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Extraction of Fundamental Component in Power Quality Application using Tunable-Q Wavelet Transform

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Abstract

Application of a Tunable-Q Wavelet Transform based technique is proposed in this paper for the extraction of Fundamental frequency component in Power Quality Disturbances. The TQWT filters are designed to extract the fundamental frequency component from the complete voltage (or) current signal. This is achieved by tuning the Q-factor and redundancy of the wavelet by primarily investigating the presence of interharmonics near the fundamental frequency. To test the effectiveness of the proposed scheme, the system is verified with various Power Quality Disturbances as per IEEE standards encountered in power system are considered here.

Keywords: *Tunable-Q Wavelet Transform, Power Quality Disturbances, Fundamental frequency component, TQWT filters, Q-factor, redundancy*

1. Introduction

With society’s growing dependence on electrical devices, the danger of equipment malfunction due to Power-quality disturbances (PQDs) have become an issue of essential importance [1]. So, the PQ (Power Quality) is like an umbrella which covers the various disturbances of the voltage and the current such as the voltage sag, swell, harmonics and oscillatory transients *etc.*, [2].

Today the PQ has become a very interesting cross-disciplinary topic, coupling power engineering and power electronics with digital signal processing, software engineering, networking and VLSI. Power quality is defined as any power problem manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer equipment and system itself. In electrical energy systems, voltages and especially currents become very irregular due to the increasing popularity of power electronics and other non-linear loads [3-4].

In recent past, the researchers have applied different signal processing techniques in order to detect and identify the disturbances. The Fourier Transform (FT) is suitable to analyze stationary signals but not suitable for non-stationary signals such as the transient signals. The Short Time Fourier transform (STFT) overcomes time localization problem of FT.According to Panigrahi *et.al.*, [4], Wavelet transform (WT) is more suitable than STFT as STFT possesses fixed window property. Transient signals are easily analyzed by WT due its multiresolution property. The time plays an important role in the power system operation. One of the important issues of PQ problem is the fast mitigation of the disturbances. Fast detection and localization of the disturbances promote the fast mitigation [5-6]. In other words; the fast detection of PQ disturbance is becoming an important factor [7] in deregulated market. In this paper TQWT based decomposition techniques are applied to extract the fundamental frequency component from the different types of power quality disturbances.

The tunable Q-factor wavelet transform (TQWT) is a recently developed wavelet transform designed so that the Q-factor is easily and continuously adjustable. The

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motivation for the TQWT is the efficient (sparse) representation of signals that exhibit some degree of oscillatory behavior. It is thought that, by adjusting the Q-factor of the wavelet transform so as to match the oscillatory behavior of the signal under analysis, a more efficient (sparse) signal representation can be obtained [8-9].The enhanced sparsity should in turn improve the performance of sparsity-based signal processing algorithms for applications such as denoising, deconvolution, classification, signal separation, *etc.*

Intended specifically for discrete-time signal processing, the TQWT is a fully-discrete transform. The derivation of the TQWT in [8] follows closely that of the classic dyadic wavelet transform filter banks, with the exception that in place of the dyadic down-sampling, the TQWT employs continuous-valued rate-changers for discrete-time signals. Therefore, the derivation of the TQWT depends on a definition of continuous-valued rate-changers; a particular definition is given in [8-9].

In this paper, a new approach for frequency estimation is discussed. The remainder of this paper is organized as follows: Section 2 presents review of TQWT technique required to analyze the signal, then TQWT Based Method to Analyze Power Quality Phenomena are listed in Section 3.Finally conclusion is given in Section 4.

2. Summary of TQWT Theory

Tunable Q-factor wavelet transform (TQWT) is an over-complete discrete wavelet transform that has recently been developed for which the Q-factor of the underlying wavelet is easily specified [8-9].The Q-factor of a wavelet transform should be appropriately chosen in according to the nature of the signal to which it is applied.

2.1. Filter Bank

The TQWT is implemented using a reversible over-sampled filter bank with real-valued sampling factors .The filters, on which the TQWT is based, are specified directly in frequency domain. The transform consists of sequence of two-channel filter banks, with low pass output of each filter bank being used as the input to the successive filter bank. The associated analysis and synthesis filter banks for the TQWT are shown in Figure 1.

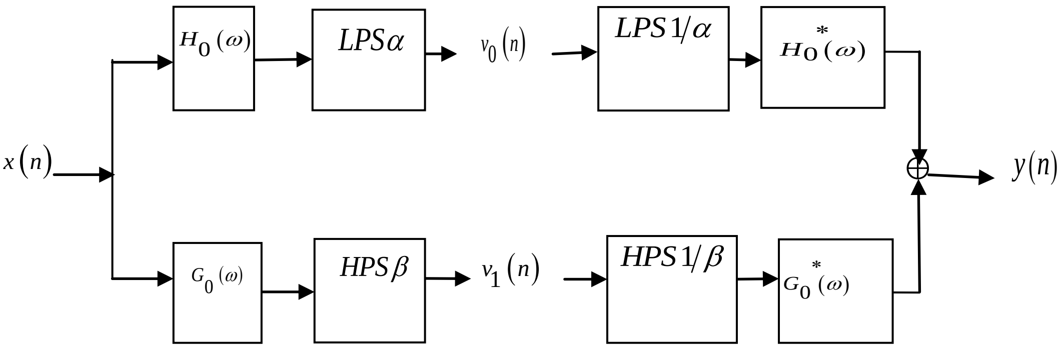

Figure 1. Analysis and Synthesis Filter Banks for the Tunable-Q Wavelet Transform

