, the spectral impedance components are extracted from the TFR impedance and the significant relationship of these components are used in identifying the harmonic source location.

2.1. S-transform

S-transform combines the element of wavelet transform (WT) and the short-time fourier transform (STFT), which inherits the advantage of WT and STFT in signal processing. In particular, ST employs a moving and scalable localizing Gaussian window in the transformation process. The Gaussian window is as shown in (2). Mathematically ST can be defined as [29],

$$ST(\tau, f) = \int_{-\infty}^{\infty} x(t) \frac{|f|}{\sqrt{2\pi}} e^{-\frac{(\tau-t)^2 f^2}{2}} e^{-j2\pi f t} dt \quad (1)$$

$$g(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}} \quad (2)$$

$$\sigma(f) = \frac{1}{|f|} \quad (3)$$

where $x(t)$ is the signal, t is the time, f is the frequency, $g(t)$ is the scalable Gaussian window, and $\sigma(f)$ is a parameter that controls the position of the Gaussian window.

2.2. Signal parameters

The parameters of power quality signals are extracted from the TFR to provide the information of the signal in time.

2.2.1. Instantaneous total non-harmonic distortion

Total harmonic distortion, THD, is used to measure of how much harmonic content in a waveform [40]. The instantaneous total harmonic distortion of a waveform is defined mathematically as (4),

$$THD(t) = \frac{\sqrt{\sum_{h=2}^H V_{h,rms}(t)^2}}{V_{1,rms}(t)} \quad (4)$$

where $V_{h,rms}(t)$ is RMS harmonic voltage and $V_{1,rms}(t)$ is RMS fundamental voltage. The instantaneous total harmonic distortion of a waveform is defined mathematically as.

2.2.2. Instantaneous total non-harmonic distortion

Besides harmonic, a signal also contains interharmonic components that are not multiple integers of the power system frequency [27]. Referring to this as the instantaneous total nonharmonic distortion, ($TnHD(t)$), then for this parameter is written as (5).

$$TnHD(t) = \frac{\sqrt{V_{rms}(t)^2 - \sum_{h=0}^H V_{h,rms}(t)^2}}{V_{1,rms}(t)} \quad (5)$$

2.3. Spectral impedance

The spectral impedance (Z_S) components are extracted from the TFR impedance (Z_{TFR}). The Z_{TFR} can be calculated using equation at each harmonic frequency and the values then plotted. The Z_{TFR} is expressed as (6) [13].

$$Z_{TFR} = \frac{S_V(t,f)}{S_I(t,f)} \quad (6)$$

where $S_V(t,f)$ is the TFR of voltage and $S_I(t,f)$ is the TFR of current. The spectral impedance consists of a fundamental impedance (Z_f), whereas the harmonic impedance (Z_h) is a harmonic impedance at the order number of harmonic.

2.4. Implementation of proposed method

In most recent studies, suggest the execution of the proposed technique can be realized as depicts in Figure 1 (a) and Figure 1 (b) using IEEE 4-bus test feeders, while the harmonic source is modeled as an inverter-based load, which is known as harmonic current source type-load [41-43], where N is a linear load, which is a resistor whereas H is a harmonic source. Besides, four specific cases are considered in this research, such as [15 , 44, 45]:

- Case 1: No harmonic source in the power network system
- Case 2: Harmonic source at downstream of the PCC
- Case 3: Harmonic sources at upstream and downstream of the PCC
- Case 4: Harmonic source at upstream of the PCC

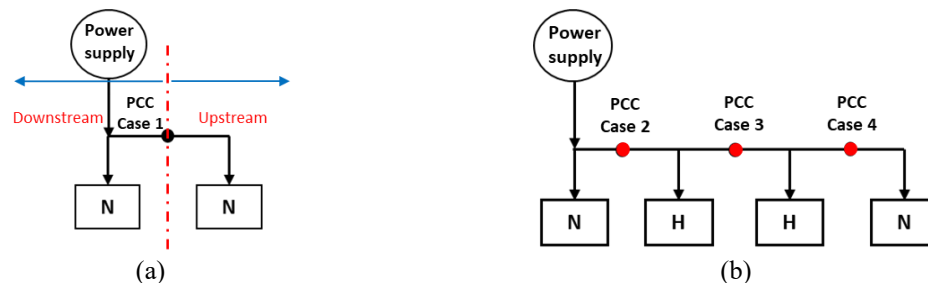


Figure 1. (a) Upstream-downstream for case 1, (b) IEEE 4-bus test feeders for case 2, 3 and 4

3. RESULTS AND ANALYSIS

In this section, it is explained the results of the research and at the same time is given the comprehensive discussion. Results can be presented in figures and tables.

