An implementation of Short Time Fourier Transform for Harmonic Signal Detection

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Abstract. Power electronic components has the tendency to induce a non-linear signal called harmonic distortion. Without proper monitoring tools, harmonic distortion can harm sensitive electronic equipment, and in worse case scenarios, may lead to unreliable operation of controller and misalignment of motoring unit. This matter can be compromised by taking safety precaution, by identifying the level of harmonic rise in the electrical system. This paper presents analysis on different characteristics of harmonic signal using frequency distribution technique, namely Fourier transform (FT), and proposal of time-frequency distribution (TFD) technique, which is a short time Fourier transform (STFT). The novelty of utilizing STFT is the analyzed signal is represented in both time and frequency marginals, hence providing extra information of the spectral over the time. Simulation was carried out using MATLAB, by means the results consisting of the magnitude of multi-frequency components signal were represented in time-frequency representation (TFR). From the TFR, parameters such as instantaneous RMS fundamental voltage, $V_{\text{RMS}}(t)$, instantaneous RMS voltage, $V_{\text{RMS}}(t)$, instantaneous total waveform distortion, $V_{\text{THD}}(t)$, instantaneous total harmonic distortion, $V_{\text{THD}}(t)$ and instantaneous total nonharmonic distortion, $V_{\text{TnHD}}(t)$ had been extracted. The performance of different harmonic signals such as normal, single-level harmonic, multi-level harmonic, short duration harmonic and interharmonic had been analyzed. The performance based on absolute percentage error (APE) index indicated average of 93% of correctness using 256 window length in STFT measurement.

1. Introduction

Harmonic has always been an issue in power systems as its impact can lead to major loss especially on the customers’ side. The demand for clean power has been expanding since the utilization of microelectronic processor especially in PC programmable rationale controllers (PLCs). The indicative
framework responsible for disproportionate signal is called harmonic distortion [1,2]. Harmonic will elevate the RMS values in electrical resulting from involvement of multi-components at AC [3,4]. Without proper prevention, the harmonic lead to malfunction of vulnerable electronic equipments, which at the same time may lead to overvoltage, data loss and heating of equipment that share similar network [5,6]. This problem can be overcome by applying harmonic filter such as voltage regulator, but for large-scale industry, it is costly, therefore, proper monitoring tools should be placed [7]. If the harmonic level exceeds the limit guided in the IEEE 519-2014 and IEC 61000-3-2 standards, then proper prevention can be taken [8,9].

Normally, a traditional technique known as Fourier transform (FT) is employed to extract the frequency contents of the measured signal [10]. Power spectrum is used to display the analyzed results, in which y-axis and x-axis represent the signal magnitude and frequency, respectively [11,12]. The weakness of this technique is when a short-term transients like impulses and oscillatory transients occur over the samples measured, this technique is unable to locate the time when the faults occur [13]. In addition, time-evolving impacts of the frequency in nonstationary signals have not been considered in FT analysis [14]. Still, this technique is favorable for real-time monitoring because of its simplicity, as detailed in [15].

To overcome the limitation of FT, time-frequency distribution (TFD) is proposed in this paper. TFD presents an analyzed signal in three-dimensional plot, whereby additional time axis is involved. Techniques such as STFT [16], Gabor transform [17], wavelet transform [18] and S-transform [19], which are parts of linear TFD, can be used to estimate the harmonic parameters in a joint time-frequency. The function is divided into several intervals in term of time marginal by multiplication with a window function outcome from Fourier transform analysis at each interval [20]. Since such a window introduces artificial discontinuities and can create unwanted problems, overlap results along the time variable will reduce the accuracy of the analysis. In concern, appropriate type and optimum size of window need to be considered [21].

By implementing the STFT, better location of harmonic distortion can be detected in both time and frequency marginals. The STFT is formulated by selecting a sliding window where the FT is applied. Conceptually, STFT adapts a fixed window length, which makes the analysis effective either in time or frequency resolution. By means, higher window length results in better frequency resolution, while lower window length yields good time resolution [22]. For a narrow window or short time interval, a great time resolution can be obtained, which makes the analysis appropriate for short-time transients [23]. A relative wide window gives a good frequency resolution determination, but gives inaccurate outcome for time resolution [24]. As an alternative, multi-scale window using wavelet transform and S-transform is necessary since the results can be good in both time and frequency resolution [25]. Unfortunately, complex algorithm using this technique raises an issue [26].