For perfect reconstruction the frequency responses $H_0(\omega)$ and $G_0(\omega)$ must be chosen so that the reconstruction signal $y(n)$ is equals the input signal $x(n)$ mathematically, the frequency responses of $H_0(\omega)$ and $G_0(\omega)$ are defined as follows [8-9]

$$H_0(\omega)=\begin{cases}1,\ for|\omega|\le(1-\beta)\pi \\ \theta\left(\dfrac{\omega+(\beta-1)\pi}{\alpha+\beta-1}\right) &,\ for(1-\beta)\pi\le|\omega|\le\alpha\pi, \\ 0,\ for\alpha\pi\le|\omega|\le\pi\end{cases} \tag{1}$$

$$G_0(\omega)=\begin{cases}0, \; for\,|\omega|\le(1-\beta)\pi\\ \theta\left(\dfrac{\alpha\pi-\omega}{\alpha+\beta-1}\right), \; for\,(1-\beta)\pi\le|\omega|\le\alpha\pi,\\ 1, \; for\,\alpha\pi\le|\omega|\le\pi\end{cases} \tag{2}$$

$$\theta(\omega)=0.5(1+\cos\omega)\sqrt{2-\cos\omega}\ \text{ for } |\omega|\le\pi \tag{3}$$

The transition function $\theta(\omega)$,originating from the Daubechies filter with two vanishing moments, is used to construct the transition bands of $H_0(\omega)$ and $G_0(\omega)$ .It can be verified that [8-9] the low pass filter $H_0(\omega)$ and high-pass filter $G_0(\omega)$ satisfy the perfect reconstruction requirement $|H_0(\omega)|^2+|G_0(\omega)|^2=1$. The variables α and β are the LPS parameters and the HPS parameter, respectively, they satisfy $0<\alpha<1;0<\beta\le1$ to ensure the wavelet transform will not be overly redundant. In order that the filter responses be well localized, it is necessary that $\alpha+\beta>1$.

2.2. TQWT Parameters

The main parameters for the TQWT are the Q-factor Q, the redundancy r, and the number of stages (or decomposition levels) J. Generally Q is a measure of the number of oscillations the wavelet exhibits. According to the definition of the Q-factor, the bandwidth varies inversely to the Q-factor for a given center frequency. Therefore, a higher Q-factor has better frequency resolution in comparison with lower Q-factor. The wavelet with a Q-factor 4 (or) greater consists of sufficient oscillatory cycles to process signals with oscillatory features. We use Q=1 for non-oscillatory signals [10-11].

The parameter redundancy r is the total number of wavelet coefficients divided by the length of the input signal to which the TQWT is applied. If the two channel filter bank is iterated with infinitely many levels, the wavelet transform is oversampled by a factor r which is given by the following equation:

$$r=\frac{\beta}{1-\alpha} \tag{4}$$

The specified values of r must be greater than 1and a value of 3 (or) greater is generally recommended. Meanwhile, it can be interpreted as a measure of how much spectral overlap exists between adjacent band-pass filters. Increasing r has the effect on increasing overlapping in the frequency domain of band-pass filters constituting the TQWT [12-13].

The parameter J denotes the number of filter banks. As illustrated in Figure 2.after performing a J-stage TQWT decomposition, there will be J+1subbands:the high-pass filter output signal of each filter bank $\left\{d_j(n), j=1,2,......,J\right\}$,and the low- pass filter out put signal of the final filter bank $a_J(n)$ .The number of maximum levels $(J_{\max})$ is [14] limited by the length of the input signal (N) and chosen scaling parameters of filters (α,β)

$$J_{\max}=\log\left(\frac{\beta N/8}{\log(1/\alpha)}\right) \tag{5}$$

The filter bank parameters α and β should be properly chosen so as to achieve a wavelet transform with the desired Q-factor and over sampling r. Scaling factors α and β can be expressed in terms of the Q-factor and redundancy r [15]

$$\beta = \frac{2}{(Q+1)}; \alpha = 1 - \beta/r \quad ; \tag{6}$$

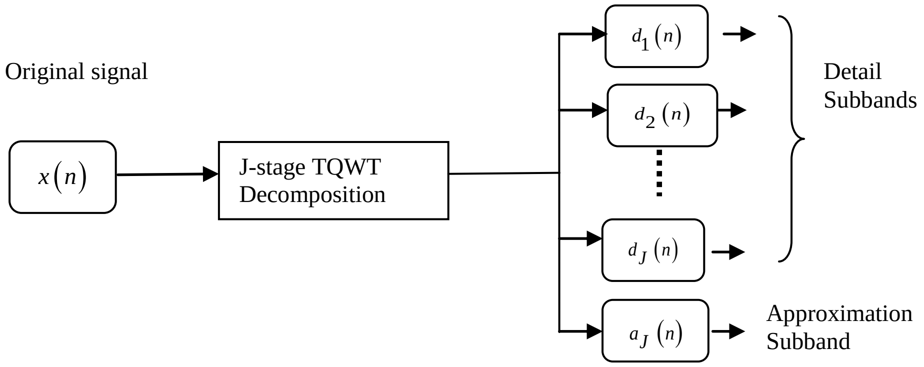

Figure 2. Performing the TQWT with J-Stage Decomposition

2.3. TQWT Wavelets and Frequency Responses

The TQWT is essentially also the constant Q-factor wavelet transform, but the Q-factor can be defined beforehand.Figure 3.a is the frequency response spectrum of TQWT with the parameters; Q=1, r=3, J=8. From Figure 3.a.the frequency response is essential a series of filters with non-constant band-width and adjacent frequency bands are not orthogonal to each other. With the increasing of J the center frequency

$$f_c = \alpha^j \frac{2-\beta}{4\alpha} f_s ; j = 1,2,....J ; \quad \text{is decreased} \tag{7}$$

and the corresponding bandwidth.

