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Research paper

Time-Frequency Analysis of Power Quality Disturbances via the Transform based Techniques

P.Murugesan[1*], S.Prabakaran[2]

[1]*Research scholar,* [2]*Associate Professor,*
Dept of EEE, SCSVMV University, Kanchipuram, Tamil Nadu, India
**Corresponding Author Email:* [1]*murugesh78_au@yahoo.co.in*

Abstract

Digital India focuses the increased usage of semiconductor devices. These power electronic devices pollute the electric power in the power system which degrades the quality of power. The polluted power affects not only the generation, transmission and distribution side but also affects the modern equipments of customers. The goal of monitoring non-stationary electric signal is to quantify the transient nature of these signals and to extract the important features, which support the smart integrated monitoring system to activate the protection on time, to provide proper maintenance scheduling and to reduce the economical burden. This paper documents an alternate method of Fourier transform, where different digital signal processing techniques has been used to analyze different power quality events to provide visual examination. Its performance has been analyzed with different time-frequency representation methods like STFT spectrogram, CWT scalogram and DWT multi-resolution technique. The DWT can detect the dynamic changes of the non stationary PQ signal accurately.

Keywords: *Power Quality Disturbances (PQD), Short Time Fourier Transform (STFT), Continuous Wavelet Transform (CWT), Discrete Wavelet transform (DWT), Space Scale Representation (SSR), Pattern of Fringes (POF), Multi Resolution Decomposition (MRD).*

1. Introduction

The Diagnosis of PQ events is an interesting research area for a couple of decades. The usage of electronic gadgets, solid state drives, static and rotating electromagnetic devices, sensors are susceptible for PQD in power system. A PQ problem could be defined as “any power problem manifested in voltage, current, or frequency deviations from the nominal values that result in failure or malfunctioning of customer equipment”. Many researchers exposed their views in several areas that are related to enhance the quality of electric power. These areas may be summarized as basic concepts and definitions, modeling and analysis, measurement and instrumentation, feature extraction techniques, sources of PQ problems, effects of PQ deterioration, problem analysis and diagnosis, solutions and mitigation of PQ problems, and educational issues related to power quality. The artificial intelligence techniques such as fuzzy logic, expert system, neural network, genetic algorithm, support vector machines and advanced mathematical techniques like wavelets have been used for the analysis of power quality [1] –[10].
The PQ disturbances are categorized as voltage sag, voltage swell, Momentary interruption, Harmonics, transient and voltage fluctuation. Among this short duration variation is considered as the most important task, therefore even minimal variations can have major functional deviation such as loss of information, data error and corruption, excessive heating and equipment failure. Many standards and commissions provide technical aspects to enhance the quality of power. Many researchers analyzed the PQD which have huge data storage and time consuming. A time frequency analysis of PQD has been discussed in this paper which has found its application in many other fields such as analysis of light beams, medical images, earth quake signal, diagnosis of defective object in mechanical field. Time Frequency Analysis is an effective and efficient method for fault detection of signals, windings in static and dynamic electromagnetic devices.
Section II explains about different types of Time frequency methods- STFT its spectrogram, WT-CWT and its Scalogram, and Discrete wavelet transform and its SSR using MRD and in section III the results of analyzing different PQD events using the above methods are presented and conclusions are given in section IV.

2. Theoretical Background

This section introduces a brief theoretical background on the topics addressed in this paper: The detection of fault in the electric power system with the help of signal processing technique is the main objective of the work. Due to continuous advancement of techniques and measuring instruments the signal processing techniques are more effective, efficient and reliable. The analysis of signal is perceived by two domains namely time and frequency domains. The time domain consists of conventional Root Mean Square method (RMS).The detection of non stationary signal by RMS method introduce a delay of one cycle with the amplitude envelope and the information about frequency is lost. The frequency domain consists of Fourier transform, FFT where the information of frequency is acquired and the information about the time is lost. To analyze the signal in time and frequency domain the following transform based techniques are implemented.

