

A Critical Review of Time-frequency Distribution Analysis for Detection and Classification of Harmonic Signal in Power Distribution System

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ABSTRACT

This paper presents a critical review of time-frequency distributions (TFDs) analysis for detection and classification of harmonic signal. 100 unique harmonic signals comprise of numerous characteristic are detected and classified by using spectrogram, Gabor transform and S-transform. The rule-based classifier and the threshold settings of the analysis are according to the IEEE Standard 1159 2009. The best TFD for harmonic signals detection and classification is selected through performance analysis with regards to the accuracy, computational complexity and memory size that been used during the analysis.

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1. INTRODUCTION

The power quality (PQ) term originates from the idea that the AC voltage supplied to the domestic and industrial equipment must be unpolluted sinusoidal and its frequency and magnitude as must be in the range of IEEE and IEC standards. Nowadays, one of the main issue of PQ is harmonic pollution, this is due to the use of different power electronics equipment and nonlinear loads [1], [2]. A harmonic pollution monitoring in the distribution system is vital for the study of the root causes, harmonic level and mitigation [3]-[5]. This harmonic pollution can decline the PQ, it additionally can increase the power losses and lead to the malfunction of equipment and measurement [6], [7].

A comprehensive research is necessary for producing an accurate, fast and reliable method for the harmonic signal detection and classification [8], [9]. Numerous methods are proposed for detection and classification of a harmonic signal, as straightforward and fast such as Fast Fourier Transform (FFT) [10]. FFT is effectively employed on stationary signals [11], [12]. Yet, FFT is not an appropriate method for non-stationary signal analysis and contributes time information loss throughout the frequency domain conversion [13], [14]. To deal with non-stationary signal, short-time Fourier transform (STFT) is introduced [14], [15].

Nevertheless, STFT is not proficient to detect the dynamic signal property because the window width fixed to affect the frequency-time resolution [6], [8], [16]. Whereas, the time-frequency resolution depends upon the size of the window [17], [5].

The constraint of STFT is resolved by utilizing Gabor transform (GT) and GT has the feature of extraction tool, due to the optimality concerning the time-frequency uncertainty characteristic [18]. As suggested by GT, the functions are well-defined as Gaussian envelope modulated by complex sinusoids with a fixed envelope for all frequencies [19]-[21]. However, the result shows that the method requires high computation complexity compared to the STFT due to the use of discrete Fourier transform (DFT) [10]. In order to overcome STFT and GT limitation, the wavelet transform (WT) is proposed [22]. WT can extract the significant information from non-stationary and it can distinguish the signal characteristics [6], [18], [23]. The major drawback of WT are the accuracy thoroughly relies on the chosen mother wavelet, sensitive to the level of noise and high computation complexity [18], [24], [25]. Subsequently, a combination of STFT and WT known as S-transform (ST) is presented due to mitigate the WT problem [6], [26], [27]. Furthermore, the ST is a reliable technique to characterize the harmonic parameters [26], [28], [22]. The ST also offers an extraordinary multiresolution analysis while characterizing the harmonic components [9], [18], [16], [22]. Based on above discussion, an evaluation and a critical review of TFDs for harmonic signal detection and classification are crucial and need to be done.

The main concern of this paper is to evaluate and review the best TFDs in harmonic signal detection and classification technique. The assessment of the harmonic signal analysis is using the TFDs such as spectrogram, GT and ST are actualized in time-frequency domain [29], [30]. The performance of each TFD is compared and validated with regards to accuracy, computational complexity and the used memory size during the analysis. The performance of these TFDs are validated by detecting and classifying the 100 unique signals with numerous characteristics of harmonic signal accordingly to the IEEE Std. 1159-2009. The best TFD is chosen by determining the most accurate method, used low memory size and additionally low computational complexity.

2. HARMONIC SIGNAL ANALYSIS

There are four primary phases in the harmonic signal detection and classification analysis as shown in Figure 1. The 1st phase is the signal normalization and representation of time-frequency representation (TFR). Meanwhile, the 2nd phase is the estimation of fundamental signals parameters. Moreover, the 3rd phase is the signal characteristics identification and finally, the 4th phase is the harmonic signal classification. The harmonic signal is standardized where the voltage magnitude is changed into the per-unit system. Meanwhile, via TFDs, the outcome of the analysis is presented in the time-frequency domain.

The parameters comprise of the RMS fundamental voltage, total waveform distortion, instantaneous of RMS voltage, total nonharmonic distortion and total harmonic distortion are calculated. Lastly, according to the IEEE Std. 1159-2009, this information is utilized as the rule-based classifier input due to classify the harmonic signals.



Figure 1. Flow chart of harmonic signal detection and classification

3. HARMONIC SIGNALS MODELING

Due to model the signals for analysis, a few parameters for each unique signal are proposed and permitted to be altered according to the IEEE Std. 1159-2009. The signal model can be written as a complex exponential signal and well-defined as [31],

$$x_{wd}(t) = e^{j2\pi f_0 t} + A e^{j2\pi f_i t} \quad (1)$$

Whereby, f_0 is the fundamental signal frequency and f_i is the harmonic or interharmonic frequency and t is the time, $f_i=250$ Hz, $A=0.25$ for harmonic and $f_i=275$ Hz, $A=0.25$ for interharmonic.

4. THE TIME-FREQUENCY DISTRIBUTIONS

Time-frequency distributions (TFDs) are excellent methods that presented a signal in time-frequency representation and recognized as time-frequency representation (TFR). In the subsequent sections, the TFDs consist of the spectrogram, GT and ST are explained.

