# Identification of harmonic source location in power distribution network

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**ABSTRACT**

This paper presents the experimental set-up of identification of harmonic source location in the power distribution network using time-frequency analysis, known as S-transform (ST) at the point of common coupling (PCC). S-transform offers high frequency resolution in analyzing the low frequency component and able to represent signal parameters in time-frequency representation (TFR) such as TFR impedance ($Z_{TFR}$). The proposed method is based on IEEE Std. 1459-2010, ST, and the significant relationship of spectral impedances components ($Z_S$) that been extracted from the $Z_{TFR}$, consist of the fundamental impedance ($Z_1$) and harmonic impedance ($Z_h$). This experiment was conducted out on an IEEE 4-bus test feeder with a harmonic producing load in numerous different scenarios. The experimental was tested and verified for three consecutive months. The findings of this study reveal that the proposed method provides 100 percent correct identification of harmonic source location.



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## 1. INTRODUCTION

Due to the rise of harmonic-producing loads, harmonic distortion has become one of the primary power quality concerns [1], [2]. Harmonic distortion, which causes voltage and current waveforms to be distorted and contain various harmonic orders, is one of the most common types of disturbances [3]–[6]. The power system is impacted by the disturbances; therefore, monitoring is required to limit the impacts, which may include equipment failures due to overheating, reduced transformer life expectancy due to deterioration of insulation levels, nuisance tripping, and increased equipment power losses [7]–[10]. Moreover, harmonics can cause overheating and damage to end-user equipment, as well as have unfavorable effects on the power system. As a result, it is critical for a power system operator to understand the system's harmonic behavior [11]–[13]. As mentioned in [14]–[18], harmonic sources, on the other hand, have complicated properties such as nonlinearity and abrupt variations that are difficult to forecast using standard methods the foremost common circumstance that needs harmonic source location is to settle the disputes over who is responsible for harmonic distortions, whether it comes upstream or downstream of the point of common coupling (PCC) [19]–[21].

The power direction method is the most popular method of identifying harmonic sources [22]–[24]. Next, the critical impedance method based on reactive power [25], [26] also offers a certain level of accuracy. Some basic assumptions are required for the approaches listed above, such as prior knowledge of source impedance [11], [27]–[29]. In contrast of active power flow direction, the reactive power methods provide always correct claims with regards to the dominant equivalent harmonic source. These approaches, however, is unable to establish the harmonic contribution of each side [30]–[34]. Other methods, such as fluctuation and regression methods, require that the major harmonic source be on the customer side and that the background harmonic voltage required to be stable [35]–[39]. Furthermore, approaches based on the detection of total harmonic distortion are insensitive to changes in the phase angle of the harmonic source, making it impossible to precisely establish the source of harmonic distortion [40]–[42]. According to [43], current techniques have been used to identify the harmonic contributions of the customer and the utility in order to detect the harmonic source. Based on the reference impedance as in [34], [44]–[47], a harmonic vector approach has been suggested to determine the utility and customer's harmonic contributions at the PCC. This method allowed for the calculation of harmonic contributions without determining customer impedance, and also improved the findings in resonance situations. The independent component analysis (ICA) methods were utilized in recent research [47]–[50], which need the impedance on the customer's side to be higher than the one on the utility side. However, when the network contains filters or capacitors on the customer side, this is impractical [7], [51].

Short-time fourier transform (STFT) and Stockwell transform or S-transform (ST), are the most common time–frequency domain transforms employed in harmonic signal detection approaches [52]–[58]. As explained in [59]–[62], STFT on the one hand, has some disadvantages such as, this transform is window-dependent and has a fixed resolution based on the window size. Furthermore, because the STFT is an Fourier transform (FT) based technique, it may have issues with the picket-fence effect [63], [64]. ST, on the other hand, because it is a multiresolution spectrum analysis technique, does not have these issues [65]–[68]. As a result, ST appears to be a potential transform for power system protection [27]. Because it incorporates information in both the temporal and frequency domains, the ST has shown to be effective in harmonic signal identification approaches [69]. Thus, this paper proposes an experimental setup based on IEEE Std.1459-2010 and ST due to identify the harmonic source location.

## 2. METHOD

### 2.1. Proposed method

The identification of harmonic source location is divided into five steps, as indicated in Figure 1. The signals are first measured for both voltage and current at the PCC of the network system. Second, four specific instances were explored for recognising harmonic sources on IEEE 4-bus test feeders [44]. The time-frequency representation (TFR) analysis was done on the PCC's voltage and current measurements in the third step ($V_{PCC}$ and $I_{PCC}$). This analysis yielded the impedance TFR ($Z_{TFR}$), which was then used to calculate the impedance spectral ($Z_S$) components by calculating the values of the $Z_{TFR}$ components. Finally, the significant association between the fundamental impedance ($Z_1$) and harmonic impedance ($Z_h$) components of impedance spectrum ($Z_S$) components was observed and employed for harmonic source detection. In this experiment, a harmonic generating load was chosen with an amplitude modulation index ($m_a$) of 1.0, a frequency modulation index ($m_f$) of 90, and an input frequency ($f_i$) of 50 Hz [70]–[73].

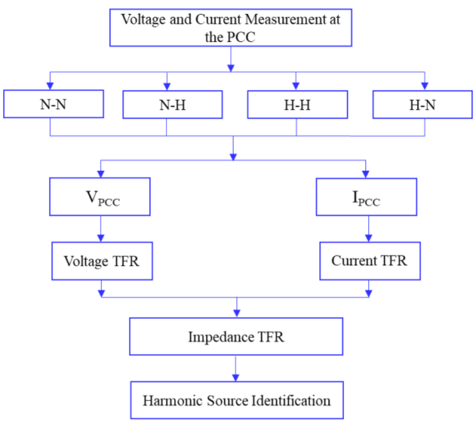


Figure 1. The implementation of the harmonic source identification method

The IEEE 4-bus test feeder is chosen and illustrated in Figures 2 and 3 in order to detect the harmonic source location in the power distribution network in consideration of upstream and downstream of the PCC. Where N is a non-harmonic source which is the resistor load and H is the harmonic producing load. In order to test and evaluate the proposed method, an experimental setup was built up in an advanced digital signal processing (ADSP) research facility, as illustrated in Figure 4.