2.1. Short Time Fourier Transform

The Time-Frequency analysis namely spectrogram has been used for the signal analysis. The STFT spectrogram of the signal represents the signal's energy at time frame t and frequency f. The time localization can be obtained by suitably pre windowing the signal, as the Discrete Fourier Transform (spectrum) does not show the time localization of frequency components explicitly. The STFT and its spectrogram is a time-frequency distribution based on the Fourier Transform of the product of a sliding window $w(t)$ with the signal $x(t)$.The following expression gives the spectrum of STFT

$$S(t,f) = \left|\int_{-\infty}^{+\infty} x(t)w(t-\tau)e^{-j2\pi ft}dt\right|^2 \quad (1)$$

The length of the sliding window $w(t)$ determines time and frequency resolution, i.e., a good frequency resolution needs a long observation window and therefore leads to a bad localization in time and vice versa. The response of STFT widens and is uniform across the entire time frequency plane and it is independent of the center of time and frequency of the window function. The window length has to be chosen based on the prior knowledge of the signal which are fixed [11] – [13].

2.2. Wavelet Transforms

Wavelets are functions used to decompose the signal and they are localized both in time and frequency domain. The PQ events are dynamic in nature, whose spectral information changes over time so wavelet transforms are used for those signals. Each wavelet possess unique characteristics. Wavelet transform adjusts its window automatically for low frequency wide wavelets and for high frequency narrow wavelets respectively. The non stationary Signals are analyzed in continuous and discrete fashion.

2.3. Continuous Wavelet Transform (CWT):

The CWT is expressed as

$$C(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} w\left(\frac{t-b}{a}\right)x(t)dt \quad (2)$$

$x(t)$ is the input signal, $w(t)$is the mother wavelet , a and b are scaling and shifting factors. The continuous wavelet transform (CWT) is the product of signal $x(t)$ with the time shifted and scaled wavelet. The product of cross correlation is a measure of the similarity between signal of the scaled and shifted wavelet. Magnitude of continuous wavelet transform is called Scalogram. It is the two dimensional representation of space or time in the horizontal axis, scale in the vertical axis and amplitude of the signal given by a color of atoms or pattern of fringes (POF).CWT has a problem of edge effects due to artifacts produced by the scaling and wavelet functions wave shapes centered at $\tau = 0$. when the value of $\tau < 0$, both the functions has a symmetric waveform irrespective to the size of the window (narrow or wide), the artifacts travel all along the signal $x(t)$ leads to discontinuity of boarder effects at end of the finite interval of the signal.

2.4. Discrete Wavelet Transform

The discrete wavelet transforms neither sampling the signal nor transforms but sampling the scaling and shifted parameters. The discrete version of CWT is known as Discrete Wavelet transform. The principle of DWT is MRD. The input signal decomposed into multi resolution levels with different frequency bands. The lower resolution signals, provides an effective way of looking at a signal at various scales and analyzing it with various resolutions. Wavelet can be shown with a very desirable frequency and time characteristics, allowing the visualization with the short window at high frequencies and long window at low frequencies. By this way, the characteristics of non-stationary signal can be monitored carefully and accurately. The DWT consists of a set of functions namely scaling and wavelet function associated with filter banks. The DWT of a signal $x(t)$ is calculated by passing it through a series of filters. First the samples are passed through a low pass filter with impulse response $g(t)$ resulting in a convolution of the two parameters are expressed as follows

$$y(n) = \sum_{k=-\infty}^{+\infty} x(k)\, g(n-k) \quad (3)$$

The signal is also decomposed simultaneously using a high pass filter $h(t)$. The output gives the detail coefficients (from the high-pass filter) and approximation coefficients (from the low pass filter) as shown in Fig. 1.

$$y_{high}(n) = \sum_{k=-\infty}^{+\infty} x(k)\, h(2n-k) \quad (4)$$

$$y_{low}(n) = \sum_{k=-\infty}^{+\infty} x(k)\, g(2n-k) \quad (5)$$

The MRD consists of filter banks of low pass and high pass filters. The high pass filter gives a fine detailed version of the signal 'd1' and low pass filter gives the coarse approximate version of the signal 'a1' at the first resolution level of decomposition, whose frequency band is divided into two equal half fs/2. During second resolution level the signal 'a1' is further decomposed into 'd2' and 'a2' whose frequency band is fs/4 . For third resolution level the frequency band is fs/8 which produces the signal 'd3' and 'a3' and the process is again repeated for different resolution levels and frequency bands.

\Fig.1 shows the flow diagram of MRD of a signal with four levels, sampled at a frequency of 6 kHz into four bands of frequency. 'a4' is the level of approximation with the lowest frequency band of low pass filter and 'd1','d2','d3' and'd4' are respective details or the high frequency(scale) band of high pass filter[14] –[21].