4.1. Spectrogram

The spectrogram is a method to represents a signal energy distribution in jointly time and frequency [32]. It is well-defined as, in this research, the Hanning window is carefully chosen as its lower peak side lobe has a feature of narrow effect on the frequency components. For this research, the length of the window is 512 and the frequency and time resolution for spectrogram is fixed for all frequencies.

$$P_x(t, f) = \left| \int_{-\infty}^{\infty} x(\tau) w(\tau - t) e^{-j2\pi f \tau} d\tau \right|^2 \quad (2)$$

4.2. Gabor Transform

The descriptor of signal's local property of Gabor transform (GT) is obtained from a set of functions that are condensed in frequency and time domains [25]. The GT is well expressed by, in GT, Hanning window is used as well as a spectrogram, however dissimilar of window length. The resolution of frequency and time for GT is always same for all frequencies.

$$C(n, k) = \int_{-\infty}^{\infty} x(\tau) h^*(n, k) d\tau \quad (3)$$

4.3. S-transform

S-transform (ST) is a hybrid of short time Fourier transform (STFT) and wavelet transform and used as a time-frequency spectral localization method [17]. ST utilizes a scalable of the Gaussian window and the resolution of frequency based on the simultaneous localization of the real and imaginary spectra [5]. The ST is well written as,

$$ST(\tau, f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} e^{\frac{-(\tau-t)^2 f^2}{2}} e^{-j2\pi f t} dt \quad (4)$$

$$g(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-t^2}{2\sigma^2}} \quad (5)$$

$$\sigma(f) = \frac{1}{|f|} \quad (6)$$

Whereby $h(t)$ is the signal, $g(t)$ is the scalable Gaussian window and $\sigma(f)$ is a control parameter for the Gaussian window. ST offers superior frequency resolution for lower frequency. Meanwhile, for higher frequency, ST delivers good time resolution. The extraction of frequency components is achieved by utilizing wide window (low frequency) and narrow window (high frequency) due to compose high frequency

components [32]. In this research, spectrogram and GT with the utilization of Hanning window are used to calculate the time and frequency. Meanwhile, the scalable Gaussian window is used for ST method.

5. SIGNAL PARAMETERS

Harmonic signals parameters are estimated from the TFR and the signal parameters consist of instantaneous RMS voltage and RMS fundamental voltage, instantaneous total waveform distortion (*TWD*), instantaneous total harmonic distortion (*THD*) and instantaneous total interharmonic distortion (*TnHD*).

5.1. Instantaneous RMS Voltage

Root-mean square (RMS) voltage, V_{rms} is defined as [32],

$$V_{rms}(t) = \sqrt{\int_0^{f_s} P_x(t, f) df} \quad (7)$$

Whereby $P_x(t, f)$ is the TFR signal and f_s is sampling frequency.

5.2. Instantaneous RMS Fundamental Voltage

From the TFR, the instantaneous RMS fundamental voltage, $V_{1rms}(t)$, can be calculated using [31],

$$V_{1rms}(t) = \sqrt{2 \int_{f_{lo}}^{f_{hi}} P_x(t, f) df} \quad (8)$$

$$f_{hi} = f_0 + 25 \text{ Hz}$$

$$f_{lo} = f_0 - 25 \text{ HZ}$$

Whereby $P_x(t, f)$ is the TFR signal, f_0 is the fundamental frequency.

5.3 Instantaneous Total Waveform Distortion

The total waveform distortion, *TWD* is well-defined as the relative signal energy existing at a non-fundamental frequency and expressed as [31],

$$TWD(t) = \frac{\sqrt{V_{rms}(t)^2 - V_{1rms}(t)^2}}{V_{1rms}(t)} \quad (9)$$

5.4. Instantaneous Total Harmonic Distortion

Total harmonic distortion, *THD*, is utilized due to measure the harmonic content in a waveform and formulated as [31],

$$THD(t) = \frac{\sqrt{\sum_{h=2}^H V_{h,rms}(t)^2}}{V_{1rms}(t)} \quad (10)$$

5.5. Instantaneous Total Nonharmonic Distortion

A signal also comprises interharmonic components and the interharmonic level can be calculated using [31],

$$TnHD(t) = \frac{\sqrt{V_{rms}(t)^2 - \sum_{h=0}^H V_{h,rms}(t)^2}}{V_{1rms}(t)} \quad (11)$$

6. SIGNAL CHARACTERISTIC

The characterization of signals is obtained from the calculated signal parameters. Average of total harmonic distortion, THD_{ave} and total nonharmonic distortion, $TnHD_{ave}$ can be calculated from instantaneous total harmonic distortion, $THD(t)$ and instantaneous total nonharmonic distortion, $TnHD(t)$, respectively. These characteristics can be expressed as [31],

$$V_{rms,ave} = \frac{1}{T} \int_0^T V_{rms}(t) dt \quad (12)$$

$$THD_{ave} = \frac{1}{T} \int_0^T THD(t) dt \quad (13)$$

$$TnHD_{ave} = \frac{1}{T} \int_0^T TnHD(t) dt \quad (14)$$

7. SIGNAL CLASSIFICATION

A deterministic classification method which is the rule-based classifier extensively employed in the practical application. This method is easy to be implemented and its performance is much reliant on the threshold settings and expert rules. The flow chart in Figure 2 describes a rule-based classifier for the harmonic signals. Furthermore, the threshold settings are set according to IEEE Std. 1159-2009.

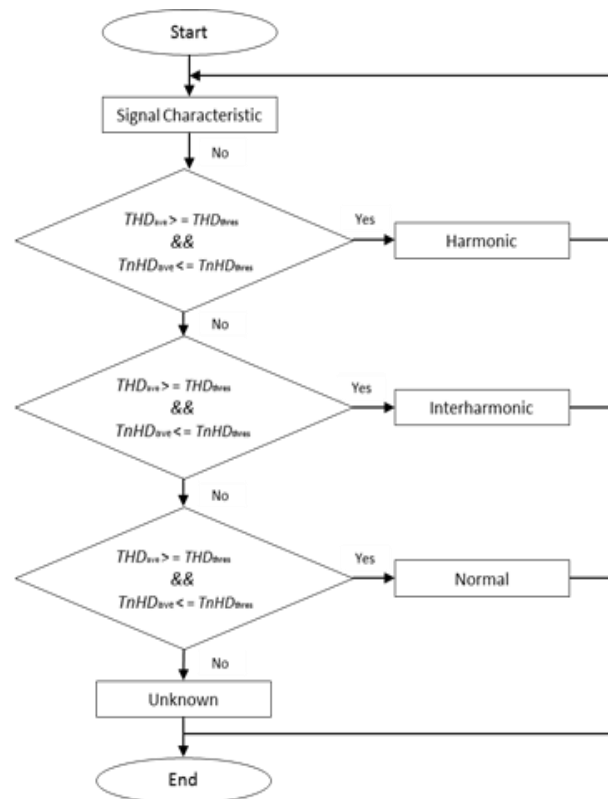


Figure 2. The rule-based classifier flow chart for harmonic signals

8. PERFORMANCE MEASUREMENTS OF TIME-FREQUENCY DISTRIBUTIONS

The performance and viability of proposed method depend on the accuracy of this technique and the evaluation of accuracy can be done as follows.