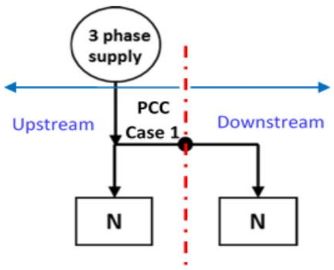


Figure 2. An upstream-downstream for case 1

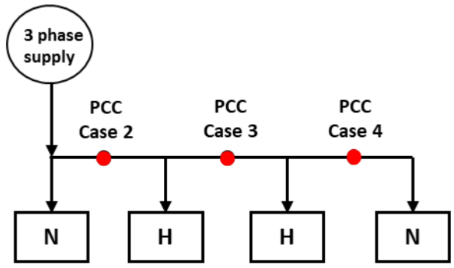


Figure 3. Cases 2, 3, and 4

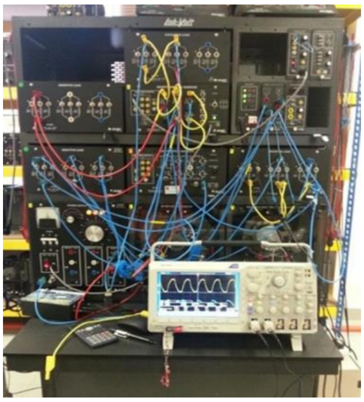

Figure 4. Experimental setup of the proposed system

### 2.2. S-transform

The S-transform (ST) is hybrid of wavelet transform (WT) and the STFT, which inherits the advantages of both in signal processing [74], [75]. In the transformation process, ST uses a moving and scalable localising Gaussian window in particular. ST can be defined as shown in:

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

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

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

#### 2.2.1. Signal parameters

The TFR is used to determine the signal parameters of power quality. Furthermore, the instantaneous value is used in the analysis to obtain real-time parameters [76].

– Instantaneous root-mean square voltage

The root-mean square (RMS) voltage of signal ($V_{rms}(t)$) can be obtained from the sampled waveform, and written as [77], [78],

$$V_{rms}(t) = \sqrt{\int_0^{f_s} P_x(t,f)\, df} \quad (3)$$

– Instantaneous root-mean square fundamental voltage
The instantaneous RMS fundamental voltage ($V_{1rms}(t)$) can be computed as [79],

$$V_{1rms}(t) = \sqrt{2\int_{f_{lo}}^{f_{hi}} P_x(t,f)\, df} \quad (4)$$

$$f_{hi} = f_0 + 25\ Hz;\ f_{lo} = f_0 - 25\ Hz$$

where $P_x$ is the power spectrum obtained from the TFR of signal and $f_0$ is the fundamental frequency corresponding to the power system frequency.

### 2.2.2. Impedance time-frequency representation analysis

The impedance TFR ($Z_{TFR}$) offered useful information about the frequency response of the system, as well as harmonic points and possible issues caused by harmonic distortions. The desired current harmonic data and the difference in voltage harmonic data at the location of interest have to be measured in order to determine the impedance TFR. The $Z_{TFR}$ at each harmonic frequency was calculated using this data, and the results were shown [80]. The $Z_{TFR}$ equation can be expressed as (5),

$$Z_{TFR} = \frac{S_V(t,f)}{S_I(t,f)} \quad (5)$$

where $S_V(t,f)$ signifies the TFR of voltage and $S_I(t,f)$ signifies the TFR of current.

### 2.2.3. Spectral impedance

The spectral impedance ($Z_S$) comprises the fundamental impedance ($Z_1$) and harmonic impedance ($Z_h$) that is obtained from $Z_{TFR}$ [81]. The fundamental impedance ($Z_1$) was an impedance at 50 Hz, which was the frequency of the power source. In the meantime, harmonic impedance ($Z_h$) was a harmonic impedance with an order of harmonics.

## 3. RESULTS AND DISCUSSION

The implementation of the proposed technique initially done by measuring the voltage and current signals at PCC with consideration of 4 specific cases as discussed in 2.1. The linear time-frequency distribution method namely S-transform is applied in the analysis. The location of harmonic sources can be distinguished by analyzing the significant relationship between $Z_1$ and $Z_h$, accordingly.

### 3.1. Case 1: No harmonic source

Only the linear loads were placed upstream and downstream of the PCC in case 1. The voltage signal in the time domain, as well as its voltage TFR, are shown in Figures 5(a) and 5(b). The maximum voltage was 342.5 V, while the maximum current was 66.5 A. Meanwhile, Figures 5(c) and 5(d) illustrate the TFR of voltage and current signals derived from S-transform analysis. The higher the magnitude, the redder the colour bar, the lower the magnitude, and the bluer the colour bar. There were no other components in the signals and the largest magnitude was only seen at 50 Hz. The results showed that there were no harmonic components in the signal. The $Z_1$ existed at 50 Hz with a resistance of 4.8 ohm and no harmonic components in the signal, as shown in Figure 5(d). Thus, in case 1, the significant relationship between $Z_1$ and $Z_h$ in the power system network at no harmonic producing load can be expressed as,

$$Z_1 \neq 0 \text{ ohm} \quad (6)$$

$$Z_h = 0 \text{ ohm} \quad (7)$$

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

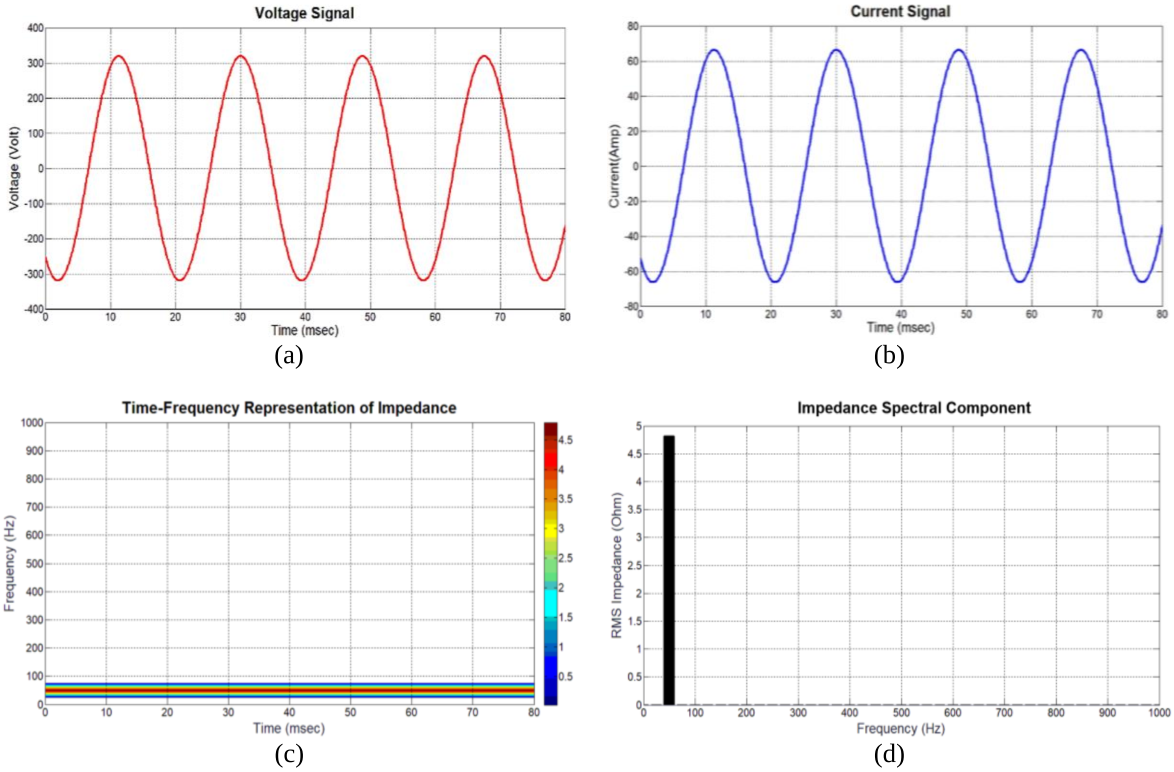


Figure 5. Case 1: (a) voltage signal in time domain, (b) current signal in time-domain, (c) TFR impedance using S-transform, and (d) spectral impedance