The commercial harmonic monitoring system today is still dependent on FT analysis. The system is able to provide accurate information about harmonic level but unfortunately lacks temporal information [27]. The disadvantage is, since the harmonic distortion only occurs at certain period of time, the location of harmonic becomes untraceable [28]. Therefore, STFT is proposed to overcome this problem by providing temporal and spectral information in time-frequency representation (TFR) [29] as presented in Section 2. The values of the TFR surface over the time-frequency plane provide indication about spectral components that change along the time, while giving a clear view on the time-localized spectrum. In this paper, differentiation between normal and harmonic signals such as signal-level harmonic, multi-level harmonic, short duration harmonic and interharmonic is discussed. The sample signals were modeled using MATLAB software. The analyzed signal for FT was presented in power spectrum while the STFT was presented by TFR. The parameters estimated were instantaneous RMS fundamental voltage, $V_{RMS}(t)$, instantaneous RMS voltage, $V_{RMS}(t)$, instantaneous total waveform
distortion, $V_{TWD}(t)$, instantaneous total harmonic distortion, $V_{THD}(t)$ and instantaneous total nonharmonic distortion, $V_{TnHD}(t)$. The simulation results based on the accuracy of the technique for the modelled signals are disclosed in Section 3. Section 4 presents the conclusions of the work.

2. Methodology

2.1. Harmonic Signal Modelling
Generally, signals are modelled by following the IEEE Std. 1159-2009, and the equation is derived using a complex exponential function. For the test signal, parameters i.e. the starting time, duration, magnitude and frequency are casually selected, and are permitted to change depending to an application or a desired outcome. The normal signal, $x_{normal}(t)$ and waveform distortion signal, $x_{wd}(t)$, including single-level harmonic, interharmonic, multi-level harmonic and short duration harmonic, are formulated respectively, as:

Normal

$$x_{normal}(t) = e^{j2\pi f_0 t}$$

(1)

Single-Level Harmonic and Interharmonic

$$x_{wd}(t) = e^{j2\pi f_0 t} + Ae^{j2\pi f_1 t}$$

(2)

Multi-Level Harmonic

$$x_{wd}(t) = e^{j2\pi f_0 t} + Ae^{j2\pi f_1 t} + Be^{j2\pi f_2 t}$$

(3)

Short Duration Harmonic

$$x_{wd}(t) = e^{j2\pi f_0 t} + Ae^{j2\pi f_1 (t_1 - t_2)}$$

(4)

where

- Single-Level Harmonic : $A = 0.5, f_1 = 400$ Hz.
- Interharmonic : $A = 0.5, f_1 = 275$ Hz.
- Multi-Level Harmonic : $A = 0.5, B = 0.25, f_1 = 350$ Hz, $f_2 = 500$ Hz.
- Short Duration Harmonic : $A = 0.5, f_1 = 250$ Hz, $t_1 = 100$ ms, $t_2 = 150$ ms.

where $A$ and $B$ are amplitudes of signal at harmonic component, $f_0$ is a fundamental frequency and is set at 50 Hz, $t$ is signal length within $t_0$ to $t_1$ with duration of 350 ms, $f_1$ and $f_2$ are the harmonic and interharmonic frequency, and $t_1$ and $t_2$ are signal length at harmonic components [30].

2.2. Fourier Transform
FT, a spectral analysis technique, was used to analyse the stationary signal in this paper. FT was also used to analyzed the continuous time signal in time marginal (aperiodic), which was then represented as a continuous frequency in the frequency marginal (aperiodic) [31]. The results of the FT illustrated smoothed version of the two-dimensional power spectrum [32]. Different magnitude produced by the FT should give possible estimation when the measured signal size is sufficiently large. The FT of a signal, $F_x(t)$ is calculated as follows.
where $T$ is signal period, $x(t)$ is time domain signal and $f$ is the analyzed frequency.

### 2.3. Short-Time Fourier Transform

Based on reviews, the main disadvantage of using FT is this technique is unable to estimate instantaneous total waveform distortion, hence the occurring short duration harmonic signal may be untraceable. By implementing the STFT as in [33], information regardless of harmonic applications like magnitude, frequency and time can be estimated. Selecting a sliding window is important to ensure the reliability of the analysis; and for this case, Hanning window, $w(t)$ was adapted since this window can avoid spectral leakage [34]. In previous studies in [35], the authors did not clearly mention appropriate window length, which is necessary for harmonic signal detection to provide good time and frequency resolution. Following the fixed window length as shown in Figure 1, the value is varied to find the best window length that can contribute to the development of real-time monitoring system.