8.1. The Analysis Accuracy

The analysis accuracy is calculated through the signal characteristics measurement accuracy. To measure the measurement accuracy, the mean absolute percentage error (MAPE) is employed as an accuracy index. The lower the MAPE, the better the performance of the signal characteristics measurement [32]. It can be written as,

$$MAPE = \frac{1}{N} \sum_{n=1}^N \left| \frac{x_i(n) - x_m(n)}{x_i(n)} \right| \times 100\% \quad (15)$$

Whereby $x_i(n)$ is an actual value, $x_m(n)$ is measured value and N is the data number. The smaller value of the MAPE, the better the accuracy is.

8.2. The Computational Complexity of the Analysis

The computational complexity of TFDs to represent the TFR of signals reliant on the parameters setting of each TFD. The spectrogram and ST both used fast Fourier transform (FFT) that deals fast computation. Meanwhile, GT executes discrete Fourier transform (DFT) and has more computational complexity compare to FFT [18]. The computational complexity index can be calculated as follows,

$$Cr_{spectrogram} = N - N_w (N_w \log_2(N_w)) \quad (16)$$

$$Cr_{Gabor} = N - N_w (N_w^2) \quad (17)$$

$$Cr_{ST} = N - N_w (N_w + N_w \log_2(N_w)) \quad (18)$$

8.3. The Memory Size of the Analysis

The signal length number and TFD parameters setting influence the size of memory used for TFR [18]. The memory is expressed as,

$$Memory_{LinearTFD} = \frac{N_w(N - N_w)}{N_s} \quad (19)$$

9. RESULTS AND ANALYSIS

This section discuss the results of harmonic signals detection and classification analysis by using TFDs and the best TFD is chosen based on the accuracy, computational complexity and memory size during the TFDs analysis. This section discuss the results of harmonic signals detection and classification analysis by using TFDs and the best TFD is chosen based on the accuracy, computational complexity and memory size during the TFDs analysis.

9.1. Harmonic Signal Analysis by Using Spectrogram

Figure 3(a) and 3(b) depict harmonic signal in the time domain and the TFRs using spectrogram. The TFRs show the signal parameters comprise of the fundamental frequency at 50Hz and the 7th harmonic component at 350Hz, respectively. Furthermore, Figure 3(c) shows that the harmonic voltage has contributed to the rise of the RMS voltage from 1.0 to 1.17 pu. However, the RMS fundamental voltage still remains at 1.0 pu. Besides that, the *TWD* and *THD* of the signals are 60% and zero *TnHD* are calculated and presented well in Figure 3(d). Hence, from the analysis show that there is no interharmonic signal is exist in the signal.

The existence of interharmonic signal is analyzed with spectrogram and its TFR is demonstrates in Figure 4(a) and 4(b), separately. As demonstrates in Figure 4(b), the signal consists of fundamental frequency at 50 Hz and the interharmonic frequency at 375 Hz, respectively. Figure 4(c) shows that the existence of interharmonic voltage has increased the RMS voltage from 1.0 to 1.17 pu. The analysis also results the *TWD* and *TnHD* are 60% and as depicts in Figure 4(d), the *THD* is zero percent. Therefore, the results of the analysis show only fundamental and interharmonic signal exist in the signal.

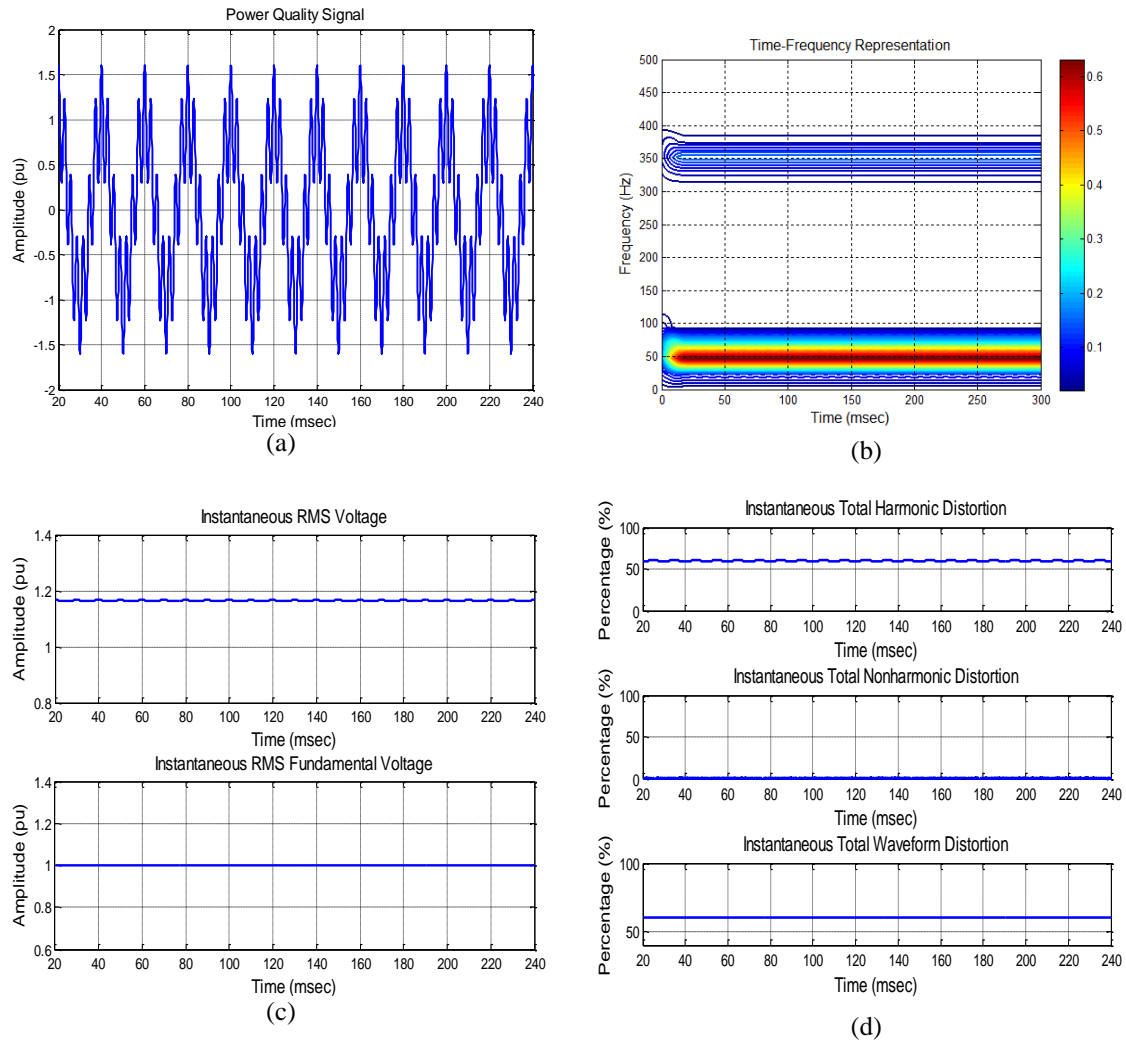


Figure 3. (a) Harmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion.