### 3.2. Case 2: Harmonic source located at point of common coupling's downstream

The linear load is positioned upstream of the PCC in case 2, while the harmonic load is located downstream. The TFR of voltage and current signals derived from the S-transform analysis is shown in Figure 6(a) and (b). It can be seen that the harmonic and interharmonic components exist between 200 and 1000 Hz, whereas the fundamental components of voltage and current have the maximum magnitudes at 50 Hz. The $Z_{TFR}$ is calculated using (5) in Figure 6(c), and the figure demonstrates that impedance components occur at frequencies of 50 Hz, 275 Hz, 375 Hz, 600 Hz, 700 Hz, and 900 Hz, respectively. The $Z_S$ is then derived by calculating the parameters of the $Z_{TFR}$, as shown in Figure 6(d).

Table 1 summarises the $Z_S$ characteristics shown in Figure 6(d). The $Z_1$ value is always higher than any $Z_h$ components, as can be seen. The relationship between the $Z_S$ components can be used to identify the location of harmonic sources, according to the findings. As a result, in instance 2, the significant relationship between $Z_1$ and $Z_h$ at the condition of the harmonic source downstream of the PCC can be stated as,

$$Z_1 \neq 0 \text{ ohm} \tag{8}$$

$$Z_h < Z_1 \tag{9}$$

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

Table 1. The spectral impedance components for case 2

| Spectral impedance | Ohm |
|---|---|
| $Z_1$ | 3.4 |
| $Z_{275}$ | 2.5 |
| $Z_{375}$ | 2.0 |
| $Z_{600}$ | 2.1 |
| $Z_{700}$ | 1.5 |
| $Z_{900}$ | 2.0 |

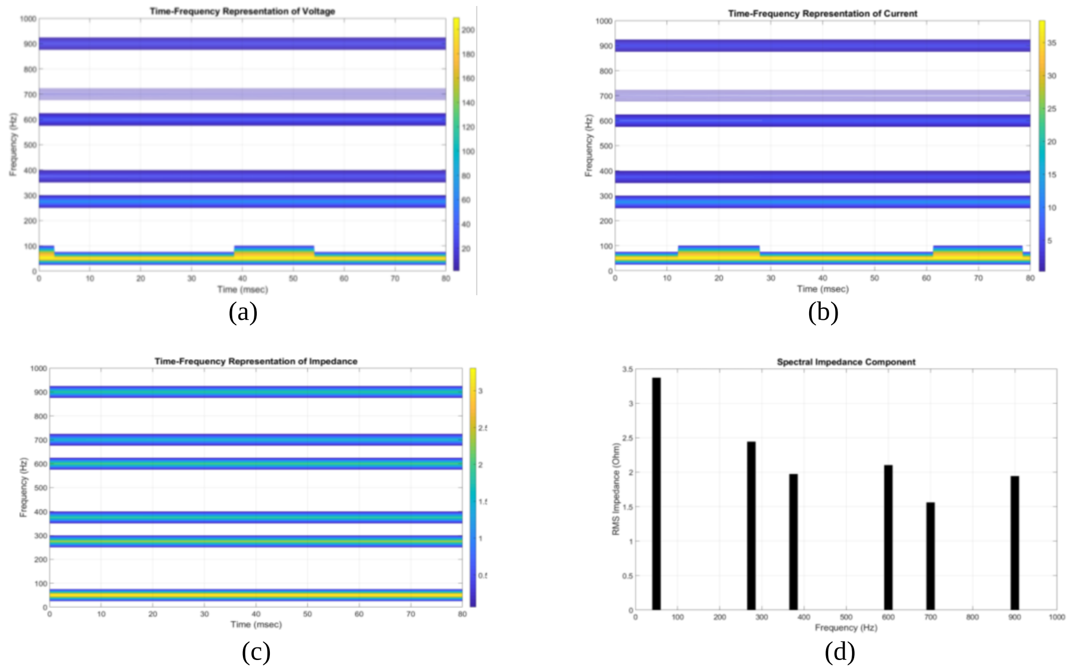


Figure 6. Case 2: (a) voltage signal in TFR using S-transform, (b) current signal in TFR using S-transform, (c) TFR impedance using S-transform, and (d) spectral impedance

### 3.3. Case 3: Harmonic sources located at point of common coupling's upstream and downstream

The TFR of voltage and current signals derived from the S-transform analysis for case 3 is shown in Figures 7(a) and 7(b). It can be seen that the harmonic and interharmonic components occur in the frequency range of 200 Hz to 1000 Hz, whereas the fundamental components of voltage and current, respectively, have the maximum magnitudes at 50 Hz. The voltage and current waveforms can be seen to be distorted due to the harmonic load located upstream and downstream of the PCC. The $Z_{TFR}$ is calculated using (5) in Figure 7(c), and the figure demonstrates that impedance components occur at frequencies of 50 Hz, 275 Hz, 375 Hz, 600 Hz, 700 Hz, and 900 Hz, respectively. The $Z_S$ is then calculated by estimating the parameters of the $Z_{TFR}$, as shown in Figure 7(d).