$$BW = \frac{1}{2}\beta\alpha^{|j-1|}\pi ; j = 1,2,....,J ; \quad \text{is decreased} \tag{8}$$

Figure 3 (a), is the frequency response spectrum and the corresponding time domain waveform with parameters: Q=1, r =3, J=8. Figure 3 (b), is the frequency response spectrum and the corresponding time domain waveform with parameters: Q=4, r =3, J=17.Three aspects of information [12] can be summarized from Figure 3 (a), and Figure 3.(b).

1. First, for certain Q-factor, the waveforms of the wavelet embedded in different subbands are different, though they are with the same Q-factor. With the increasing of the decomposition level, the time domain duration of the wavelet becomes wider, and the oscillation period of the wavelet increases.
2. The width of the band pass filter is determined by the Q-factor, for low Q-factor, the band pass filters are quite wide, and relative few levels are needed to cover the spectral content of the signal of interest .In contrast, for high Q-factor, each bandpass filter is narrow and hence more levels are needed to cover the spectrum of the signal.
3. Third, the role of the Q-factor can also be easily observed in the shape of the wavelet. For high Q-factor ,the wavelets has more sign changes and consist of more oscillatory cycles .This property allows effective sparse representation and processing of oscillatory signals. Meanwhile, for a low Q-factor, the wavelets have fewer sign changes and consist

of fewer oscillatory cycles, which are more suitable for the extraction of transient components.

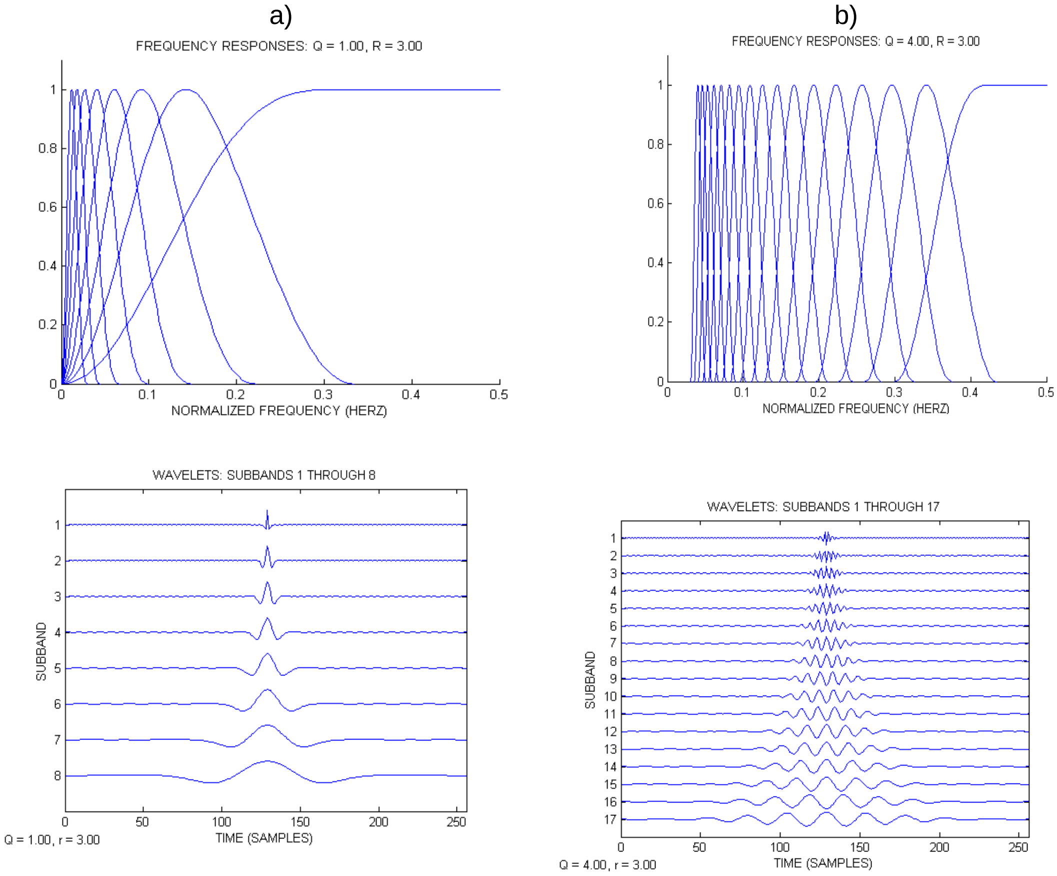

Figure 3. a. Frequency Responses and Wavelet Functions of Wavelet Subband of TQWT Basis:(a) Q=1,r=3,J=8 (b)Q=4,r=3,J=17

3. TQWT Based Method to Analyze Power Quality Phenomena

In this section, the performance of the proposed algorithm is discussed. To demonstrate the effectiveness of this method, Various disturbances as per IEEE standards encountered in power system are considered here [2], containing Voltage Sag ,Voltage Swell, Interruption, Flicker, Oscillatory transient ,Harmonics, Sag with Harmonic, Swell with Harmonic, Spike, Notch, will be investigated comprehensively by using this new TQWT method. Using TQWT, the signal is decomposed into various subbands.From these subbands fundamental component is extracted.