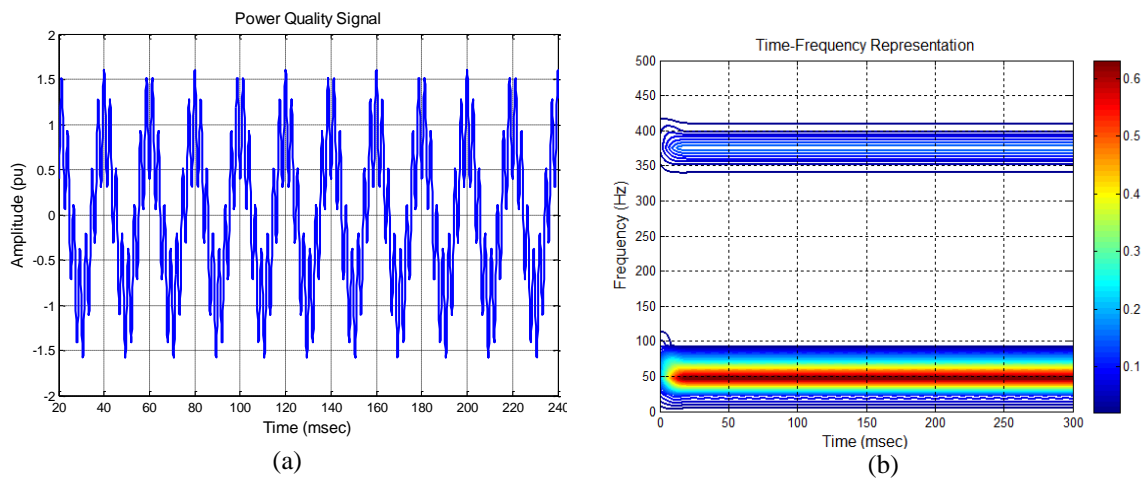


Figure 4. (a) Interharmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion.

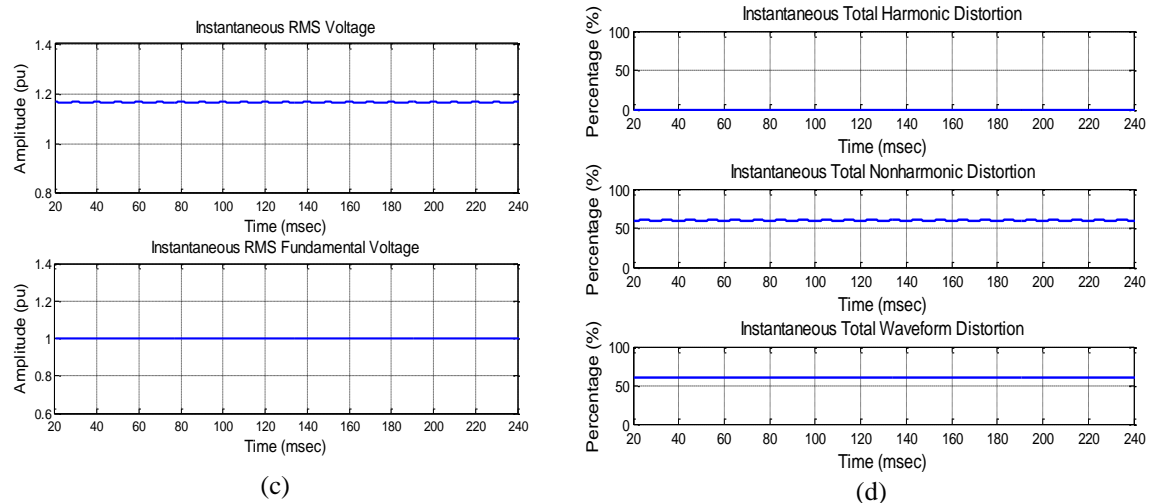


Figure 4. (a) Interharmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion.

9.2. Signal Analysis Using Gabor Transform

Figure 5(a) and 5(b) present harmonic signal in time domain and the TFR by using GT. From the TFR, it is shown that the signal contains fundamental frequency at 50 Hz and the 7th harmonic component at 350 Hz. In the meantime, Figure 5(c) shows that the existence of harmonic voltage has increased the RMS voltage from 1.0 to 1.17 pu. The analysis outcome in Figure 5(d) shows that the TWD and THD of the signal are at a value of 60% and the TnHD is zero percent as figured in Figure 5(d). Thus, it is clearly shown that no interharmonic component exists in the signal.

Figure 6(a) and 6(b) show the analysis outcome of the signal with interharmonic component and the TFR using GT. From the TFR, it is shown that only the fundamental frequency at 50 Hz and the interharmonic component at 375 Hz exist in the signal. Meanwhile, as shown in Figure 6(c), the existence of interharmonic voltage has increased the RMS voltage from 1.0 to 1.17 pu. In addition, from Figure 6(d), the analysis also presents the value of TWD and TnHD is 60% and zero percent for THD. Thus, from the analysis, it clearly shows that only fundamental and interharmonic components exist in the signal.