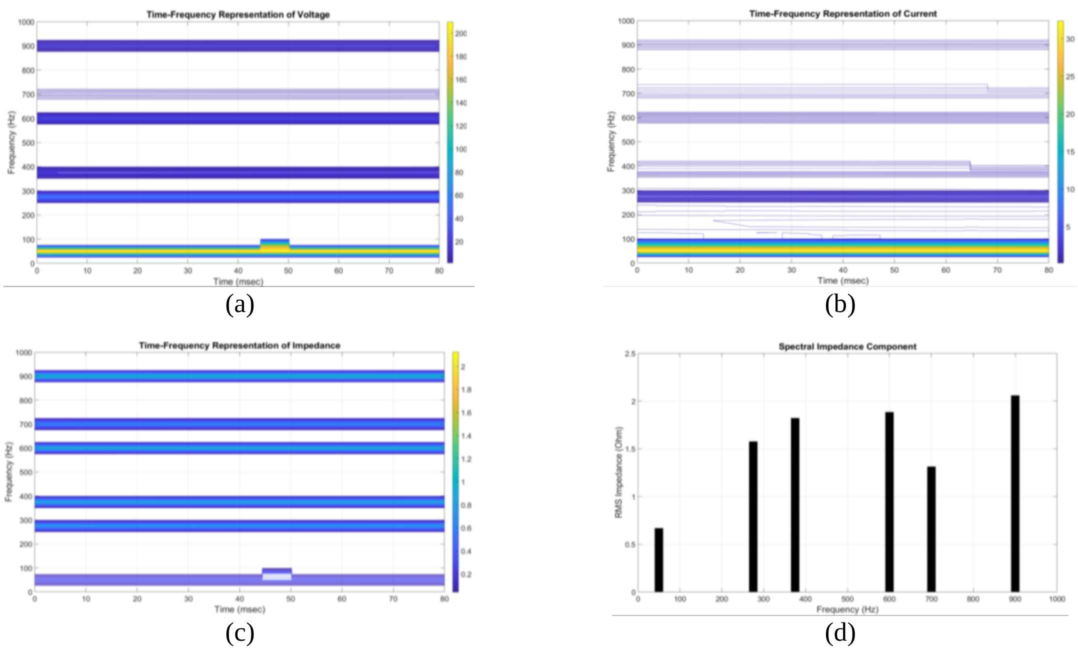


Figure 7. Case 3: (a) voltage signal in TFR using S-transform, (b) current signal in TFR using S-transform, (c) TFR impedance using S-transform, and (d) spectral impedance

Table 2 summarises the ZS characteristics shown in Figure 7(d). The Z1 value is always lower than any Zh components, as can be shown. The relationship between the $Z_S$ components can be utilised to pinpoint the location of harmonic sources, according to the findings. As a result, in case 3, the significant relationship between $Z_1$ and $Z_h$ at the condition of the harmonic source positioned upstream and downstream of the PCC may be expressed as shown in:

$$Z_1 \neq 0 \text{ ohm} \tag{10}$$

$$Z_h > Z_1 \tag{11}$$

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

Table 2. The spectral impedance components for case 3

| Spectral impedance | Ohm |
|---|---|
| $Z_1$ | 0.7 |
| $Z_{275}$ | 1.6 |
| $Z_{375}$ | 1.8 |
| $Z_{600}$ | 1.9 |
| $Z_{700}$ | 1.4 |
| $Z_{900}$ | 2.1 |

### 3.4. Case 4: Harmonic source located at point of common coupling's upstream

The harmonic load is positioned upstream of the PCC in case 4. Figures 8(a) and (b) illustrate the voltage and current signals acquired from S-transform analysis in the TFR. Between 200 Hz and 1000 Hz, the lowest-magnitude harmonic and interharmonic components are present, with the maximum component magnitude at 50 Hz. The $Z_{TFR}$ is calculated using equation 5 in Figure 8(c), and the figure demonstrates that impedance components occur at frequencies of 50 Hz, 275 Hz, 375 Hz, 600 Hz, 700 Hz, and 900 Hz, respectively. The $Z_S$ is then calculated by estimating the parameters from the $Z_{TFR}$, as shown in Figure 8(d).

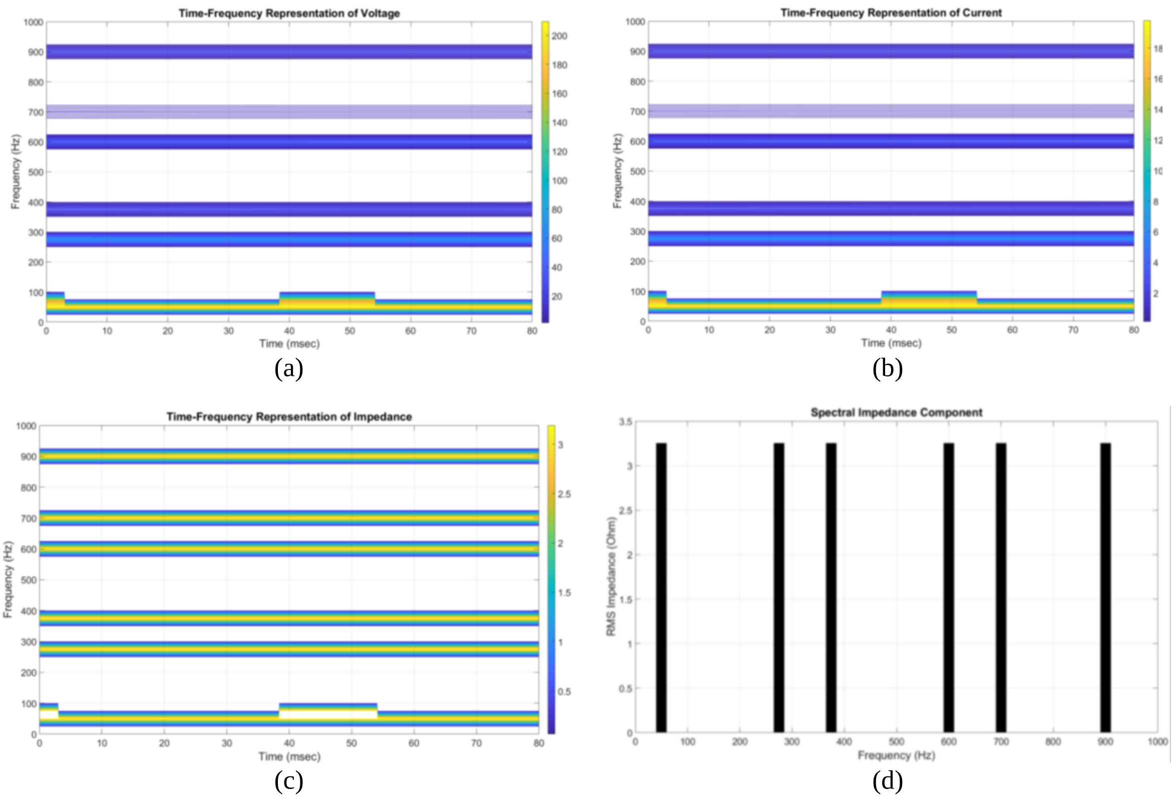


Figure 8. Case 4: (a) voltage signal in TFR using S-transform, (b) current signal in TFR using S-transform, (c) TFR impedance using S-transform, and (d) spectral impedance ($Z_S$)

Table 3 summarizes the $Z_S$ characteristics shown in Figure 8(d). The $Z_1$ value is the same for all $Z_h$ components, as can be observed. At the condition of the harmonic source positioned upstream of the PCC, the significant relationship between $Z_1$ and $Z_1$ can be stated as,

$$Z_1 \neq 0 \text{ ohm} \tag{12}$$

$$Z_h = Z_1 \tag{13}$$

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

Table 3. The spectral impedance components for case 4

| Spectral impedance | Ohm |
|---|---|
| $Z_1$ | 3.3 |
| $Z_{275}$ | 3.3 |
| $Z_{375}$ | 3.3 |
| $Z_{600}$ | 3.3 |
| $Z_{700}$ | 3.3 |
| $Z_{900}$ | 3.3 |