3.1. Case 1: No harmonic source in the power network system

The linear load, which is resistive loads, are located upstream and downstream of the PCC. As can be seen in Figures 2 (a) and (b) show the measured voltage and current signals in the time domain. The peak voltage is 326.5 V. In contrast, the peak current is 66.5 A, respectively. Besides, Figure 2 (c) shows the $THD(t)$ and $TnHD(t)$ of voltage and both parameters are zero percent. Meanwhile, Figure 2 (d) presents the $THD(t)$ and $TnHD(t)$ of current and both parameters are zero percent too. It shows that the voltage and current signal have neither harmonic nor interharmonic components. Figure 2 (e) shows the Z_{TFR} of the PCC, while Figure 2 (f) presents the Z_S . The most striking result from Z_S , it is shown that the Z_1 at 50 Hz is of 4.8 ohm and no harmonic impedances exist. Thus, for case 1, the significant relationship between Z_l and Z_h at the condition of no harmonic source in the power system network, where for harmonic component, h is any positive integer whereas, for interharmonic, h is any positive non-integer. can be written as:

$$Z_1 \neq 0 \text{ ohm} \tag{7}$$

$$Z_h \neq 0 \text{ ohm} \tag{8}$$

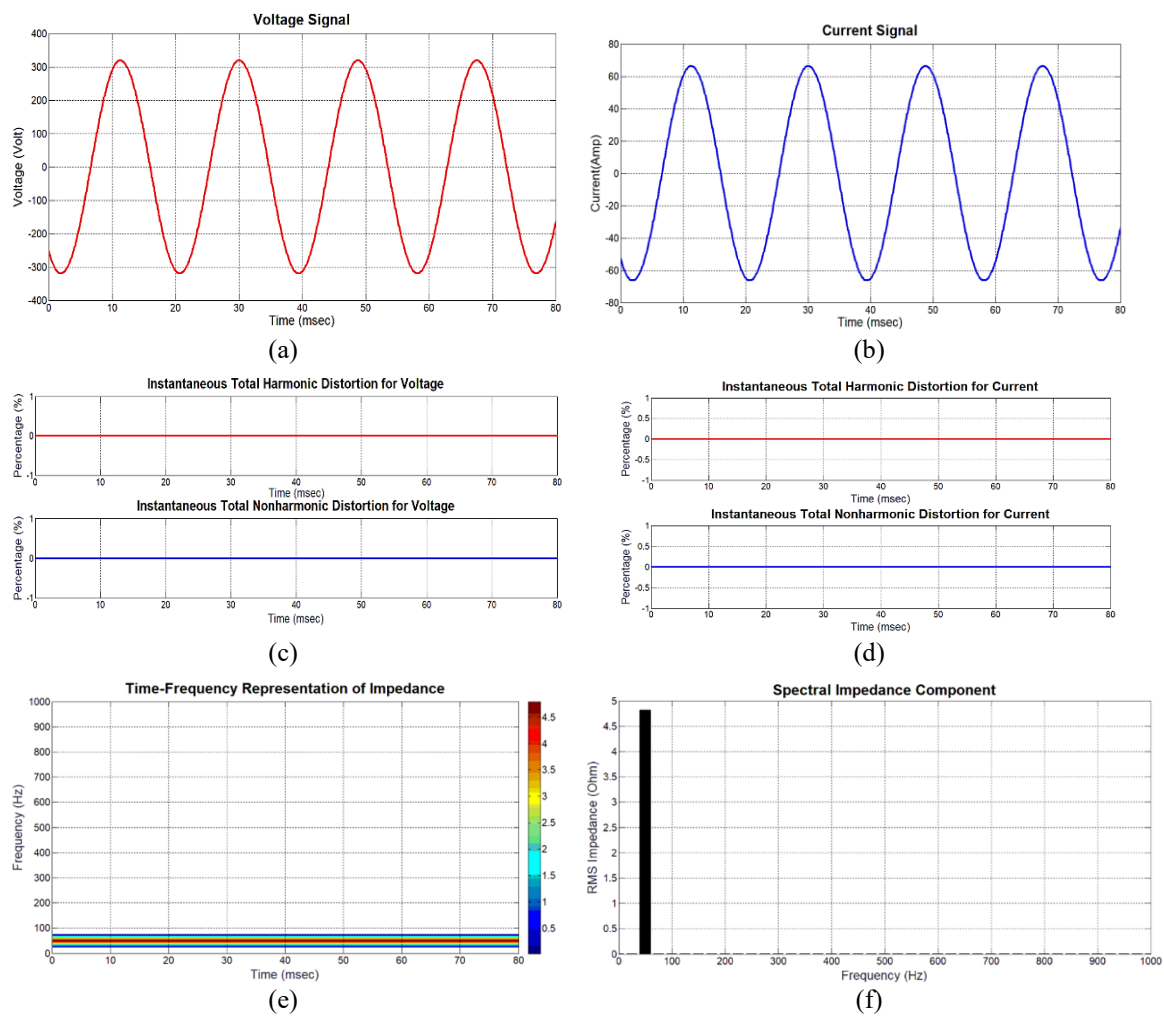


Figure 2. Case 1; (a) voltage signal in time domain, (b) current signal in time domain, (c) $THD(t)$ and $TnHD(t)$ of voltage, (d) $THD(t)$ and $TnHD(t)$ of current, (e) TFR of impedance (Z_{TFR}), (f) spectral impedance component

3.2. Case 2: Harmonic source at downstream of the PCC