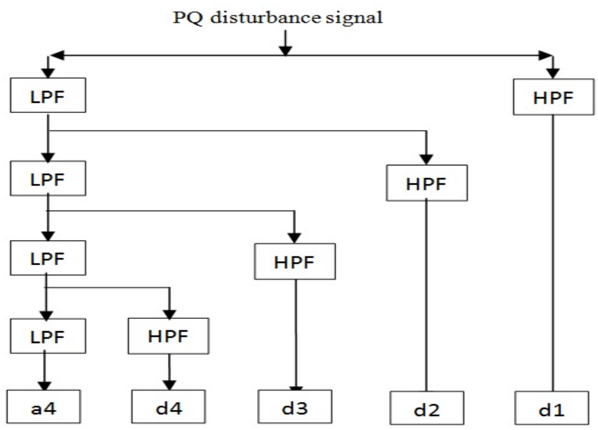
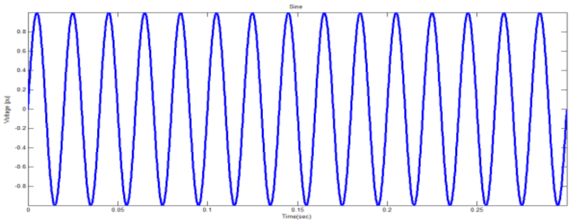


Fig. 1: Flow Diagram of MRD

3. Case Study

Fig.2.(a).shows the pure sinusoidal waveform of fifteen cycles with the amplitude of 1.0p.u and the frequency of 50 Hz with the sampling frequency of 6 KHz has 1800 samples. Fig.2.(b and c).shows the time frequency representation of STFT of the pure sine waveform whose fundamental frequency is tracked.Fig.2.(d).shows the scalogram of pure sine waveform with thirty concentric circles for fifteen cycles. Each half a cycle posses a concentric circle called fringes (atoms). Therefore positive half a

cycle possess one concentric circle and negative half cycle possess one concentric circle. Therefore a cycle consists of two fringes. The edge effects are visible at starting and ending of two atoms, where as the other atoms color code was spread equally. Fig.2.(e). shows the output waveform of DWT. The approximate a1 resembles the input signal and Detail d1 signal are very smooth without any distortion.



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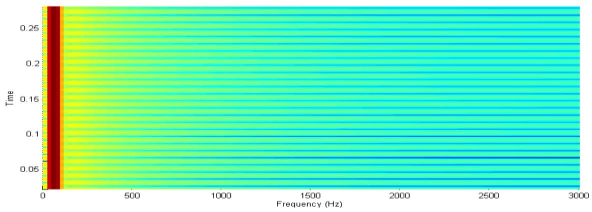

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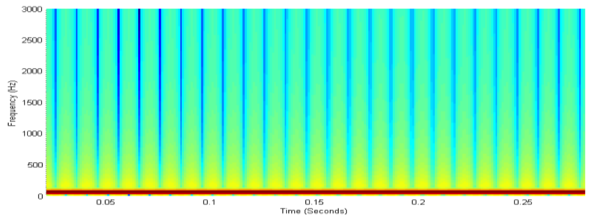

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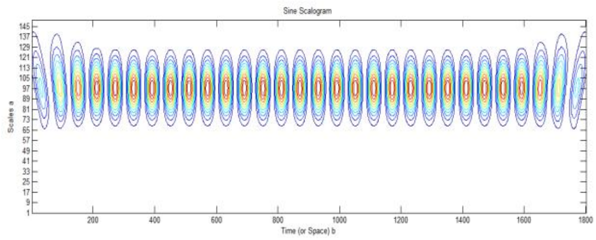

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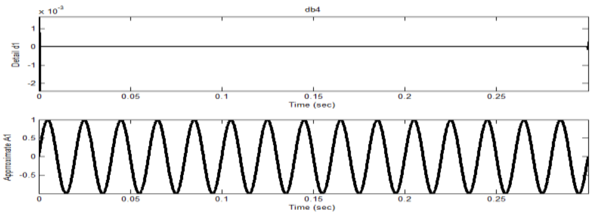
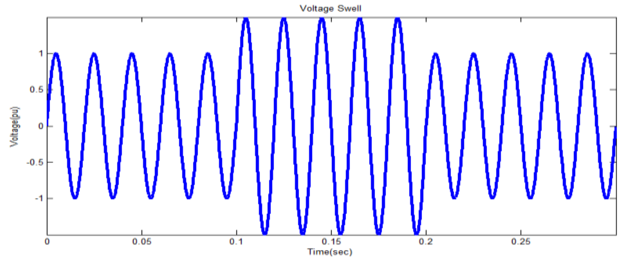