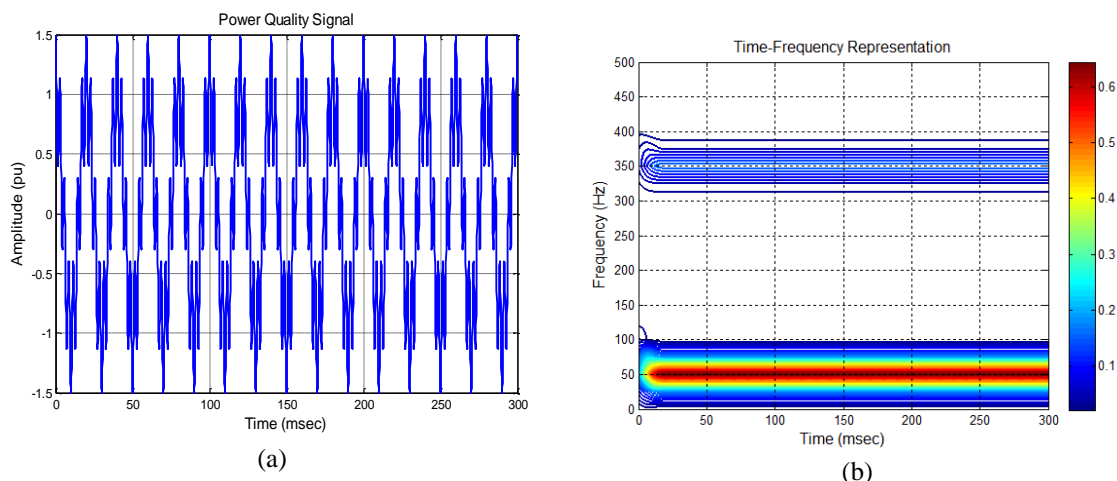


Figure 5. (a) Harmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion

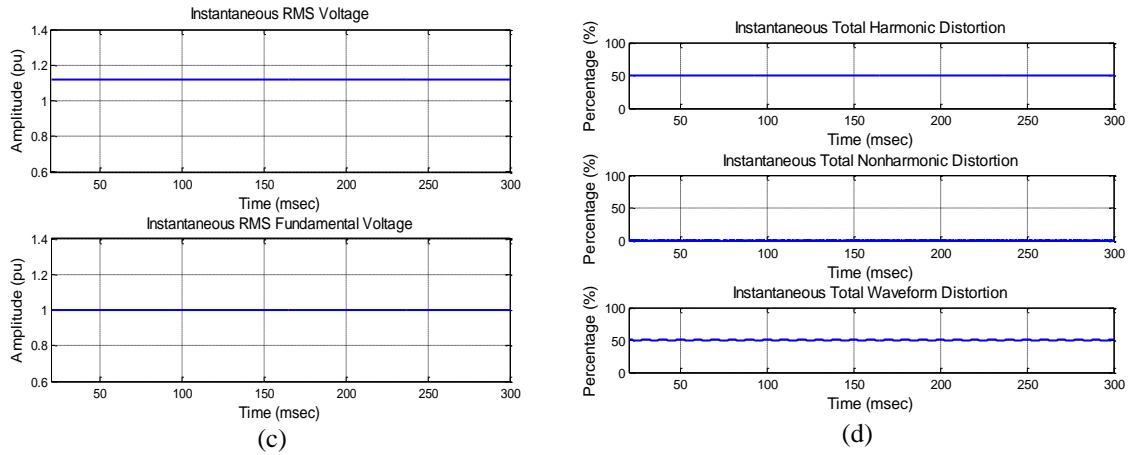


Figure 5. (a) Harmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion

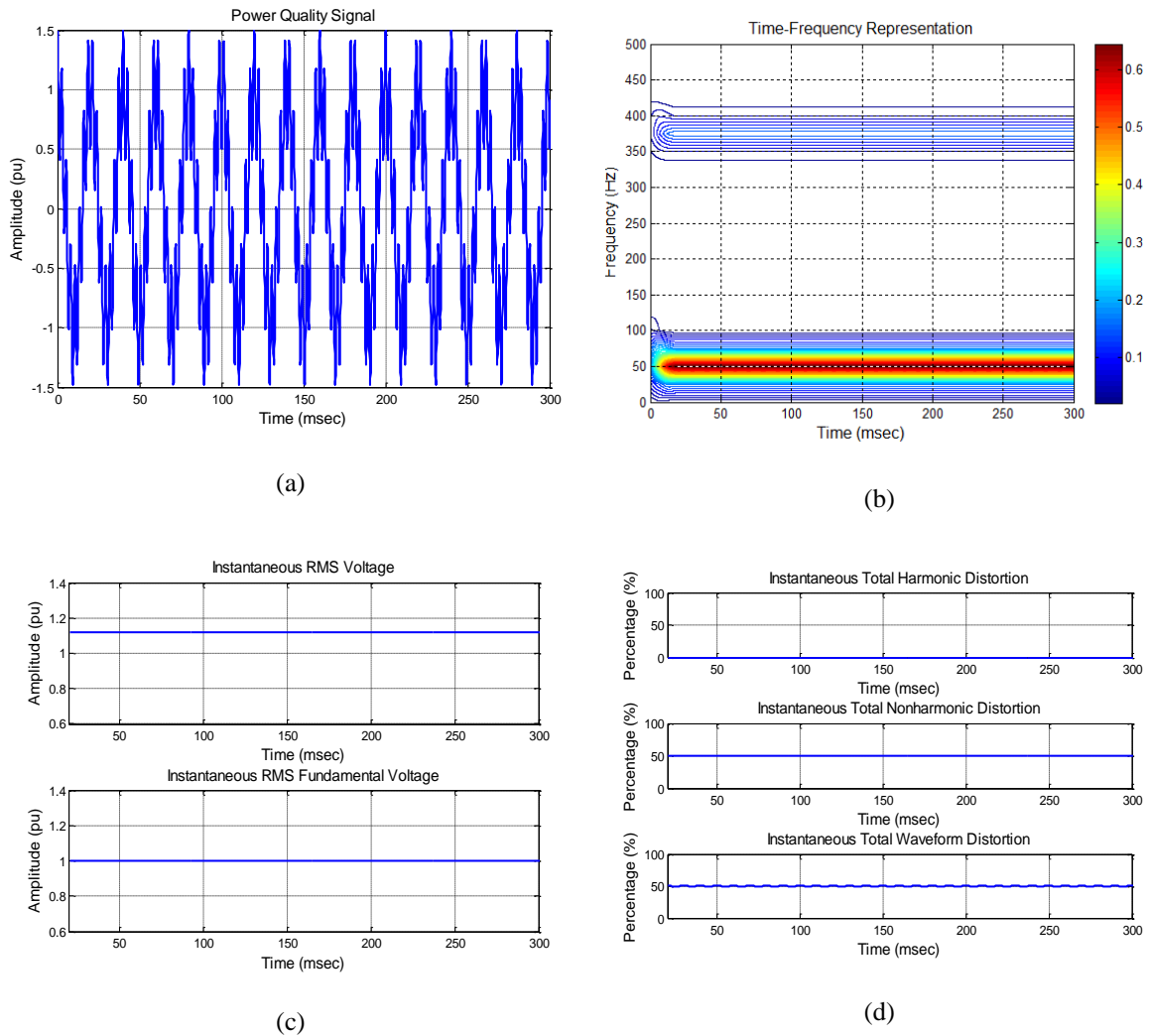


Figure 6. (a) Interharmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion

9.3. Signal Analysis Using S-transform

Figure 7(a) and 7(b) present harmonic signal in time domain and the TFR by using ST. From the TFR, it is clearly figured that the signal comprises the fundamental frequency at 50Hz and the 7th harmonic component at 350 Hz. In the meantime, Figure 4(c) shows that the existence of harmonic component has increased the RMS voltage from 1.0 to 1.1 pu. In addition, Figure 4(d) demonstrates the magnitude of *TWD* and *THD* is 10% and zero percent for the *TnHD*. Hence, from the analysis, it is plainly shown that no interharmonic component exists in the signal.