For case 2, the harmonic source is located downstream of the PCC. As can be seen in Figure 3 (a) and Figure 3 (b) show the measured voltage and current signals in the time domain. The peak voltage is 326.5 V. In contrast, the peak current is 66.5 A, respectively. In addition, Figure 3 (c) shows the $THD(t)$ and $TnHD(t)$ mean of voltage are 1.51% and 6.05%, respectively. In the meantime, Figure 3 (d) presents the $THD(t)$ and $TnHD(t)$ mean of current, which are 1.67% and 6.68%, respectively. The values of $THD(t)$ and $TnHD(t)$ show

that the voltage and current signals do have harmonic and interharmonic components. Figure 3 (e) shows the Z_{TFR} of the PCC and the Z_S is obtained by extracting the parameters from the Z_{TFR} . Meanwhile, Figure 3 (f) presents the Z_S that consists of the Z_l . In contrast the harmonic impedance consists of Z_{275} , Z_{375} , Z_{600} , Z_{700} , Z_{825} and Z_{900} , respectively. It is crucial to observe the relationship of Z_S components due to identify the harmonic source location in the power system network. Interestingly, as shown in Table 1, the Z_l value at 50 Hz, is always higher than any Z_h . Thus, for case 2, the significant relationship between Z_l and Z_h at the condition of the harmonic source located at downstream of the PCC can be concluded and written as:

$$Z_1 \neq 0 \text{ ohm} \tag{9}$$

$$Z_h < Z_1 \tag{10}$$

where for harmonic component, h is any positive integer whereas, for interharmonic, h is any positive non-integer.