Furthermore, the proposed method was tried and verified on an experimental setup in October, November, and December 2021, with the harmonic producing load in the linear area (amplitude modulation index is $0 \leq ma \leq 1$ and inverter switching frequency range is between 2 kHz and 15 kHz) [82]. Surprisingly, as demonstrated in Figure 9, the proposed method offers 100 percent accurate harmonic source location detection. According to Table 4, the proposed method is 100 percent correct in each scenario, and the significant relationship of $Z_S$ for harmonic source location identification is summarized as shown in:

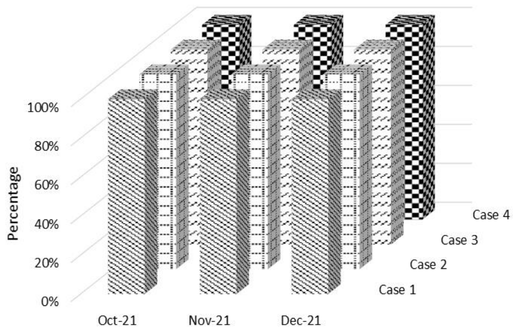


Figure 9. The correctness of the proposed method

Table 4. Result of proposed method

| $Z_1$ | $Z_h$ | Remark |
|---|---|---|
| $Z_1 \neq 0$ ohm | $Z_h = 0$ | Case 1: No harmonic source |
| $Z_1 \neq 0$ ohm | $Z_h < Z_1$ | Case 2: Harmonic source located at PCC downstream |
| $Z_1 \neq 0$ ohm | $Z_h > Z_1$ | Case 3: Harmonic source located at upstream and downstream of PCC |
| $Z_1 \neq 0$ ohm | $Z_1 = Z_h$ | Case 4: Harmonic source located at PCC downstream |

## 4. CONCLUSION

Time-frequency distribution analysis namely S-transform has shown tremendous result in this analysis. The major contribution of this study is the discovery of a significant relationship between $Z_S$ components that acquired from S-transform analysis in locating harmonic source location. As a result of the proposed method's results, the harmonic source site can be identified using the significant relationship of spectral impedances in a fast, cost-effective, and accurate manner.

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## REFERENCES


[1] F. Xu, H. Yang, J. Zhao, Z. Wang, and Y. Liu, "Study on Constraints for Harmonic Source Determination Using Active Power Direction," in *IEEE Transactions on Power Delivery*, vol. 33, no. 6, pp. 2683–2692, December 2018, doi: 10.1109/TPWRD.2018.2828034.

[2] Y. E. Shklyarskiy, A. Y. Shklyarskiy, and E. O. Zamyatin, "Analysis of distortion-related electric power losses in aluminum industry," *Tsvetnye Met*, vol. 4, pp. 84–91, 2019.

[3] Chang-Song Li, Zhi-Xuan Bai, Xian-Yong Xiao, Ya-Mei Liu, and Yi Zhang, "Research of harmonic distortion power for harmonic source detection," *2016 17th International Conference on Harmonics and Quality of Power (ICHQP)*, 2016, pp. 126–129, doi: 10.1109/ICHQP.2016.7783437.

[4] A. Eslami, M. Negnevitsky, E. Franklin, and S. Lyden, "Review of AI applications in harmonic analysis in power systems," *Renewable and Sustainable Energy Reviews*, vol. 154, p. 111897, February 2022, doi: 10.1016/j.rser.2021.111897.

[5] J. Afsharian, D. Xu, B. Wu, B. Gong, and Z. Yang, "The Optimal PWM Modulation and Commutation Scheme for a Three-Phase Isolated Buck Matrix-Type Rectifier," in *IEEE Transactions on Power Electronics*, vol. 33, no. 1, pp. 110–124, January 2018, doi: 10.1109/TPEL.2017.2661242.

[6] D. C. Bhonsle and R. B. Kelkar, "Analyzing power quality issues in electric arc furnace by modeling," *Energy*, vol. 115, pp. 830–839, November 2016, doi: 10.1016/j.energy.2016.09.043.

[7] R. Sinvula, K. M. Abo-Al-Ez, and M. T. Kahn, "Harmonic Source Detection Methods: A Systematic Literature Review," in *IEEE Access*, vol. 7, pp. 74283–74299, 2019, doi: 10.1109/ACCESS.2019.2921149.

[8] E. A. Bulycheva and S. A. Yanchenko, "Real-time harmonic identification under varying grid conditions," *SJEE*, vol. 18, no. 1, pp. 29–48, February 2021, doi: 10.2298/SJEE2101029B.

[9] I. Bogdanov and B. Abramovich, "Improving the efficiency of autonomous electrical complexes of oil and gas enterprises," *Journal of Mining Institute*, vol. 249, pp. 408–416, 2021, doi: 10.31897/PML2021.3.10.

[10] A. F. N. Azam, A. Jidin, M. A. Said, H. Jopri, and M. Manap, "High performance torque control of BLDC motor," *2013 International Conference on Electrical Machines and Systems (ICEMS)*, 2013, pp. 1093–1098, doi: 10.1109/ICEMS.2013.6754396.

[11] A. S. S. Murugan and V. S. Kumar, "Determining true harmonic contributions of sources using neural network," *Neurocomputing*, vol. 173, pp. 72–80, January 2016, doi: 10.1016/j.neucom.2015.06.081.

[12] S. V. Borisov, E. A. Koltunova, and S. N. Kladiev, "Traction asynchronous electric drive of mine electric locomotivesimulation model structure improvement," *Journal of Mining Institute*, vol. 247, pp. 114–121, 2021, doi: 10.31897/PMI.2021.1.12.

[13] M. J. Carrizosa, N. Stankovic, J.-C. Vannier, Y. E. Shklyarskiy, and A. Bardanov, "Multi-terminal DC grid overall control with modular multilevel converters," *Journal of Mining Institute*, vol. 243, pp. 357–370, 2020, doi: 10.31897/PMI.2020.3.357.

[14] M. V. A. Stošović, D. S. Stevanović, and P. M. Petković, "Application of a Standard Power Meter for Detection Source of Harmonic Pollution and Reducing Economic Losses at Power Grid," *Electric Power Components and Systems*, vol. 48, no. 1–2, pp. 42–55, April 2020, doi: 10.1080/15325008.2020.1731879.

[15] D. Carta, C. Muscas, P. A. Pegoraro, and S. Sulis, "Identification and Estimation of Harmonic Sources Based on Compressive Sensing," in *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 1, pp. 95–104, January 2019, doi: 10.1109/TIM.2018.2838738.