![Figure 1. STFT resolution.](image)

Conceptually, the input signal, $x(t)$ in STFT is transformed into a frequency domain similar to FT, and the graph is plotted in two-dimensional including the magnitude. Then, a windowed function, $w(\tau-t)$ is multiplied by the signal, on the other word shifted along the time marginal by one sample, hence allowing the signal to be represented in three-dimensional TFR [36]. The mathematical representation of STFT is:

$$\text{STFT}_x(t,f) = \int_{-\infty}^{\infty} x(t)w(\tau-t)e^{-j2\pi ft} d\tau,$$

The centre position of the shifted window $w(\tau-t)$ is depicted by $\tau$, which gives relevant time towards FT. As equation (6) is square modulus (see equation (7)), or often called as the spectrogram, will represent the signal power that varies over the time and frequency [37].

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

### 2.4. Signal Parameters

Signal feature is related to harmonic application such as instantaneous RMS voltage, $V_{RMS}(t)$, instantaneous RMS fundamental voltage, $V_{/RMS}(t)$, instantaneous total waveform distortion, $TWD(t)$, instantaneous total harmonic distortion, $THD(t)$ and instantaneous total nonharmonic distortion,
$TnHD(t)$, which are estimated from TFR. These parameters are extracted from different frequency level where the signal magnitude is plotted over the time.

2.4.1. Instantaneous RMS Voltage
$V_{RMS}(t)$ is estimated from DC and AC components. The value includes the fundamental magnitude at 50 Hz, as well as harmonic magnitude that occurs at higher frequency components. The $V_{RMS}(t)$ is expressed as:

$$V_{RMS}(t) = \sqrt{\int_{0}^{f_{max}} S_x(t,f) df}, \quad (8)$$

where $S_x(t,f)$ is the signal from TFR and $f_{max}$ is the maximum frequency measured. In this study, $f_{max}$ was indicated by 6000 Hz, taking 12000 Hz as a sampling frequency. Based on the standard, the measurement of harmonic should be up to or more than 50 components, by means the $f_{max}$ for 50Hz system should be more than 2500 Hz. Sampling frequency of 12000 Hz would give the benefit for measurement up to 120 components [38].

2.4.2. Instantaneous RMS Fundamental Voltage
Different from $V_{RMS}(t)$, $V_{1RMS}(t)$ from equation (9) is formulated from the estimation of fundamental frequency, $f_0$ component. For this study, the value of $f_0$ was set at 50 Hz, where the magnitude at this component is considered as normal signal without the harmonic disturbance.

$$V_{1RMS}(t) = \sqrt{\int_{f_{hi}}^{f_{lo}} S_x(t,f) df}, \quad (9)$$

where $f_{hi} = f_0 + 25$Hz and $f_{lo} = f_0 - 25$Hz.

2.4.3. Instantaneous Total Waveform Distortion
From all deviations of the ideal voltage signal, the waveform distortion should show the magnitude or frequency over the time [39]. $TWD(t)$ includes the harmonic and nonharmonic distortions, can be simply expressed as:

$$TWD(t) = \frac{\sqrt{V_{RMS}(t)^2 - V_{1RMS}(t)^2}}{V_{1RMS}(t)}, \quad (10)$$

2.4.4. Instantaneous Total Harmonic Distortion
Total harmonic distortion is estimated from the ratio between RMS values of harmonic over the RMS of fundamental frequency. Since the first component is a fundamental, the magnitude that appears at higher components ($h = 2, 3, 4, ..., H$) are considered as harmonic. Instantaneous form of total harmonic distortion can be written as [40]:

$$THD(t) = \frac{\sum_{h=2}^{H} V_{h,RMS}(t)^2}{V_{1RMS}(t)}, \quad (11)$$

where $V_{h,RMS}(t)$ is the RMS harmonic voltage and $H$ is the highest measured harmonic component.

2.4.5. Instantaneous Total Nonharmonic Distortion
Total nonharmonic distortion is usually distinguished as a noise that is not of multiple integer of targeted system frequency. This so called interharmonic randomly appears at certain frequency, for example 275 Hz taking 50 Hz as fundamental. $TnHD(t)$ can be calculated as [41]:

$$TnHD(t) = \frac{\sqrt{V_{RMS}(t)^2 - \sum_{h=0}^{H} V_{h,RMS}(t)^2}}{V_{1RMS}(t)}. \quad (12)$$
3. Results and Discussion

Signal processing techniques, namely FT and STFT had been evaluated in this study, to identify the harmonic for the performance of the system. Time varying harmonic signals had been modelled following equations (1) to (4), as graphically shown in Figure 2. Quantities such as the magnitude against frequency of voltage or current were modelled over time for a short or long period of time (0 ms to 350 ms) depending on the number of samples captured. For the purpose of illustration, the window length was set to a fixed value of 512, and was varied for the performance analysis that would take place later. The number of sample was 3000.