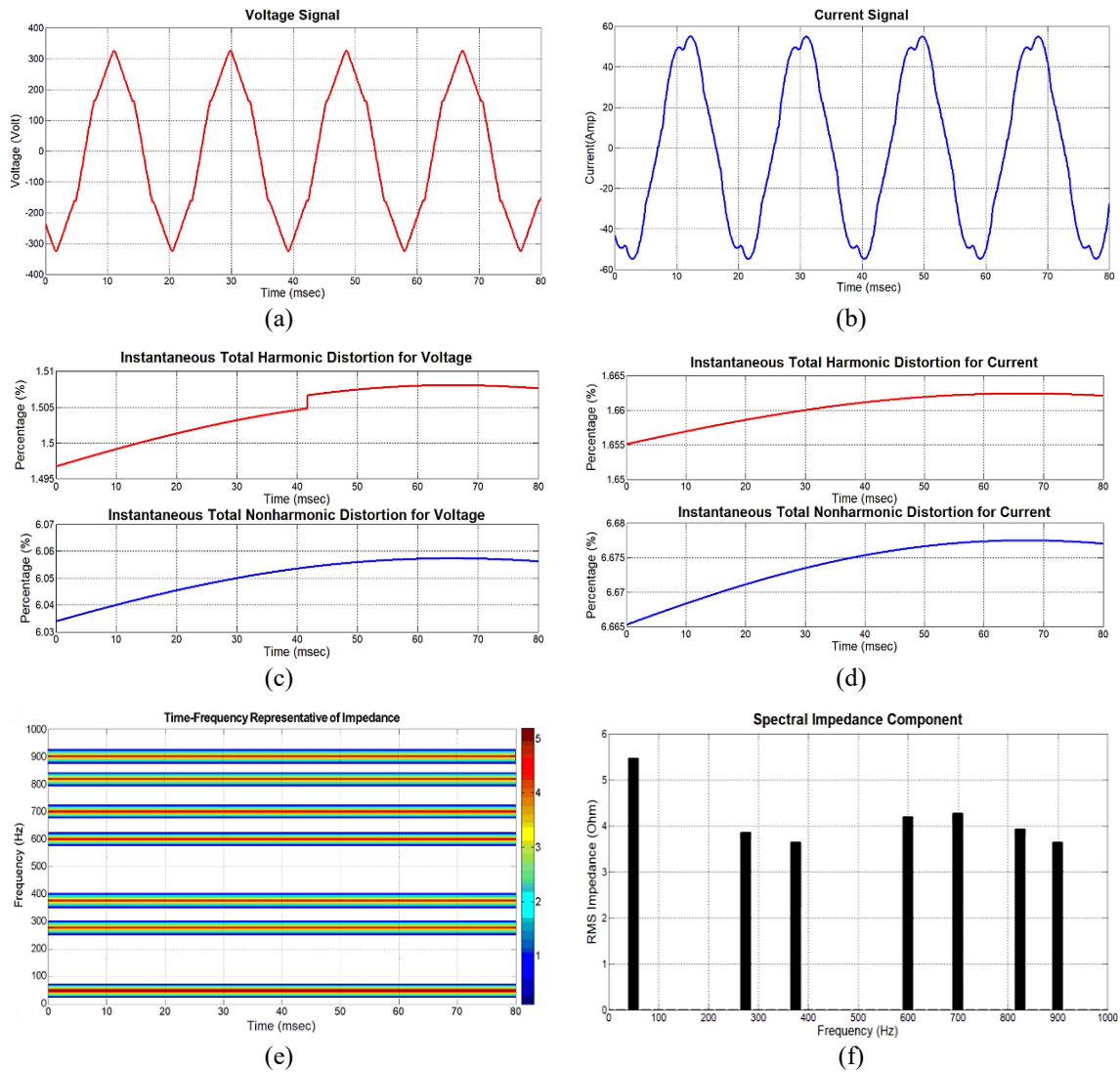


Figure 3. Case 2; (a) voltage signal in time domain, (b) current signal in time domain, (c) $THD(t)$ and $TnHD(t)$ of voltage, (d) $THD(t)$ and $TnHD(t)$ of current, (e) TFR of impedance (Z_{TFR}), (f) spectral impedance component

3.3. Case 3: Harmonic sources at upstream and downstream of the PCC

For case 3, the harmonic source is located upstream and downstream of the PCC. As can be seen in Figures 4 (a) and (b) show the measured voltage and current signals in the time domain. The peak voltage is

324.7 V, while the peak current is 44.6 A, respectively. Besides, Figure 4 (c) shows the $THD(t)$ and $TnHD(t)$ mean of voltage are 1.47% and 6.04%, respectively. In the meantime, Figure 4 (d) presents the $THD(t)$ and $TnHD(t)$ mean of current, which are 1.91% and 45.18%, respectively. The values of $THD(t)$ and $TnHD(t)$ show that the voltage and current signals do have harmonic and interharmonic components. Figure 4 (e) shows the Z_{TFR} of the PCC, while Figure 4 (f) presents the Z_S that been extracted from the Z_{TFR} . Furthermore, Figure 4 (f) shows that the Z_1 is 5.36 ohm; in contrast the harmonic impedance consists of Z_{275} , Z_{375} , Z_{400} , Z_{600} , Z_{700} and Z_{900} , respectively. The characteristic of the spectral impedance, Z_S are summarized in Table 2. What is surprising is that the value of Z_1 is always smaller than any harmonic impedances, Z_h . It is apparent from the result that the Z_S components can be characterized due to identify the location of the harmonic source. As a result, for case 3, the significant relationship between Z_1 and Z_h at the condition of the harmonic source located downstream of the PCC can be written as:

$$Z_1 \neq 0 \text{ ohm} \quad (11)$$

$$Z_h > Z_1 \quad (12)$$

where for harmonic component, h is any positive integer whereas, for interharmonic, h is any positive non-integer.