(e)

Fig. 2(a): Pure sinusoidal waveform.(b).STFT time in y axis and frequency in x axis.(c).STFT time in x axis and frequency in y axis.(d).output of CWT.(e) DWT with its approximate and detail output of 1st level.

Fig.3.(a).shows the 80% of voltage swell for the time duration of 0.1- 0.2sec. Fig.3.(b and c).shows the time frequency representation of STFT of the voltage swell whose fundamental frequency is distorted with bursts at the time duration of 0.1- 0.2 sec was tracked along with the fundamental frequency band. Fig.3.(d).shows the output of CWT of voltage swell signal, the POF or atoms color code are increased at the portion of PQ disturbance and the reddish color of concentric circle are disappeared in the area of pure normal sine wave form was observed between 600-1200 samples.Fig.3. (e).shows the output waveform of DWT, which tracks the dynamic variation in the signal from 0.1-0.2 sec accurately in detail and approximate version of signal.



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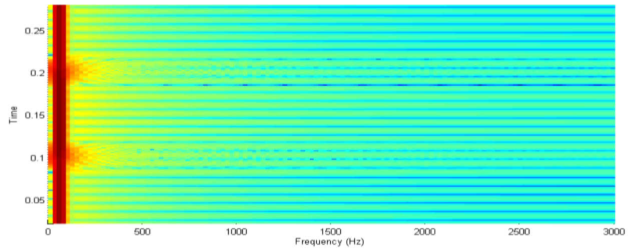

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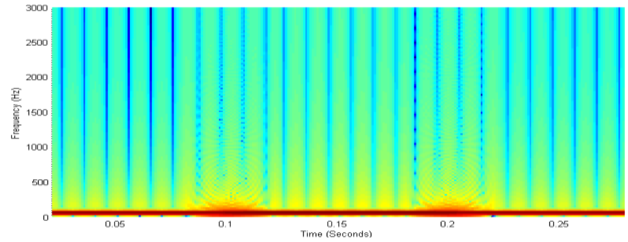

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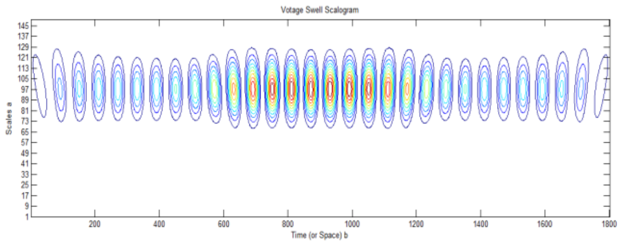

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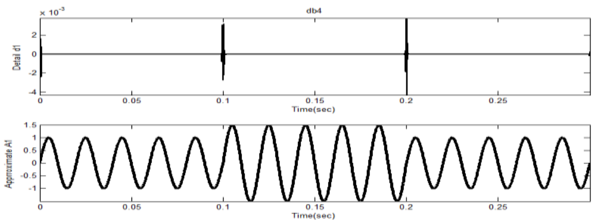

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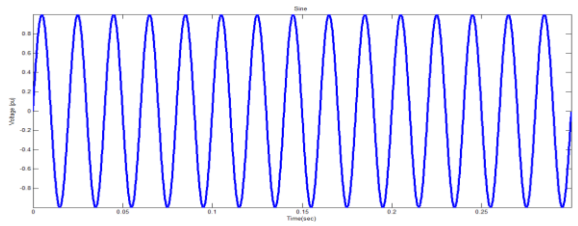
Fig. 3(a): signal with voltage swell waveform.(b).STFT time in y axis and frequency in x axis.(c). STFT time in x axis and frequency in y axis.(d).CWT output of voltage swell (e) DWT of voltage swell with its approximate and detail output at 1st level.