The results for the single-level harmonic versus time modelled are shown in Figure 2 (b). The signal seemed to be distorted, producing non-sinusoidal waveform. As shown by power spectrum in Figure 2 (b), the first components gave the highest magnitude, compared to the other levels of harmonic components. The harmonic components measured were at 8th order, which was 250 Hz. The specialty of STFT in presenting the analyzed signal in TFR gives extra information along the time. The results of single-level harmonic indicated involvement of harmonic from 0 ms to 350 ms. Significantly, harmonic source can be identified by taking the direction of active power flow between the positive and negative sides, at point of common coupling, which usually appear on customers’ side [42].

As shown in Figure 2 (c), harmonic distortion seemed to appear not only at 7th component or 350 Hz, but also at 10th components, or 500 Hz. The window length may affect the signal characteristics from the TFR, since narrow window length provides good time resolution while wide window length provides good frequency resolution. Selecting wider window length is recommended in harmonic signal analysis, as the signal information requires high frequency resolution in determining the harmonic characteristics at AC components. Besides, improper selection of window length may cause the TFR for the 10th harmonic component in Figure 2 (c) cannot be estimated, as well as interharmonic signal, as shown in Figure 2 (d).

As shown in the TFR graph in Figure 2 (e), one interesting fact that can be observed for short duration harmonic, the STFT was capable to estimate the harmonic components. Looking into power spectrum, the representation at 250 Hz lacked time, by which the harmonic appeared at duration of 100 ms to 150 ms. On the other hand, the magnitude shown in power spectrum could not be clearly seen as in TFR, although A (see equations (2) and (4)) had been chosen similar to that of single level harmonic. For the purpose of illustration, Figure 2 show the parameter estimation for $V_{RMS}(t)$, $V_{1RMS}(t)$, $V_{THD}(t)$, $V_{THD}(t)$ and $V_{TWD}(t)$.

The $V_{RMS}(t)$ and $V_{1RMS}(t)$ illustrated in Figure 3 (a) were both measured in per unit, pu. The amplitude of $V_{1RMS}(t)$ estimated at 50 Hz, or often called as fundamental component, seemed to be fixed to 1 pu, following the parameters modelled in equation (2). When there was an involvement of harmonic, in this case occurring at 400 Hz frequency, the $V_{RMS}(t)$ was overlapped by 0.1 pu. Along with this case, it can be proven that harmonic will increase the RMS voltage [22], and for filter purpose, should be similar to $V_{1RMS}(t)$. For $V_{THD}(t)$ case, 50 % of normal signal would be distorted, in worst case, could reach up to 100 %. Besides, in $V_{THD}(t)$, there was no involvement of interharmonic by means the signal modelled was an integer multiple of the first harmonic component (50 Hz). To sum up, $V_{TWD}(t)$ indicated was similar to $V_{THD}(t)$ since $V_{THD}(t)$ was zero.
Figure 2. Test signal, power spectrum and TFR for (a) normal signal, (b) single-level harmonic, (c) multi-level harmonic (d) interharmonic, and (e) short duration harmonic.
As graphically shown in Figure 3 (b), the $V_{RMS}(t)$ and $V_{IRMS}(t)$ for interharmonic indicated a similar value as single level harmonic. There was an increment in $V_{RMS}(t)$ when there was an involvement of interharmonic at 275 Hz. Interharmonic is usually distinguished as noise that is not multiple integer of targeted system frequency, which randomly appears at certain frequencies, for example 275 Hz taking 50 Hz as fundamental. To determine whether the signal was distorted, the values of $V_{THD}(t)$, $V_{THD}(t)$ and $T_{THD}(t)$ had been estimated from TFR. The $V_{THD}(t)$ as in Figure 3 (b) reflected the absence of harmonic, whereas the $T_{THD}(t)$ reflected the presence of interharmonic, and in this case was 50 %.

Apart from single level harmonic and interharmonic, short duration harmonic is presented, as the novelty of this paper, by means STFT is capable to capture the short duration distortion. Even though there was a slip of time before the signal was normalized between 100 ms to 150 ms, the presence of harmonic was detected at 250 Hz (see TFR in Figure 2 (e)). On the other hand, without involvement of harmonic from 0 ms to 100 ms, as well as from 150 ms to 350 ms as in Figure 3 (c), amplitude values indicated by $V_{RMS}(t)$ and $V_{IRMS}(t)$ were equivalent. Based on parameters in equation (4), the harmonic appeared at 250 Hz with 0.5 in amplitude, therefore $V_{TWD}(t)$ was zero while $V_{THD}(t)$ was at 50% within duration of 100 ms to 150 ms, as in Figure 3 (c).