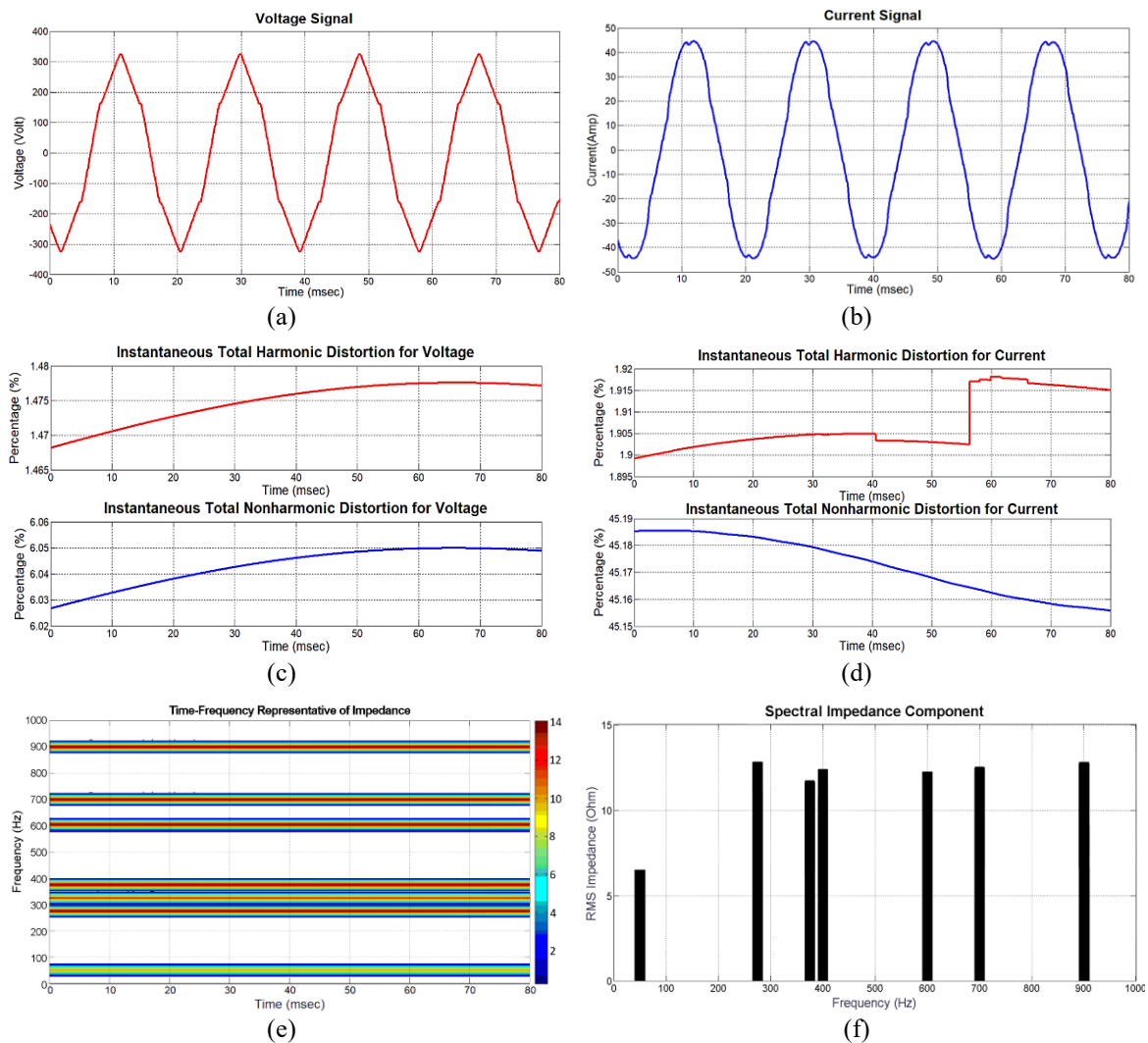


Figure 4 Case 3; (a) voltage signal in time domain, (b) current signal in time domain, (c) $THD(t)$ and $TnHD(t)$ of voltage, (d) $THD(t)$ and $TnHD(t)$ of current, (e) TFR of impedance (Z_{TFR}), (f) spectral impedance component

Table 1. Magnitudes of the spectral impedance for case 2 using S-transform technique