[16] Y. E. Shklyarskiy, D. D. Guerra, E. V Iakovleva, and A. Rassõlkin, "The influence of solar energy on the development of the mining industry in the Republic of Cuba," *Journal of Mining Institute*, vol. 249, pp. 427–440, 2021, doi: 10.31897/PML2021.3.12.

[17] W. Huihui and W. Ping, "Comparison of detection methods for power quality in micro-grid," *2015 6th International Conference on Power Electronics Systems and Applications (PESA)*, 2015, pp. 1–8, doi: 10.1109/PESA.2015.7398883.

[18] A. H. Fahad, P. P. Dutta, and A. H. Chowdhury, "A voltage flicker severity analysis module for multiple electric arc furnace operation," *8th International Conference on Electrical and Computer Engineering*, 2014, pp. 643-646, doi: 10.1109/ICECE.2014.7026997.

[19] S. Cieślik, "On the problem of harmonic source detection in electric power networks," *2016 10th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, 2016, pp. 82–87, doi: 10.1109/CPE.2016.7544163.

[20] R. Lin, L. Xu, and X. Zheng, "A Method for Harmonic Sources Detection based on Harmonic Distortion Power Rate," *IOP Conference Series: Materials Science and Engineering*, vol. 322, no. 7, p. 072038, March 2018. [Online] Available: https://iopscience.iop.org/article/10.1088/1757-899X/322/7/072038/meta [accessed February 25, 2020].

[21] J. M. Munoz-Guijosa, S. B. Kryltcov, and S. V Solovev, "Application of an Active Rectifier used to mitigate currents distortion in 6-10 kV distribution grids," *Journal of Mining Institute*, vol. 236, pp. 229–238, 2019, doi: 10.31897/PMI.2019.2.229.

[22] W. Xu, X. Liu, and Y. Liu, "An investigation on the validity of power-direction method for harmonic source determination," in *IEEE Transactions on Power Delivery*, vol. 18, no. 1, pp. 214–219, January 2003, doi: 10.1109/TPWRD.2002.803842.

[23] P. Joshi and S. K. Jain, "Harmonic Source Identification Using Modified Power Direction Method," *2019 4th International Conference on Recent Trends on Electronics, Information, Communication & Technology*, 2019, pp. 480–485, doi: 10.1109/RTEICT46194.2019.9016776.

[24] S. Kryltcov, A. Makhovikov, and M. Korobitcyna, "Novel Approach to Collect and Process Power Quality Data in Medium-Voltage Distribution Grids," *Symmetry*, vol. 13, no. 3, p. 460, March 2021, doi: 10.3390/sym13030460.

[25] C. Li, W. Xu, and T. Tayjasanant, "A "critical impedance"-based method for identifying harmonic sources," in *IEEE Transactions on Power Delivery*, vol. 19, no. 2, pp. 671–678, April 2004, doi: 10.1109/TPWRD.2004.825302.

[26] Y. E. Shklyarskiy, A. I. Bardanov, and A. Y. Shklyarskiy, "Novel approach to control of active rectifier during voltage dips," *IOP Conference Series: Earth and Environmental Science*, vol. 194, no. 5, p. 052022, 2018.

[27] C. Chen, X. Liu, D. Koval, W. Xu and T. Tayjasanant, "Critical impedance method-a new detecting harmonic sources method in distribution systems," in *IEEE Transactions on Power Delivery*, vol. 19, no. 1, pp. 288–297, January 2004, doi: 10.1109/TPWRD.2003.820424.

[28] M. E. Balci and M. H. Hocaoglu, "On the validity of harmonic source detection methods and indices," *Proceedings of 14th International Conference on Harmonics and Quality of Power-ICHQP 2010*, 2010, pp. 1–5, doi: 10.1109/ICHQP.2010.5625310.

[29] S. V. D. A. Kumar and K. R. Reddy, "Study on Identification of Harmonic Contributions Between Utility and Customer," *(IJCSE) International Journal on Computer Science and Engineering*, vol. 02, no. 09, pp. 3106–3110, 2010.

[30] F. Safargholi, K. Malekian, and W. Schufft, ""Voltage-Current Ratio Difference" Concept for identifying the dominant harmonic source," *International Journal of Electrical Power & Energy Systems*, vol. 121, p. 106147, October 2020, doi: 10.1016/j.ijepes.2020.106147.

[31] B. Y. Vasil'ev and V. S. Dobush, "Modulation algorithms for controlling semiconductor converters," *Russian Electrical Engineering*, vol. 86, no. 4, pp. 172–179, June 2015, doi: 10.3103/S1068371215040100.

[32] I. Papič, *et al.*, "A Benchmark Test System to Evaluate Methods of Harmonic Contribution Determination," in *IEEE Transactions*