Fig.4.(a).shows the 20% of voltage sag for the time duration of 0.1-0.2sec. Fig.4.(b and c).shows the time frequency representation of STFT of the voltage sag, the fundamental frequency is distorted with bursts at the time duration of 0.1-0.2 sec was observed along with the band of fundamental frequency.Fig.4.(d). shows the output of CWT of voltage sag signal, the POF or atoms are reduced in size and the reddish color of concentric circles are disappeared in the portion of voltage sag region was observed between 600-1200 samples.Fig.4.(e).shows the output waveform of DWT, the variation of signal from normal

value are detected precisely through approximate signal a1 and Detail version of the signal d1 for the duration 0.1-0.2 sec.



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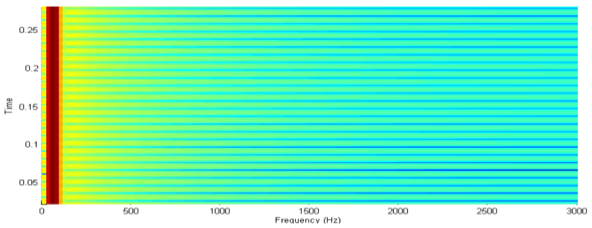

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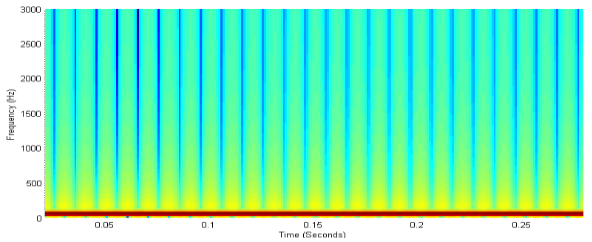

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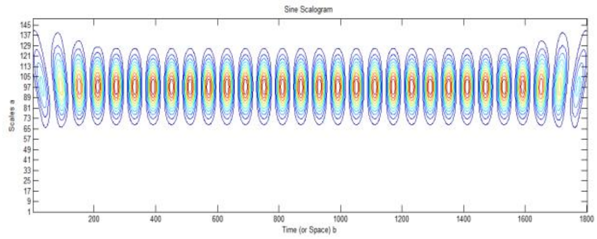

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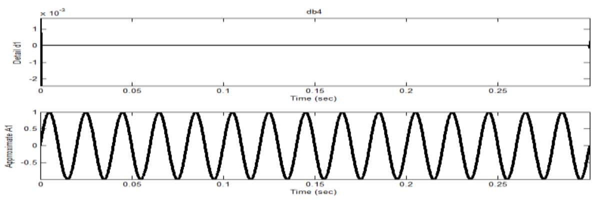

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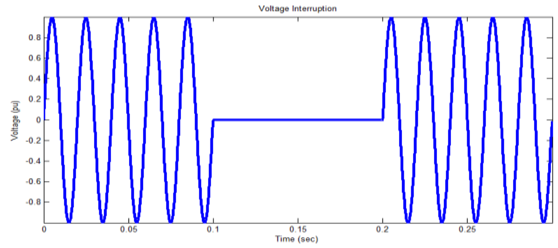
Fig. 4(a): signal with voltage sag waveform.(b).STFT time in y axis and frequency in x axis.(c).STFT time in x axis and frequency in y axis.(d).CWT output of voltage sag .(e). DWT of voltage sag with its approximate and detail output at 1st level.

Fig.5.(a)shows the 100% of power failure of signal with voltage interruption for the time duration of 0.1-0.2sec.Fig.5.(b and c).shows the time frequency representation of STFT of the voltage interruption, whose the fundamental frequency band is disconnected during the period of 0.1-0.2sec was tracked accurately.Fig.4.(d). shows the scalogram of voltage interruption, the POF or atoms disappeared during interruption of the signal between 600-1200 samples.Fig.4.(e).shows the output waveform of DWT, the approximate signal a1 resembles the input signal and Detail version d1 of the signal detects the discontinuity of the signal with its starting time t=0.1 sec to ending time t=0.2 sec of PQD accurately.