![Graphical representation](image)

**Figure 3.** Instantaneous RMS voltage, instantaneous RMS fundamental voltage, instantaneous total harmonic distortion, instantaneous total non-harmonic distortion, and instantaneous total waveform distortion parameters for a) single level harmonic, (b) interharmonic, and (c) short duration harmonic.

### 3.1. Accuracy of the Analysis

For a simple analysis, the performance for four different harmonic signals, including a normal signal, had been simulated using the statistical absolute percentage error (APE) approaches. It can be calculated as measured value deducted by actual value divided by actual values. Smaller value of APE indicates more accurate results. The accuracy of measurement is dependent on the sampling frequency and window length. By assuming perfect knowledge on the harmonic signals, the performance of the STFT with various window lengths ($N_w = 128, 256, 512, .., 8192$) had been analyzed, as shown in Table 1. The window length was varied for five different signals, and the measurement of APE had been recorded.
Table 1. Percentage APE for various harmonic signals.

| Length | Window | 128 | 256 | 512 | 1024 | 2048 | 4096 | 8192 |
|--------|--------|-----|-----|-----|------|------|------|------|
| Normal | 100%   | 0.59% | 1.09% | 2.16% | 4.32% | 8.64% | 17.00% |
| Single-Level Harmonic | 100% | 6.09% | 0.378% | 0.31% | 9.85e+12% | 0.10% | 0.54% |
| Multi-Level Harmonic | 100% | 0.38% | 0.39% | 0.33% | 9.40e+12% | 0.10% | 0.68% |
| Short Duration Harmonic | 1056.36% | 29.07% | 76.61% | 264.34% | 483.50% | 652.70% | 1056.36% |
| Interharmonic | 100.13% | 0.38% | 0.52% | 0.46% | 2.01e+13% | 0.28% | 17.64% |

In this study, the window lengths were chosen based on the pre-computation in Figure 1. The \( N_w = 128 \) was not appropriate for harmonic signal analysis since the error exceeded 100% in almost all the cases. It can be clearly seen that in high frequency application like radar in [43], the use of low window length less than 128 may produce less errors. Similar situation happened for case 2048, where it was expected to produce less errors when involving low frequency applications like battery [44]. By increasing the \( N_w \) to 256, both normal and short duration harmonics indicated less error. For this case, the use of short window length may be advantageous in TFR time localization, which is necessary for short duration harmonic. For such power quality cases like transient, sag and swell, similar observation can be made and the use of this window length may be appropriate. In addition, the outcome for 512 window length showed the percentage of APE for three different cases, namely single-level harmonic, multi-level harmonic and interharmonic signals were less the 1%. Even for normal signal, the error only increased slightly by 0.5%.

Based on results for \( N_w = 4096 \), the reliability of measurement of single-level harmonic, multi-level harmonic and interharmonic signals were high since these three signal characteristics required wide window length for a good frequency localization. However, short duration harmonic signal suffered from the gigantic amount of error and the APE for five different signals calculated was 132.37% on average. By taking consideration of all five cases, \( N_w \) with 256 was selected as the optimal window length for harmonic signal analysis.

As presented in Figure 4, the accuracy of the proposed technique focusing on interharmonic signal is benchmarked against other linear TFDs. It can be clearly seen that Gabor transform in [45] indicated the highest error compared to others. In this work, the error was 60% lower than Gabor but indicated 58% higher than spectrogram. The use of multi-scale Gaussian window in [46] made this technique able to compute the harmonic accurately. However, S-transform technique suffered from large memory size and was high in complexity [47]. For a low cost monitoring system, it is recommended to implement STFT, and for future work, other accuracy techniques should be further investigated since the error for a short duration harmonic is considerably high.
4. Conclusion

This paper presents the analysis of harmonic signal using a TFD namely STFT. The signals are modelled based on IEEE standard for different harmonic characteristics at different time duration and frequency. Comparison based on frequency analysis techniques i.e. FT and TFD technique has been conducted. The analysis reveals that STFT is suitable for harmonic signal analysis and from the use of the observation window in STFT provides good time and frequency resolution. For different harmonic characteristics, parameters such as instantaneous RMS voltage, instantaneous RMS fundamental voltage, instantaneous total waveform distortion, instantaneous total harmonic distortion and instantaneous total nonharmonic distortion are extracted from TFR. The outcomes show the capability of STFT in detecting the time varying harmonic signal correctly and the contribution can clearly be seen on short duration harmonic signal detection. Thus, it can be concluded that the proposed technique is very appropriate to be implemented for real-time monitoring system for harmonic signal detection.

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