*on Power Delivery*, vol. 34, no. 1, pp. 23–31, February 2019, doi: 10.1109/TPWRD.2018.2817542.
[33] M. Farhoodnea, A. Mohamed, H. Shareef, and H. Zayandehroodi, “An enhanced method for contribution assessment of utility and customer harmonic distortions in radial and weakly meshed distribution systems,” *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 222–229, December 2012, doi: 10.1016/j.ijepes.2012.05.013.
[34] B. Blazic and T. Pfajfar, "A modified harmonic current vector method for harmonic contribution determination," *IEEE PES Power Systems Conference and Exposition, 2004.*, vol. 3, pp. 1470–1475, 2004, doi: 10.1109/PSCE.2004.1397605.
[35] J. Hui, H. Yang, S. Lin, and M. Ye, "Assessing Utility Harmonic Impedance Based on the Covariance Characteristic of Random Vectors," in *IEEE Transactions on Power Delivery*, vol. 25, no. 3, pp. 1778–1786, July 2010, doi: 10.1109/TPWRD.2010.2046340.
[36] K. Dartawan, L. Hui, R. Austria, and M. Suehiro, “Harmonic Issues That Limit Solar Photovoltaic,” *Proceedings of the World Renewable Energy Forum, Denver, CO, USA*, pp. 13–17, May 2012.
[37] A. Stetco, *et al.*, “Machine learning methods for wind turbine condition monitoring: A review,” *Renew. Energy*, vol. 133, pp. 620–635, April 2019, doi: 10.1016/j.renene.2018.10.047.
[38] G. Graditi, S. Ferlito, and G. Adinolfi, “Comparison of Photovoltaic plant power production prediction methods using a large measured dataset,” *Renewable Energy*, vol. 90, pp. 513–519, May 2016, doi: 10.1016/j.renene.2016.01.027.
[39] N. Huang, H. Peng, G. Cai, and J. Chen, “Power Quality Disturbances Feature Selection and Recognition Using Optimal Multi-Resolution Fast S-Transform and CART Algorithm,” *Energies*, vol. 9, no. 11, p. 927, November 2016, doi: 10.3390/en9110927.
[40] P. Sinha, S. K. Goswami, and S. Nath, “Wavelet-based technique for identification of harmonic source in distribution system,” *International Transactions on Electrical Energy Systems*, vol. 26, no. 12, pp. 2552–2572, 2016, doi: 10.1002/etep.2219.
[41] Y. E. Shklyarskiy and A. Y. Shklyarskiy, “Registration of reactive power for case of distortions in electric grid,” *IOP Conference Series: Earth and Environmental Science*, vol. 87, no. 3, p. 32041, October 2017.
[42] A. R. Abdullah, N. A. Abidullah, N. H. Shamsudin, N. H. H. Ahmad, and M. H. Jopri, “Performance Verification of Power Quality Signals Classification System,” *Applied Mechanics and Materials*, vol. 753, pp. 1158–1163, 2015, doi: 10.4028/www.scientific.net/AMM.752-753.1158.
[43] T. Pfajfar and I. Papič, "Harmonic emission level estimation based on measurements at the point of evaluation," *2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 1–5, doi: 10.1109/PES.2011.6039642.
[44] A. S. Hussin, A. R. Abdullah, M. H. Jopri, T. Sutikno, N. M. Saad, W. Tee, “Harmonic load diagnostic techniques and methodologies: A review,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 9, no. 3, pp. 690–695, March 2018, doi: 10.11591/ijeecs.v9.i3.pp690-695.
[45] F. Salim, K. M. Nor, and D. M. Said, "Experience in online power quality monitoring through VPN," *2012 IEEE 15th International Conference on Harmonics and Quality of Power*, 2012, pp. 481–485, doi: 10.1109/ICHQP.2012.6381282.
[46] M. Farhoodnea, A. Mohamed, H. Shareef, and R. A. J. Khan, “An improved method for determining contribution of utility and customer harmonic distortions in a power distribution system,” *International Journal on Electrical Engineering and Informatics*, vol. 2, no. 3, pp. 204–215, 2010.
[47] F. Karimzadeh, S. Esmaeili, and S. H. Hosseinian, "A Novel Method for Noninvasive Estimation of Utility Harmonic Impedance Based on Complex Independent Component Analysis," in *IEEE Transactions on Power Delivery*, vol. 30, no. 4, pp. 1843–1852, August 2015, doi: 10.1109/TPWRD.2015.2398820.
[48] F. Karimzadeh, S. Esmaeili, and S. H. Hosseinian, “Method for determining utility and consumer harmonic contributions based on complex independent component analysis,” *IET Generation, Transmission & Distribution*, vol. 10, no. 2, pp. 526–534, 2016.
[49] X. Zhao and H. Yang, "A New Method to Calculate the Utility Harmonic Impedance Based on FastICA," in *IEEE Transactions on Power Delivery*, vol. 31, no. 1, pp. 381–388, February 2016, doi: 10.1109/TPWRD.2015.2491644.
[50] A. Hyvärinen and E. Oja, “Independent component analysis: algorithms and applications,” *Neural networks*, vol. 13, no. 4–5, pp. 411–430, June 2000, doi: 10.1016/S0893-6080(00)00026-5.
[51] A. R. Abdullah, M. H. Jopri, M. Manap, and M. R. Yusoff, “An Improved Spectrogram to Identify Multiple Harmonic Sources in Distribution System with Inverter Loads,” *Proceedings of the International MultiConference of Engineers and Computer Scientists*, vol. 2, p. 5, March 2017, [Online]. Available: http://www.iaeng.org/publication/IMECS2017/IMECS2017_pp678-683.pdf.
[52] É. M. Lima, C. M. dos S. Junqueira, N. S. D. Brito, B. A. de Souza, R. de A. Coelho, and H. G. M. S. de Medeiros, “High impedance fault detection method based on the short-time Fourier transform,” *IET Generation, Transmission & Distribution*, vol. 12, no. 11, pp. 2577–2584, 2018.
[53] N. Q. Z. Abidin, A. R. Abdullah, N. Norddin, A. Aman, and K. A. Ibrahim, "Leakage current analysis on polymeric surface condition using time-frequency distribution," *2012 IEEE International Power Engineering and Optimization Conference Melaka, Malaysia*, 2012, pp. 171–175, doi: 10.1109/PEOCO.2012.6230855..
[54] E. M. Lima, R. de A. Coelho, N. S. D. Brito, and B. A. de Souza, "High Impedance Fault Detection based on Stockwell Transform," *2018 IEEE PES Transmission & Distribution Conference and Exhibition-Latin America*, 2018, pp. 1–5, doi: 10.1109/TDC-LA.2018.8511711.
[55] P. A. Karthick, D. M. Ghosh, and S. Ramakrishnan, “Surface electromyography based muscle fatigue detection using high-resolution time-frequency methods and machine learning algorithms,” *Computer Methods and Programs in Biomedicine*, vol. 154, pp. 45–56, February 2018, doi: 10.1016/j.cmpb.2017.10.024.
[56] P. Srikanth and C. Koley, “Intelligent System for Monitoring and Recognising the Type of Domestic Harmonic Loads,” in *Advances in Intelligent Systems and Computing*, Springer, vol. 1096, pp. 249–267, 2020, doi: 10.1007/978-981-15-1532-3_11.
[57] M. Biswal and P. K. Dash, "Measurement and Classification of Simultaneous Power Signal Patterns With an S-Transform Variant and Fuzzy Decision Tree," in *IEEE Transactions on Industrial Informatics*, vol. 9, no. 4, pp. 1819–1827, 2013, doi: 10.1109/TII.2012.2210230.
[58] C. Y. Mei, A. Z. Sha’ameri, and B. Boashash, “Efficient phase estimation for the classification of digitally phase modulated signals using the cross-WVD: a performance evaluation and comparison with the S-transform,” *EURASIP Journal on Advances in Signal Processing*, vol. 2012, no. 1, pp. 1–12, March 2012, doi: 10.1186/1687-6180-2012-65.
[59] N. H. T. H. Ahmad, A. R. Abdullah, N. A. Abidullah, and M. H. Jopri, “Analysis of Power Quality Disturbances Using Spectrogram and S-transform,” *International Review Electrical Engineering (IREE)*, vol. 3, no. 3, pp. 611–619, June 2014.
[60] N. A. Abidullah, A. R. Abdullah, N. H. Shamsudin, N. H. T. H. Ahmad, and M. H. Jopri, "Real-time power quality signals monitoring system," *2013 IEEE Student Conference on Research and Developement*, 2013, pp. 433–438, doi: 10.1109/SCOReD.2013.7002626.
[61] J. R. Macedo, J. W. Resende, C. A. Bissochi, D. Carvalho, and F. C. Castro, “Proposition of an interharmonic-based methodology for high-impedance fault detection in distribution systems,” *IET Generation, Transmission & Distribution*, vol. 9, no. 16, pp. 2593–2601, 2015.
[62] G. N. Lopes, T. S. Menezes, G. G. Santos, L. H. P. C. Trondoli, and J. C. M. Vieira, “High Impedance Fault detection based on harmonic energy variation via S-transform,” *International Journal of Electrical Power & Energy Systems*, vol. 136, p. 107681,