Spectral Impedance	Ohm
Z_1	5.36
Z_{275}	3.81
Z_{375}	3.68
Z_{600}	4.19
Z_{700}	4.34
Z_{825}	3.94
Z_{900}	3.68

Table 2. Magnitudes of the spectral impedance for case 3 using S-transform technique

Spectral Impedance	Ohm
Z_1	6.5
Z_{275}	12.8
Z_{375}	11.8
Z_{400}	12.3
Z_{600}	12.2
Z_{700}	12.5
Z_{900}	12.9

3.4. Case 4: Harmonic source at upstream of the PCC

In case 4, the harmonic source is located upstream of the PCC. The voltage and current signals in the time domain are measured at the PCC are shown in Figures 5 (a) and (b). The peak voltage is 324.3 V, whereas the peak current is 30.65 A and the fundamental frequency is 50 Hz. These signals are used as the inputs for analyzing harmonic sources using the S-transform technique. It can be seen from the waveforms that the voltage and current waveforms are distorted because of the harmonic source presents in the network system. Furthermore, Figure 5 (c) shows the $THD(t)$ and $TnHD(t)$ mean of voltage, which are 1.47% and 6.04%, respectively. Moreover, Figure 5 (d) shows the $THD(t)$ and $TnHD(t)$ mean of current are 1.5% and 6.05%, respectively. The values of $THD(t)$ and $TnHD(t)$ show that the voltage and current signals do have harmonic and interharmonic components. The Z_S components are extracted from the Z_{TFR} shown in Figure 5 (e). As shown in Figure 5 (f), the spectral impedance, Z_S , consists of fundamental impedance, Z_1 at 50 Hz, whereas the harmonic impedances such as Z_{275} , Z_{300} , Z_{375} , Z_{400} , Z_{600} , Z_{700} , Z_{900} , respectively.