3.1. Sag PQD Event

Voltage sag is a decrease to between 0.1 to 0.9pu (per unit) in rms voltage at the power frequency for duration of 0.5 cycles to 1 minute [1]. The equation for Sag power Quality disturbance is given in equation (9), and the parameters used in this equation are given in (10). Equation Model is [2]

$$h(t)=\left[1-\alpha\left(u\left(t-t_1\right)-u\left(t-t_2\right)\right)\right]\sin\left(\omega_b t\right) \tag{9}$$

Parameters $0.1\le\alpha\le 0.9; T\le t_2-t_1\le 9T; \omega_b=2\pi.50; T={}^1\!/_{50}$ (10)

Sag type power Quality disturbance signal is shown in Figure 4.a.for the parameters

$\alpha = 0.9; t_1 = 0.05; t_2 = 0.15; f_s = 10000;$ TQWT with parameters Q=5, r =3, J=19(These TQWT parameters are suitable for all the parameters shown in equation (10)) is applied to Sag type signal. Distribution of signal energy with respect subband is shown in Figure 4.b; Subbands of Signal is shown in Figure 4.c.By applying ITQWT (Inverse TQWT) on subband 20(All of the signal energy is concentrated on subband 20) we can extract fundamental component of a signal and it is shown in Figure 4.d. from which we can observe that the extracted signal is Sag type of signal. The Magnitude spectrum of reconstructed fundamental component signal is shown in Figure 4.e.