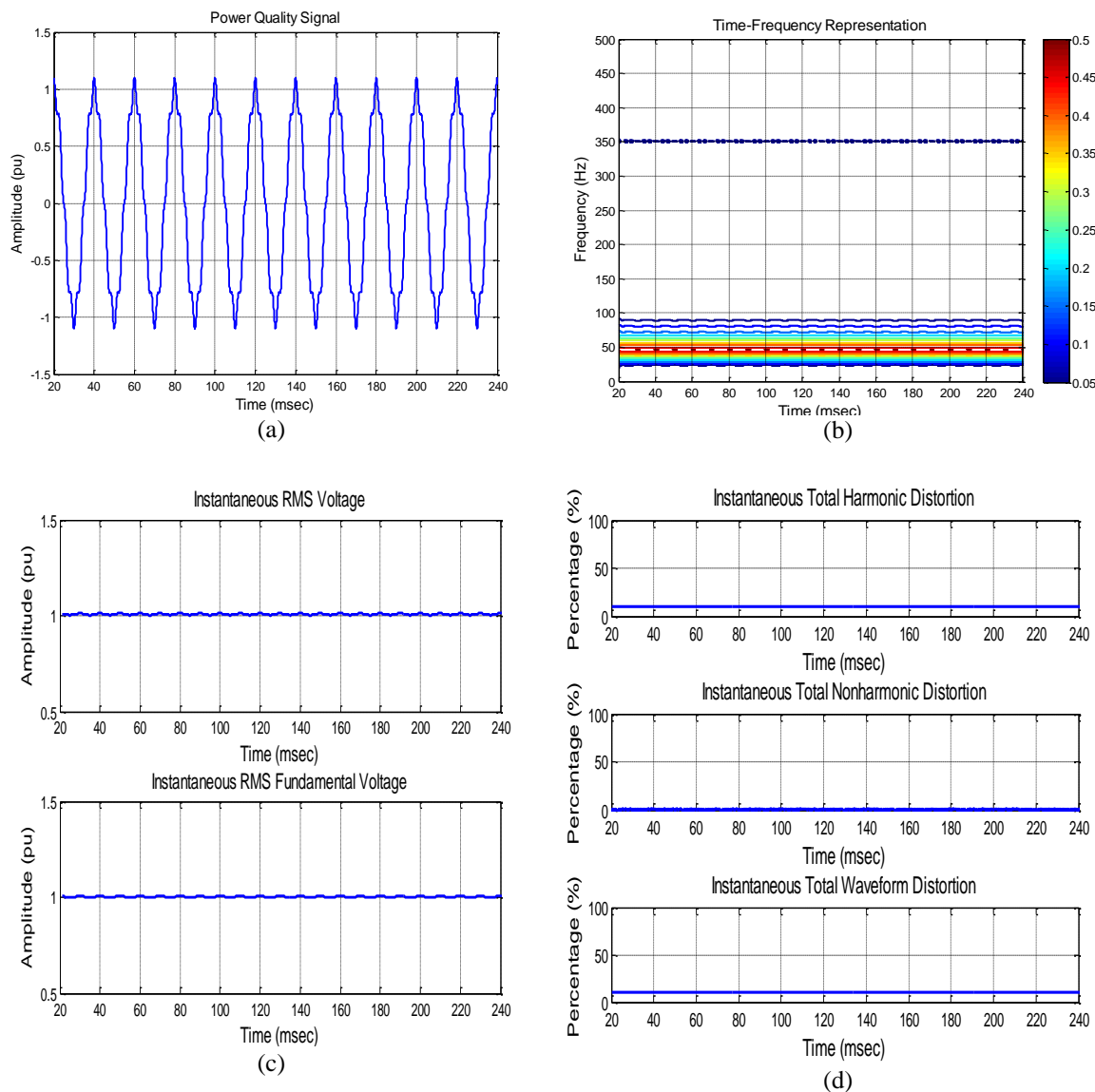


Figure 7. (a) Harmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion

Figure 8(a) and 8(b) present the interharmonic signal and the TFR by using ST, respectively. The signal has a fundamental component at 50 Hz and interharmonic component at 375 Hz. Figure 8(c) shows that the interharmonic voltage contributes to the rise of RMS from 1.0 to 1.1 pu. In addition, the signal analysis presents the magnitude of *TWD* and *TnHD* with a value of 10% and zero percent for the *THD* as shown in Figure 8(d). Thus, the analysis clearly shows that only the fundamental and interharmonic components exist in the signal.