March 2022, doi: 10.1016/j.ijepes.2021.107681.
[63] A. Soheili, J. Sadeh, and R. Bakhshi, "Modified FFT based high impedance fault detection technique considering distribution non-linear loads: Simulation and experimental data analysis," *International Journal of Electrical Power & Energy Systems*, vol. 94, pp. 124–140, January 2018, doi: 10.1016/j.ijepes.2017.06.035.
[64] W. Tee, M. R. Yusoff, A. R. Abdullah, M. H. Jopri, N. S. N. Anwar, and H. Musa, "Spectrogram based window selection for the detection of voltage variation," *International Journal of Integrated Engineering*, vol. 11, no. 3, pp. 240–247, 2019, doi: 10.30880/ijie.2019.11.03.025.
[65] H. Lala, S. Karmakar, and S. Ganguly, "Detection and localization of faults in smart hybrid distributed generation systems: A Stockwell transform and artificial neural network-based approach," *International Transactions on Electrical Energy Systems*, vol. 29, no. 2, p. e2725, 2019, doi: 10.1002/etep.2725.
[66] W. Tao, *et al.*, "Classification of power quality disturbance signals based on S-transform and HHT," *Proceedings of the 32nd Chinese Control Conference*, 2013, pp. 3639–3644.
[67] P. K. Dash, B. K. Panigrahi, and G. Panda, "Power quality analysis using S-transform," in *IEEE Transactions on Power Delivery*, vol. 18, no. 2, pp. 406–411, April 2003, doi: 10.1109/TPWRD.2003.809616.
[68] M. Pujiantara, D. O. Anggriawan, A. Tjahjono, D. Permadi, A. Priyadi, and M. H. Purnomo, "A Real-Time Current Harmonic Monitoring System Based on Stockwell Transform Method," *International Review of Electrical Engineering*, vol. 11, no. 2, pp. 193–199, 2016, doi: 10.15866/iree.v11i2.8227.
[69] M. Biswal and P. K. Dash, "Detection and characterization of multiple power quality disturbances with a fast S-transform and decision tree based classifier," *Digital Signal Processing*, vol. 23, no. 4, pp. 1071–1083, 2013, doi: 10.1016/j.dsp.2013.02.012.
[70] B. Y. Vasiliev, A. E. Kozyaruk, and D. V Mardashov, "Increasing the Utilization Factor of an Autonomous Inverter under Space Vector Control," *Russian Electrical Engineering*, vol. 91, no. 4, pp. 247–254, July 2020, doi: 10.3103/S1068371220040082.
[71] O. S. Vasilkov and V. S. Dobysh, "Features of Application Hybrid Energy Storage in Power Supply Systems," *2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, 2019, pp. 728–730, doi: 10.1109/EIConRus.2019.8656802.
[72] R. Nair, A. Jidin, M. N. Othman, M. H. Jopri, and M. Manap, "Comparison performance of 3-Level and 5-Level Cascaded H-Bridge multilevel inverter of DTC of Induction Machine," *2013 International Conference on Electrical Machines and Systems (ICEMS)*, 2013, pp. 2100–2104, doi: 10.1109/ICEMS.2013.6713181.
[73] L. R. L. V. Raj, A. Jidin, Z. Ibrahim, K. A. Karim, M. A. Said, and M. H. Jopri, "Optimal torque control performance of DTC of 5-phase induction machine," *2013 International Conference on Electrical Machines and Systems (ICEMS)*, 2013, pp. 2094–2099, doi: 10.1109/ICEMS.2013.6713180.
[74] M. H. Jopri, M. R. Ab Ghani, A. R. Abdullah, M. Manap, T. Sutikno, and J. Too, "K-nearest neighbor and naïve bayes based diagnostic analytic of harmonic source identification," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 6, pp. 2650-2657, September 2020, doi: 10.11591/eei.v9i6.2685.
[75] A. Amirou, Z. Zidelmal, and D. Ould-Abdeslam, "Stockwell-transform for electrical defaults localization," *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, 2015, pp. 1–6, doi: 10.1109/IRSEC.2015.7454937.
[76] N. Z. Saharuddin, N. A. Abidullah, N. S. Ahmad, M. Manap, and M. H. Jopri, "Performance Comparison of VSI Switches Faults Analysis Using STFT and S Transform," *Applied Mechanics Materials*, vol. 785, pp. 210–214, 2015, doi: 10.4028/www.scientific.net/amm.785.210.
[77] M. H. Jopri, M. R. Ab Ghani, A. R. Abdullah, T. Sutikno, M. Manap, and J. Too, "Naïve bayes and linear discriminate analysis based diagnostic analytic of harmonic source identification," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 20, no. 3, pp. 1626–1633, December 2020, doi: 10.11591/ijeecs.v20.i3.pp1626-1633.
[78] J. Deng, C. S. Lam, M. C. Wong, S. W. Sin, and R. P. Martins, "Instantaneous power quality indices detection under frequency deviated environment," *IET Science, Measurement & Technology*, vol. 13, no. 8, pp. 1111–1121, 2019, doi: 10.1049/iet-smt.2018.5123.
[79] M. H. Jopri, A. R. Abdullah, M. Manap, M. R. Yusoff, T. Sutikno, and M. F. Habban, "An Improved of Multiple Harmonic Sources Identification in Distribution System with Inverter Loads by using Spectrogram," *International Journal of Power Electronics and Drive System (IJPEDS)*, vol. 7, no. 4, pp. 1355–1365, December 2016, doi: 10.11591/ijpeds.v7i4.pp1355-1365.
[80] M. H. Jopri, A. R. Abdullah, M. Manap, M. R. Yusoff, T. Sutikno, and M. F. Habban, "An improved detection and classification technique of harmonic signals in power distribution by utilizing spectrogram," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 7, no. 1, pp. 12–20, February 2017, doi: 10.11591/ijece.v7i1.pp12-20.
[81] M. H. Jopri, A. R. Abdullah, M. Manap, T. Sutikno, and M. R. Ab Ghani, "An identification of multiple harmonic sources in a distribution system by using spectrogram," *Bulletin of Electrical Engineering and Informatics*, vol. 7, no. 2, pp. 244–256, June 2018, doi: 10.11591/eei.v7i2.1188.
[82] M. K. Rathi and N. R. Prabha, "Grid interconnected photo voltaic system using shunt active filter for power quality improvement," *International Journal of Power Electronics and Drive System (IJPEDS)*, vol. 9, no. 1. pp. 365–376, March 2018, doi: 10.11591/ijpeds.v9n1.pp365-376.

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