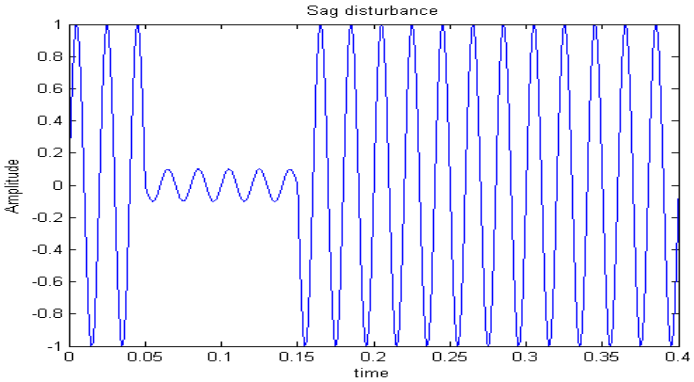

Figure 4. a. Sag Sisturbance Signal

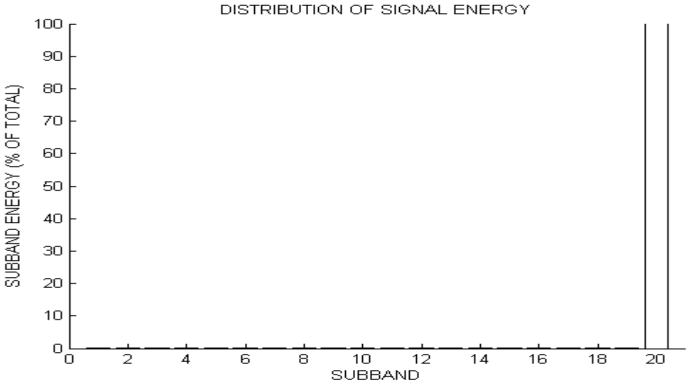

Figure 4. b. Distribution of Signal Energy

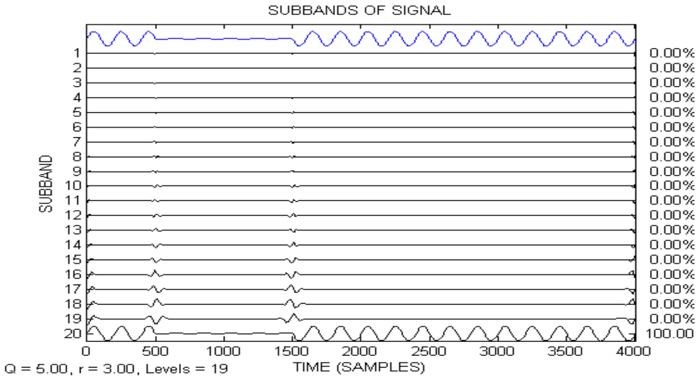

Figure 4. c. Subbands of Signal

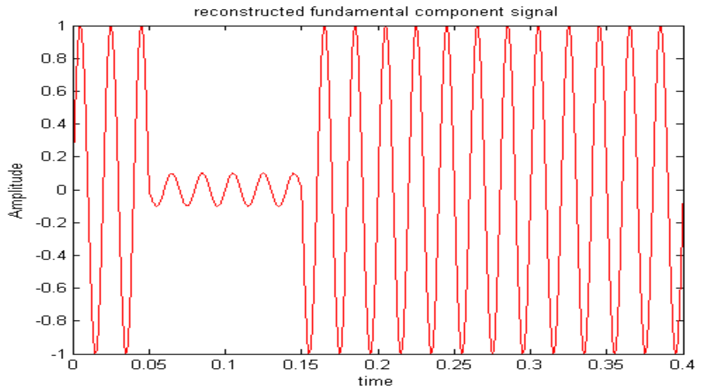

Figure 4. d. Reconstructed Signal

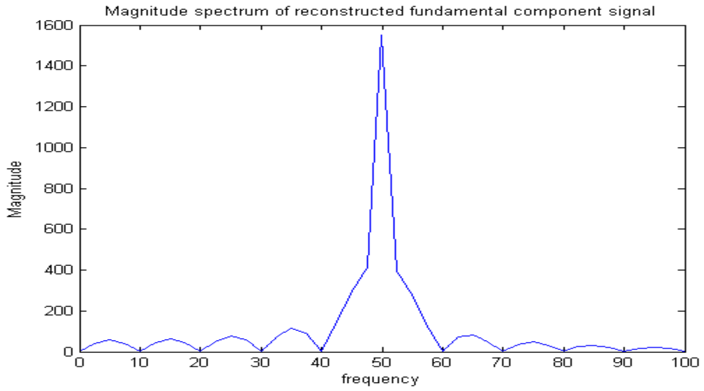

Figure 4. e. Magnitude Spectrum of Reconstructed Signal

3.2. Swell PQD Event

A swell is defined as an increase in rms voltage at the power frequency for durations from 0.5 cycles to 1 minute. Typical magnitudes are between 1.1 and 1.8pu [1].The equation for Swell type power Quality disturbance is given in Equation (11), and the parameters used in this equation are given in (12).Equation Model is [2]

$$h(t)=\left[1+\alpha\left(u\left(t-t_1\right)-u\left(t-t_2\right)\right)\right]\sin\left(\omega_b t\right) \tag{11}$$

Parameters $0.1\leq\alpha\leq 0.8; T\leq t_2-t_1\leq 9T; \omega_b=2\pi.50; T={}^{1}\!/_{50}$ (12)

Swell PQD signal is shown in Figure 5. a. for the parameters $\alpha=0.8; t_1=0.05; t_2=0.15; f_s=10000;$ TQWT with parameters Q=5, r =3, J=19 (These TQWT parameters are suitable for all the parameters shown in Equation (12)) is applied to Swell type signal. Distribution of signal energy with respect subband is shown in Figure 5.b; Subbands of Signal is shown in Figure 5.c.By applying ITQWT on subband 20(All of the signal energy is concentrated on subband 20) we can extract fundamental component of a signal and it is shown in Figure 5.d. from which we can observe that the extracted signal is Swell type of signal. The Magnitude spectrum of reconstructed fundamental component signal is shown in is Figure 5.e.