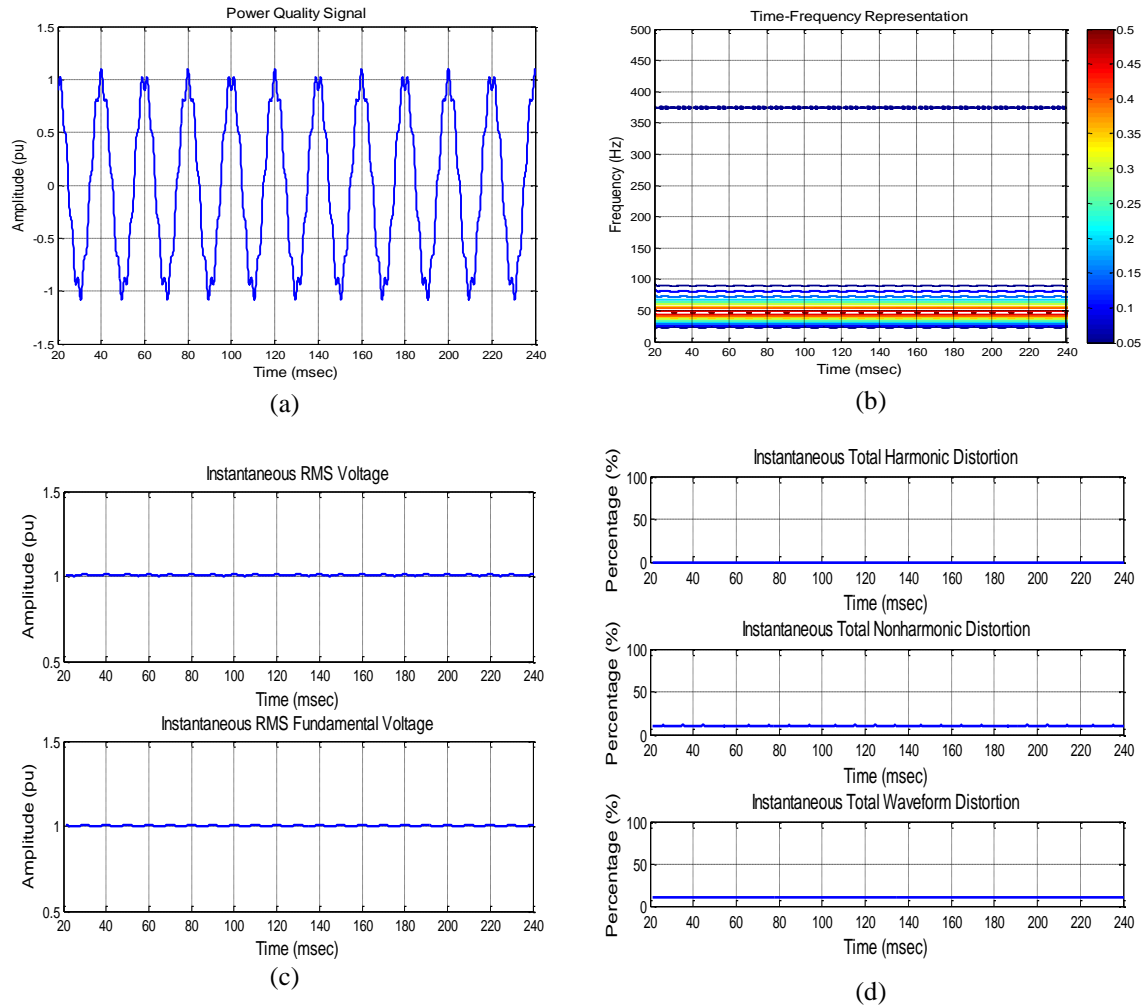


Figure 8. (a) Interharmonic signal in time domain, (b) Harmonic signal in TFR, (c) Instantaneous RMS voltage and RMS fundamental voltage, (d) Instantaneous total harmonic distortion, total nonharmonic distortion and total waveform distortion

9.4. The Performance Analysis of the Time-frequency Distributions

To identify the best method for harmonic signal analysis, TFDs are compared in terms of the accuracy, used memory size and computational complexity of the algorithm. 100 unique signals are generated and employed in the analysis.

9.4.1. The Accuracy of the Analysis

Harmonic signals are classified and the mean absolute percentage error (MAPE) of the signal characteristics is calculated as shown in Table 1. The table indicates that the ST gives an excellent accuracy of V_{rms} , THD and $TnHD$. This is due to the method offers an excellent time resolution for high frequency and excellent frequency resolution for low frequency.

Table 1. MAPE of Simulation Results of the TFDs

| Signal Characteristics | TFDs | | |
|------------------------|-------------|-----------------|-------------|
| | Spectrogram | Gabor Transform | S-transform |
| $V_{rms_{ave}}$ | 0.1572 | 0.5293 | 0.0426 |
| THD_{ave} | 0.1551 | 0.9967 | 0.0541 |
| $TnHD_{ave}$ | 0.1595 | 0.9331 | 0.0533 |

The tabulation of Table 1 is presented in the bar graph in order to have a good observation on MAPE value. The lower the MAPE value, the accurate the results are. Hence, the result plainly shows that the ST is the best method to measure the signal characteristics.

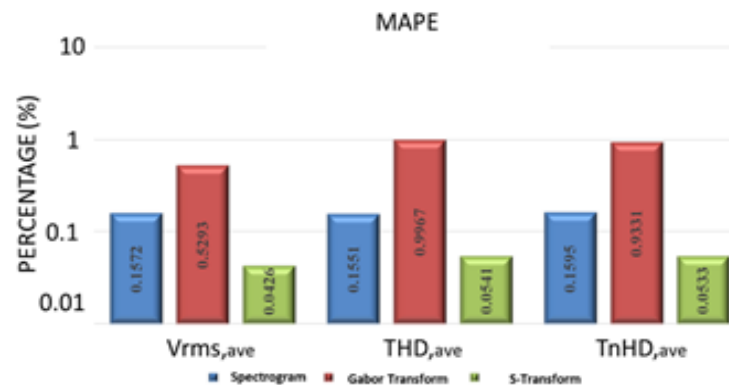


Figure 9. Average of MAPE for the TFDs

9.4.2. The Computational Complexity of the Analysis

The computational complexity of the analysis for each TFD is tabulated in Table 2. As demonstrates in the table, spectrogram, GT and ST contribute same computational ratio. This is because the windows length and a number of the signal are same for each TFD.

Table 2. Computation Complexity of the TFDs

| Signal | TFDs | | |
|---------------|-------------|-----------------|-------------|
| | Spectrogram | Gabor Transform | S-transform |
| Normal | 20,680,704 | 1,041,408,000 | 22,978,560 |
| Harmonic | 20,680,704 | 1,041,408,000 | 22,978,560 |
| Interharmonic | 20,680,704 | 1,041,408,000 | 22,978,560 |

The bar graph as presents in Figure 10, point out that spectrogram offers the lowest computational complexity, while GT is the highest. Hence, it is summarize that the spectrogram offers the fastest speed for harmonic signal analysis and then ST while GT is the slowest.