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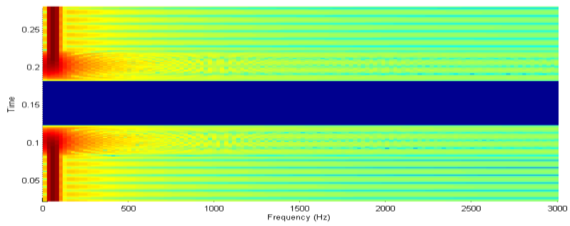

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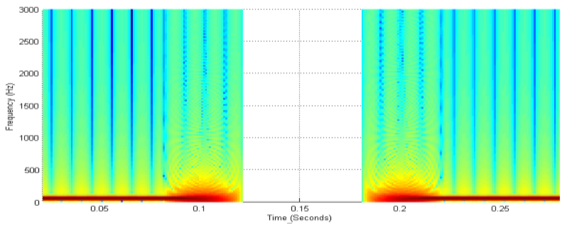

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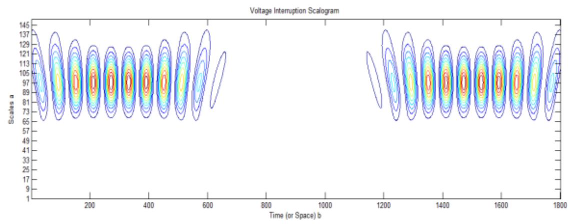

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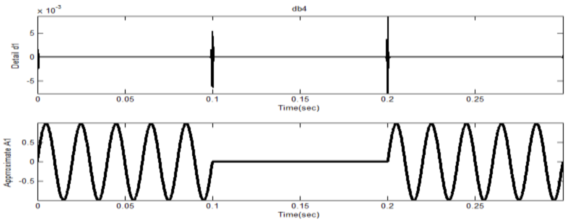
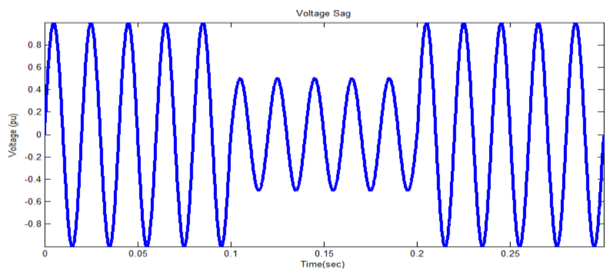


(e)

Fig. 5(a): signal with voltage Interruption waveform.(b).STFT time in y axis and frequency in x axis.(c) STFT time in x axis and frequency in y axis.(d). CWT output of voltage Interruption. (e).DWT of voltage Interruption with its approximate and detail output at 1st level.

Fig.6.(a).shows the input signal with different order of Harmonics for the time duration of 0.1-0.2sec. Fig.6.(b and c).shows the time frequency representation of STFT of the signal with the band of fundamental frequency, along with third, fifth and seventh order harmonics showing the frequency band at 150 Hz ,250 Hz and 350Hz respectively during the period of 0.1-0.2 sec.



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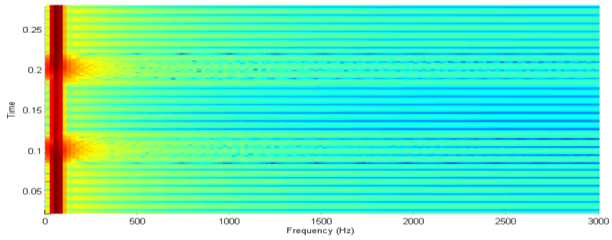

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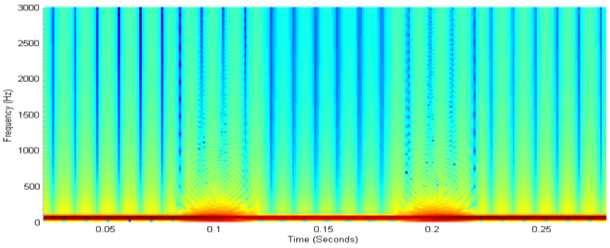

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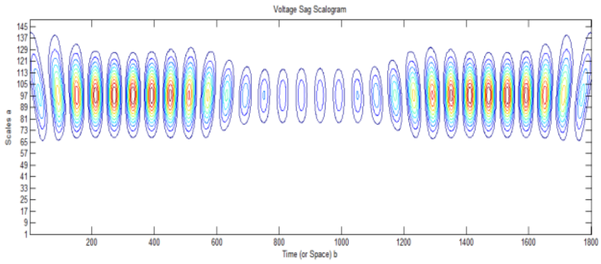