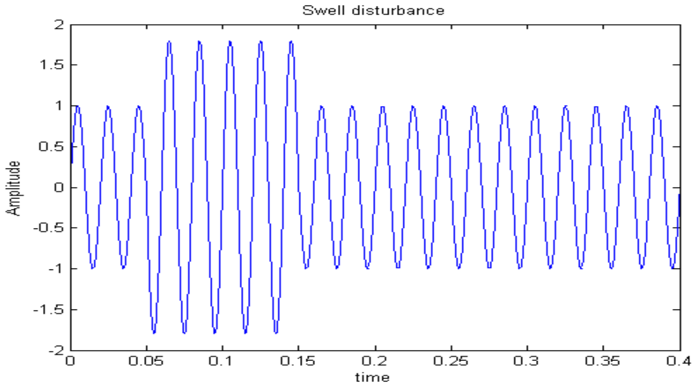

Figure 5. a. Swell Disturbance Signal

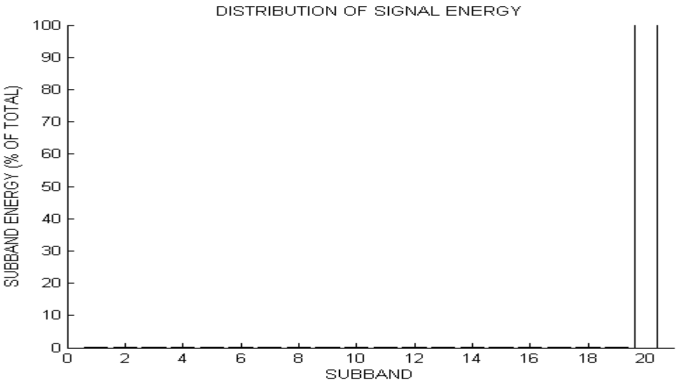

Figure 5. b. Distribution of Signal Energy

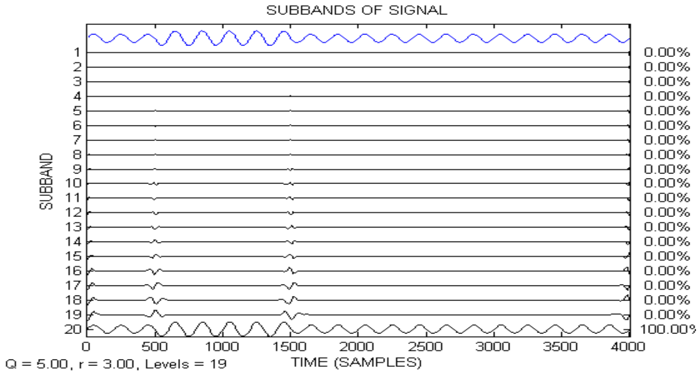

Figure 5. c. Subbands of Signal

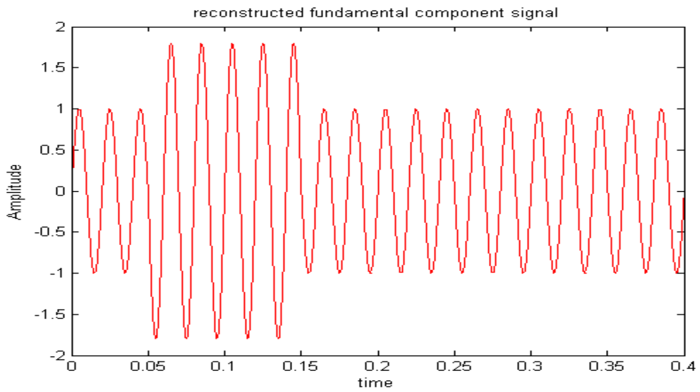

Figure 5. d. Reconstructed Signal

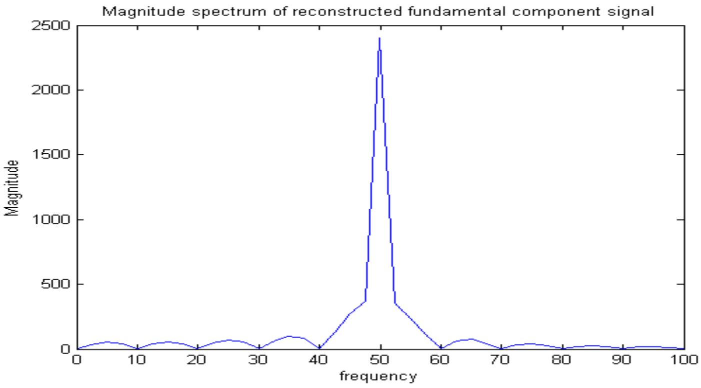

Figure 5. e. Magnitude Spectrum of Reconstructed Signal

3.3. Interruption PQD Event

An interruption occurs when the supply voltage or load current decreases to less than 0.1pu for a period of time not exceeding 1 minute [1]. The equation for Interruption type power Quality disturbance is given in Equation (13), and the parameters used in this equation are given in (14).Interruption Equation Model is given by [2]

$$h(t)=\left[1-\alpha\left(u\left(t-t_1\right)-u\left(t-t_2\right)\right)\right]\sin\left(\omega_b t\right) \tag{13}$$

Parameters $0.9 \le \alpha \le 1; T \le t_2 - t_1 \le 9T; \omega_b = 2\pi.50; T = {}^{1}\!/_{50}$ (14)

Interruption PQD signal is shown in Figure 6.a.for the parameters

$\alpha = 1; t_1 = 0.05; t_2 = 0.15; f_s = 10000;$

TQWT with parameters Q=5, r=3, J=19 (These TQWT parameters are suitable for all the parameters shown in equation (14)) is applied to Interruption type signal. Distribution of signal energy with respect subband is shown in Figure 6.b; Subbands of Signal is shown in Figure 6.c.By applying ITQWT on subband 20(All of the signal energy is concentrated on subband 20) we can extract fundamental component of a signal and it is shown in Figure 6.d. from which we can observe that the extracted signal is Interruption type of signal. The Magnitude spectrum of reconstructed fundamental component signal is shown in Figure 6.e.