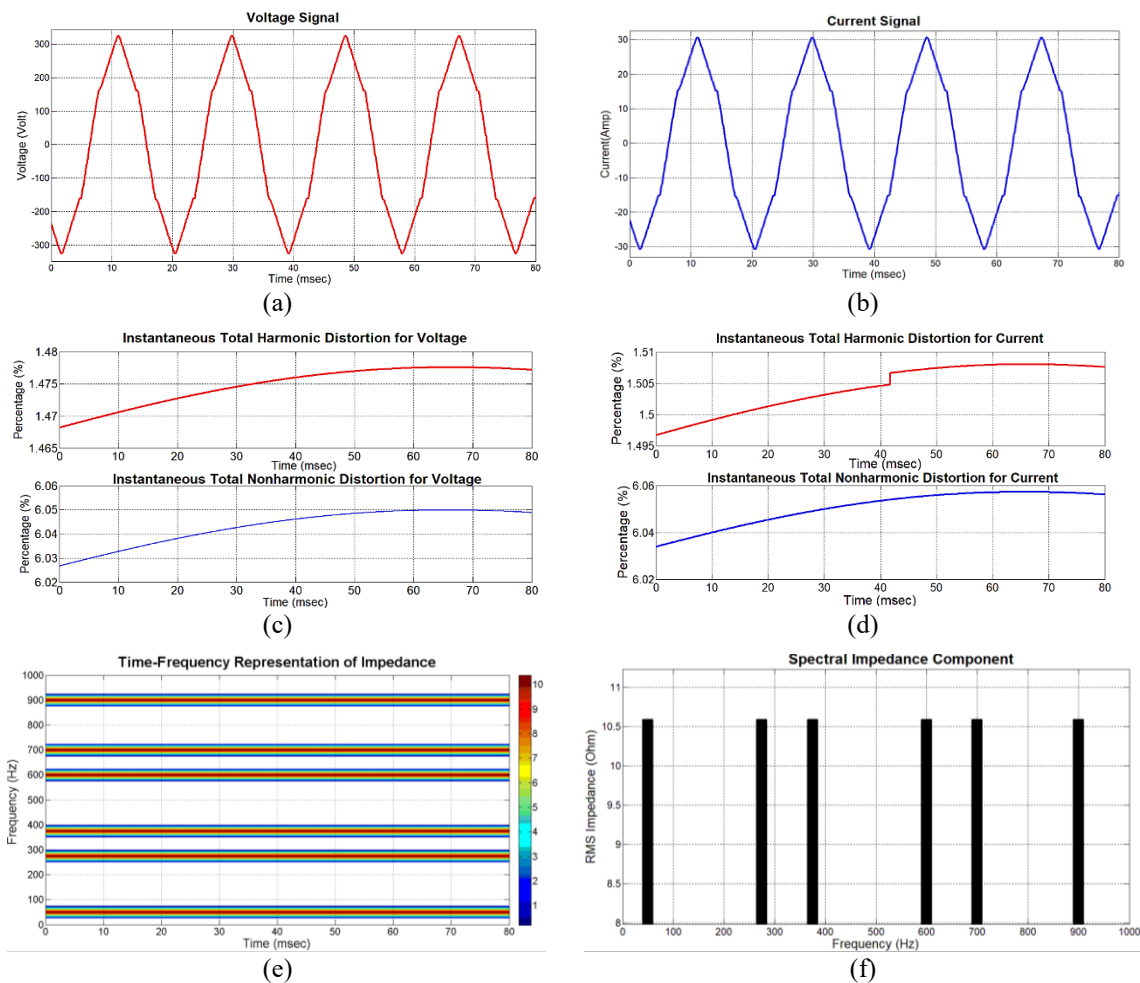


Figure 5. Case 4, (a) Voltage signal in time domain, (b) Current signal in time domain, (c) $THD(t)$ and $TnHD(t)$ of voltage, (d) $THD(t)$ and $TnHD(t)$ of current, (e) TFR of impedance (Z_{TFR}), (f) Spectral impedance component

The Z_S components relationship are the critical driving factor of harmonic source identification and the values of the components are summarized in Table 3. It can be seen that the Z_I is always the same value as all harmonic impedances, Z_h . Based on the results, it can be concluded that the Z_S components can be used to identify the location of harmonic sources. Hence, for case 4, the significant relationship between Z_I and Z_h at the condition of the harmonic source located at downstream of the PCC can be written as:

$$Z_I \neq 0 \text{ ohm} \quad (13)$$

$$Z_h = Z_I \quad (14)$$

where for harmonic component, h is any positive integer whereas, for interharmonic, h is any positive non-integer.

Table 3. Magnitudes of the spectral impedance for case 4 using S-transform technique

Spectral Impedance	Ohm
Z_I	10.6
Z_{275}	10.6
Z_{300}	10.6
Z_{375}	10.6
Z_{400}	10.6
Z_{600}	10.6
Z_{700}	10.6
Z_{900}	10.6

3.5. Performance of the proposed method

This research provides an exciting opportunity to advance the understanding of harmonic source identification using the S-transform technique. The main contribution of this analysis is the significant relationship of the spectral impedance components, Z_S such as fundamental impedance, Z_I and harmonic impedance, Z_h in identifying the location of the harmonic source in the network system. The spectral impedance characteristics are used to identify the location of harmonic sources and the performance of this proposed method are summarizes in Table 4.

Table 4. Performance of harmonic source identification using spectral impedance components characteristics

Case	Upstream side	Downstream side	Spectral impedance, Z_S characteristic	% Correct identification
1	N	N	$Z_I \neq 0 \text{ ohm}$ $Z_h = 0 \text{ ohm}$	100
2	N	H	$Z_I \neq 0 \text{ ohm}$ $Z_I > Z_h$	100
3	H	H	$Z_I \neq 0 \text{ ohm}$ $Z_h > Z_I$	100
4	N	H	$Z_I \neq 0 \text{ ohm}$ $Z_h = Z_I$	100

4. CONCLUSION

The main concern of this research is to identify the location of harmonic source that connected to the distribution system utilizing the S-transform technique. The main contribution of this research is the significant relationship of Z_S components that obtained from the S-transform analysis in identifying the location of harmonic sources. Based on Table 4, the correctness of the proposed method is 100% for each case and the significant relationship of Z_S for identification of harmonic source location are summarized as follow:

- If $Z_I \neq 0$ and $Z_h = 0$, there is no source in the network system.
- If $Z_I \neq 0$ and $Z_I > Z_h$, there is a harmonic source located at downstream of the PCC.
- If $Z_I \neq 0$ and $Z_h > Z_I$, there are a harmonic sources located at upstream and downstream of the PCC.
- If $Z_I \neq 0$ and $Z_I = Z_h$, there is a harmonic source located at upstream of the PCC.

Consequently, considering the results, this method can be used accurately in distinguishing the location of the harmonic source.

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