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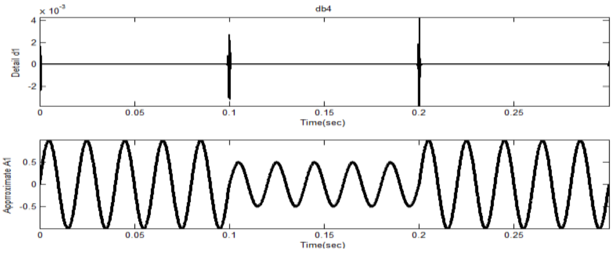
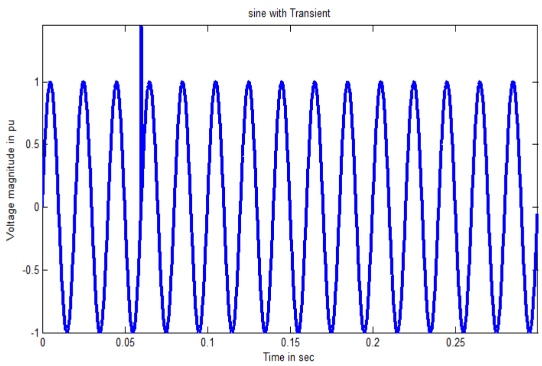


(e)

Fig. 6(a): signal with Harmonics waveform.(b).STFT time in y axis and frequency in x axis.(c).STFT time in x axis and frequency in y axis.(d). CWT output of sine with Harmonics.(e). DWT of sine with Harmonics with its approximate and detail output at 1st level.

Fig.6.(d).shows the scalogram of Sine waveform with Harmonics, the POF or atoms forms a clustering during Harmonics region between 600-1200 samples and in the region of sine waveform with fundamental frequency ,the normal atoms or POF disappear. Fig.6.(e).shows the output waveform of DWT ,the approximate signal a1 resembles the input signal and Detailed version d1 of the signal detects the variation of signal PQD accurately.



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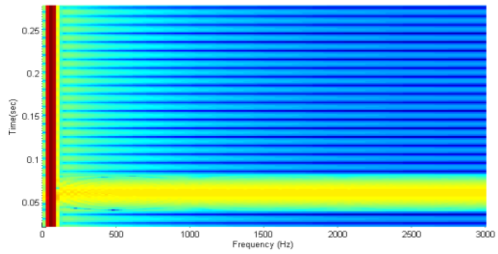

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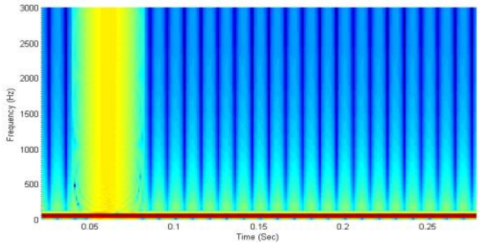

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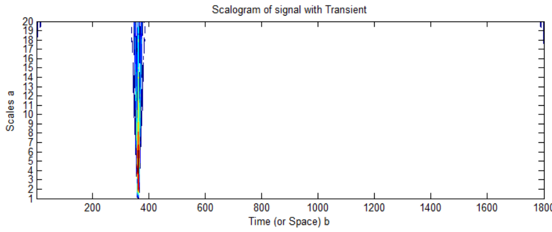

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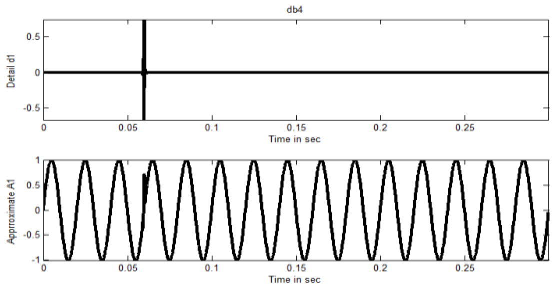

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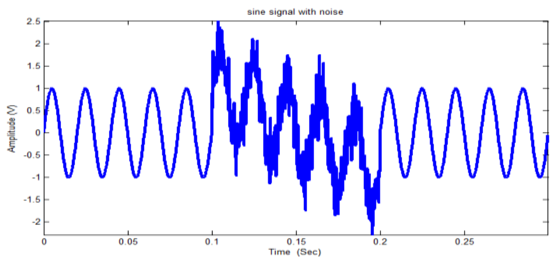
Fig. 7(a): signal with Transient waveform.(b).STFT time in y axis and frequency in x axis.(c) .STFT time in x axis and frequency in y axis.(d).CWT output of transient signal (e).DWT of transient signal with its approximate and detail output at 1st level.