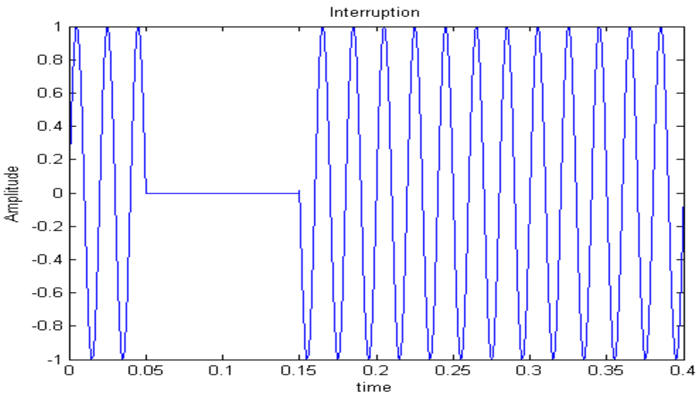

Figure 6. a. Interruption

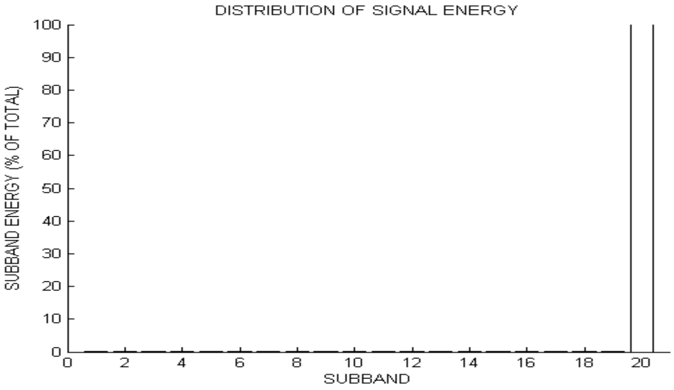

Figure 6. b. Distribution of Signal Energy

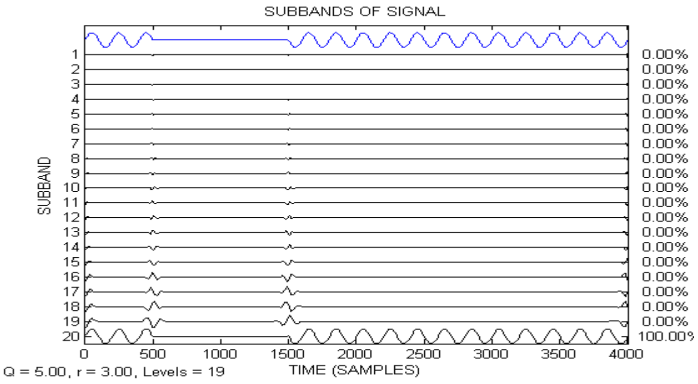

Figure 6. c. Subbands of Signal

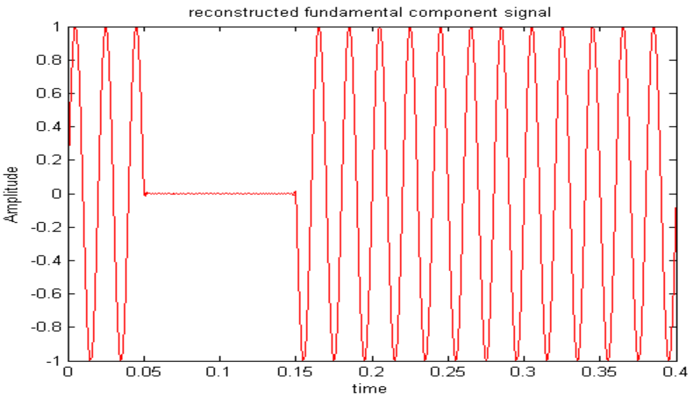

Figure 6. d. Reconstructed Fundamental Component Signal

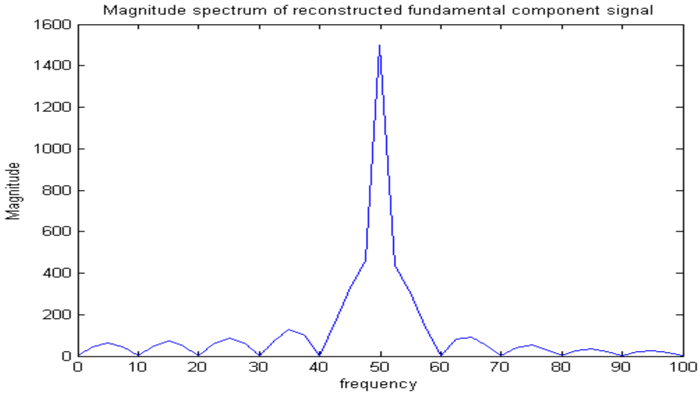

Figure 6. e. Magnitude Spectrum of Reconstructed Signal

3.4. FlickerPQD Event

Flicker can be defined as small amplitude changes in voltage levels occurring at frequencies less then 25Hz.Flicker is caused by large, rapidly fluctuating loads such as arc furnaces and electric welders [1]. The equation for Flicker type power Quality disturbance is given in equation (15), and the parameters used in this equation are given in (16). [2]

$$h(t) = \left[1 + \alpha \sin(2\pi\beta t)\right] \sin\left(\omega_b t\right) \tag{15}$$

Parameters $0.1 \le \alpha \le 0.2; 5HZ \le \beta \le 20HZ; \omega_b = 2\pi.50;$ (16)

Flicker PQD signal is shown in Figure 7.a. for the parameters
$\alpha = 0.2; \beta = 20; f_s = 10000;$

TQWT with parameters Q=5, r=2, J=28(These TQWT parameters are suitable for all the parameters shown in Equation (16)) is applied to Flicker type signal. Distribution of signal energy with respect subband is shown in Figure 7.b; Subbands of Signal is shown in Figure 7.c.By applying ITQWT on subbands 24, 25, 26 (most of the signal energy is concentrated on subband 24, 25, 26) we can extract fundamental component of a signal and it is shown in Figure 7.d.The Magnitude spectrum of reconstructed fundamental component signal is shown in Figure 7.e. from which we can observe that the extracted signal is a 50 HZ. Sinusoidal signal.