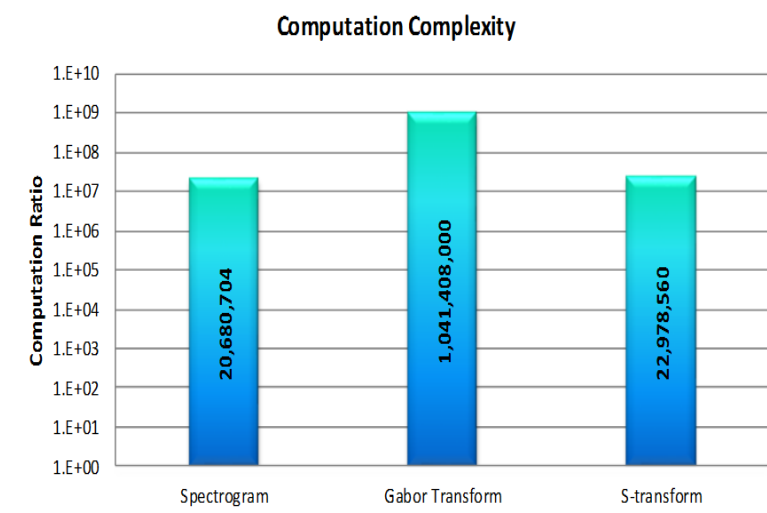


Figure 10. An average of computation complexity used for the TFDs

9.4.3. The Memory Size of Data Analysis

Table 3 presents the average memory size used during the signal analysis for each TFD. Meanwhile, the graph as presented in Figure 11 show that the GT offers the lowest used memory size while spectrogram and ST utilized the biggest during the analysis. The memory size for spectrogram and ST are similar due to the same window size in the analysis.

Table 3. Used Memory Size of TFRs for the TFDs

| Signal | TFDs, (Mbyte) | | |
|---------------|---------------|-----------------|-------------|
| | Spectrogram | Gabor Transform | S-transform |
| Normal | 2,297,856 | 2,250,000 | 2,297,856 |
| Harmonic | 2,297,856 | 2,250,000 | 2,297,856 |
| Interharmonic | 2,297,856 | 2,250,000 | 2,297,856 |

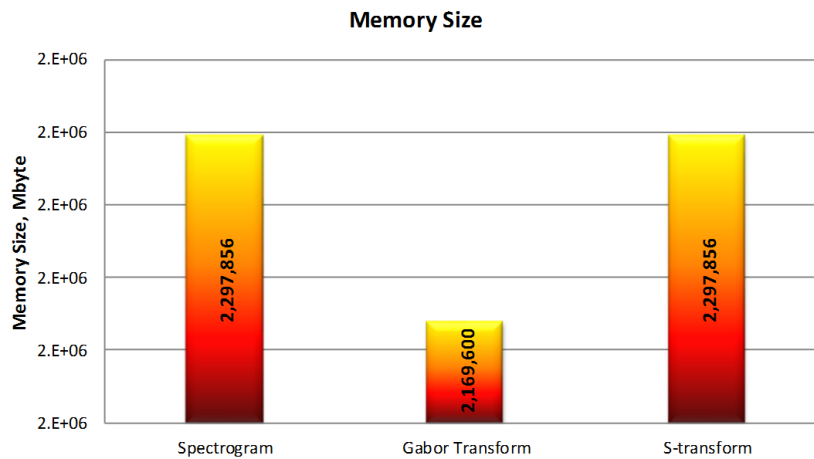


Figure 11. Average of memory size used for the harmonic signal analysis

9.4.3. The Best Time-frequency Distribution Technique

The results of the accuracy, computational complexity and used memory size of are depict in Figure 12. The performance evaluation of the best TFD based on the highest priority of criteria which is an accuracy, followed by the computational complexity and memory size.

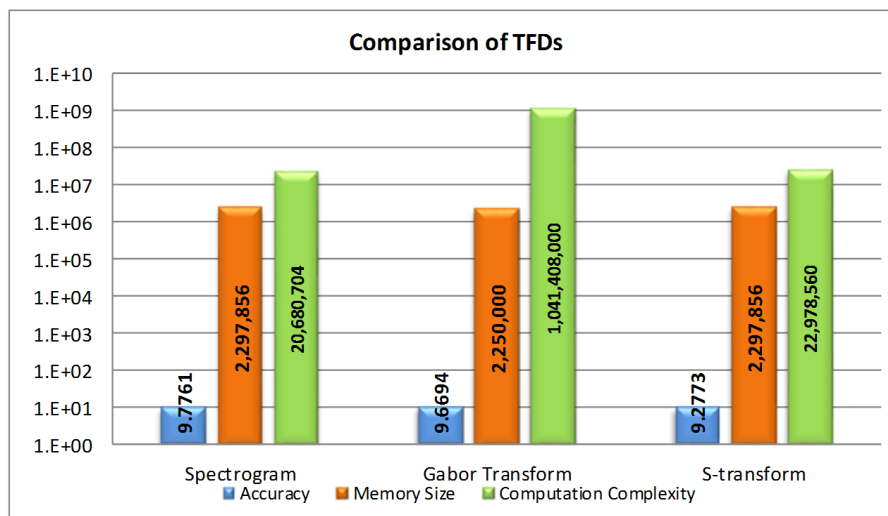


Figure 12. The performance comparison of TFDs

As demonstrate in Figure 12, the spectrogram offers the lowest computational complexity. However, it used high memory size and provides the lowest accuracy. The poorest TFD is GT that request high computational complexity and offers low accuracy. Aimed at ST, it offers the highest accuracy, low memory size and additionally low computational complexity. Thus, the outcome, unmistakably, demonstrates that the ST is the best TFD for harmonic signal detection.

9.4.3. The Classification of Harmonic Signal

ST has been identified as the best TFD in this research for harmonic signals detection. The results of the signals classification using the ST are present in Table 4. The 100 unique signals with numerous characteristics were generated and classified. The classification results show that the ST provides 100% correct classification for all harmonic signals. From the outcomes, it can be inferred that ST is the best technique for harmonic signal detection and classification.

Table 4. Performance of Power Quality Signal Classification for S-transform

| Signal | S-transform | |
|---------------|---------------------|--------------------------|
| | Number of data sets | % Correct Classification |
| Harmonic | 100 | 100 |
| Interharmonic | 100 | 100 |
| Normal | 100 | 100 |

10. CONCLUSION

The main concern of this paper is to evaluate and review the best TFD in harmonic signal detection and classification. The evaluation of the harmonic signal analysis using the TFDs actualized in time-frequency domain and compared in terms of accuracy, computational complexity and used memory size during the analysis. The performance of these methods are confirmed by detecting and classifying 100 unique signals with numerous characteristics of the harmonic signal. The outcomes demonstrate that ST is the best TFD with a criteria of the most accurate method, used low memory size and additionally low computational complexity.

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