Fig.7.(a).shows the voltage signal with impulsive transient at the time t=0.06 sec. Fig.7.(b and c).shows the time frequency representation of STFT of the transient signal with the fundamental frequency 50 Hz and the yellow band represents the presence of transient.Fig.7.(d).shows the CWT output atoms of transient, the POF or atoms are diminished for normal signal and in the region of transient the shape of atom observed as spikes at the sample of 350. Fig.7.(e).shows the output waveform of DWT, the approximate signal a1 resembles the input signal and Detailed version d1 of the signal detects the presence of transient accurately.



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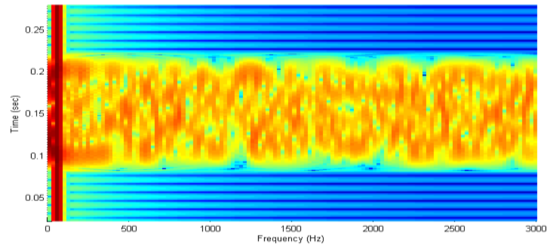

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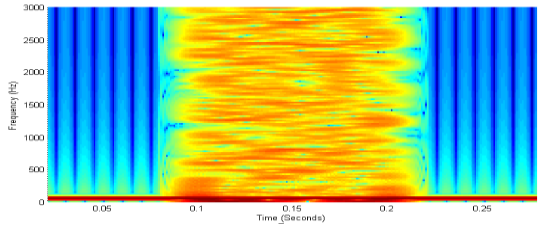

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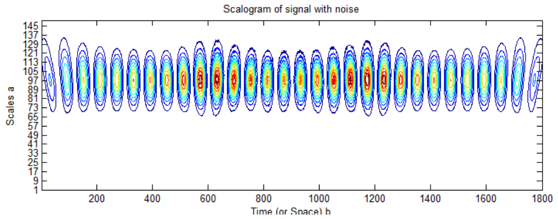

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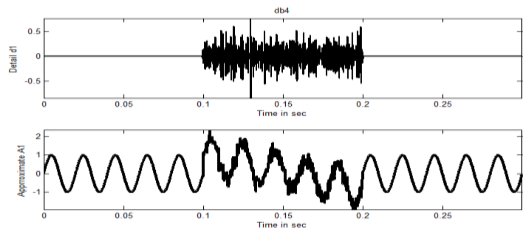

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Fig. 8(a): signal with Gaussian noise.(b).STFT time in y axis and frequency in x axis.(c).STFT time in x axis and frequency in y axis.(d).CWT output of Gaussian noise .(e). DWT of Gaussian noise signal with its approximate and detail output at 1st level.

Fig.8.(a).shows the voltage signal added with 10 db of Gaussian noise during the time duration of 0.1-0.2 sec. Fig.8.(b and c).shows the time frequency representation of STFT of the signal with the fundamental frequency 50 Hz and the wider yellow band represents the presences of Gaussian noise . Fig.8.(d).shows the CWT output atoms of noisy signal, the POF or atoms possess wrinkles at the outer surface of the concentric circle in the noisy region and for normal signal the concentric circles are smooth at outer surface. Fig.8.(e).shows the output waveform of DWT, the approximate signal a1 resembles the input signal and Detail version d1 of the signal detects the presences of Gaussian noise accurately in the duration of 0.1-0.2 sec.

4. Conclusion

The power quality disturbances of short duration variations such as voltage sag, swell and interruption, harmonics and transient are simulated by coding using MATLAB 2013 software. The results of PQD signals are compared with STFT spectrogram, CWT scalogram, and DWT MRD methods. The DWT MRD analysis detects the signal amplitude variations and time accurately and precisely than CWT and STFT. The outputs of spectrogram gives the valuable information about the frequency spectrum of harmonics and other PQ issues with poor frequency resolution and that of scalogram are distorted by edge effects. The DWT is an effective and efficient technique to track the non stationary signal with less computational time, even in the presences of noise. Yet, the choice of selection of wavelet is great task. The future contribution will be implementing of wavelet transform in field programmable gate arrays.

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