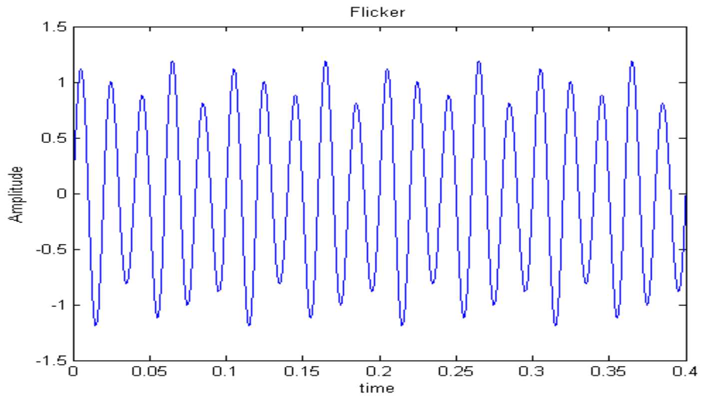

Figure 7. a. Flicker

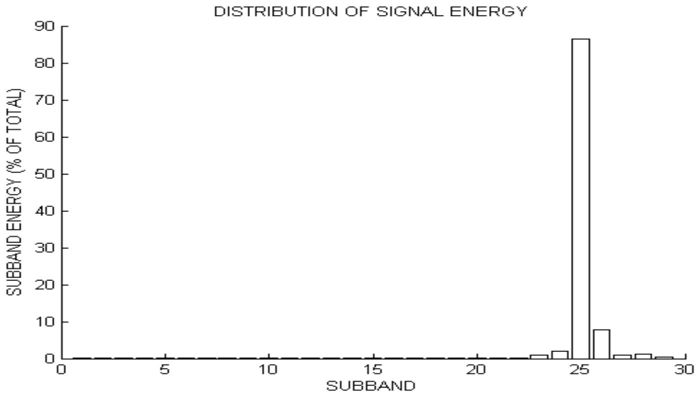

Figure 7. b. Distribution of Signal Energy

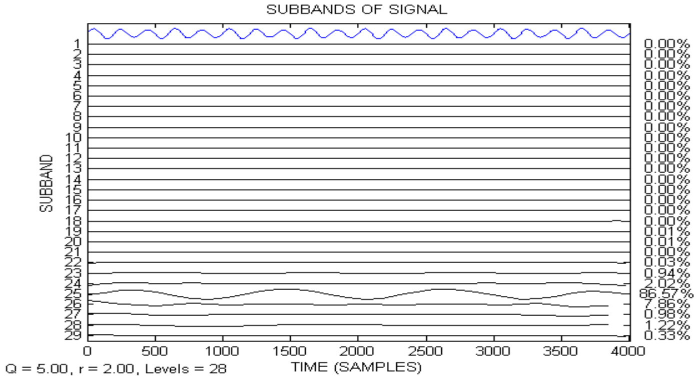

Figure 7. c. Subbands of Signal

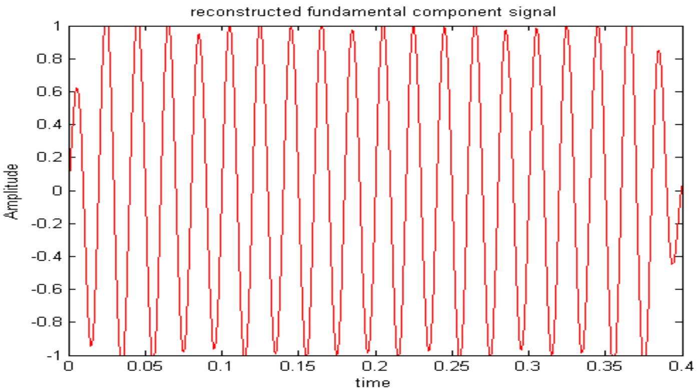

Figure 7. d. Reconstructed Fundamental Component Signal

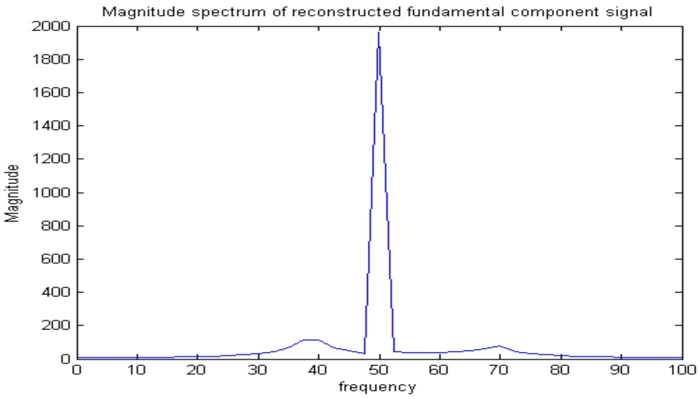

Figure 7. e. Magnitude Spectrum of Reconstructed Fundamental Component Signal.

3.5. Oscillatory Transient PQD Event

Oscillatory transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds are considered high-frequency oscillatory transient. A transient with a primary frequency component between 5 and 500 kHz with duration measured in tens microseconds is termed a medium frequency transient and considered as a low-frequency transient if frequency component less than 5 kHz and duration from0.3to 50 ms [1].The equation for Oscillatory transient type power Quality disturbance is given in (17), and the parameters used in this equation are given in (18) [2]

$$h(t)=\sin\left(\omega_b t\right)+\alpha\exp\left(-\left(t-t_1\right)/\tau\right)\left(u\left(t-t_1\right)-u\left(t-t_2\right)\right)\sin\left(2\pi f_n t\right) \qquad (17)$$

Parameter

$$0.1\le\alpha\le0.8; 0.5T\le t_2-t_1\le3T; 300HZ\le f_n\le900HZ; 8ms\le\tau\le40ms; \omega_b=2\pi.50; T={}^1\!/_{50} \qquad (18)$$

Oscillatory transient PQD signal is shown in Figure 8. a. for the parameters
$\alpha=0.8;\ f_n=300; t_1=0.041; t_2=0.071;\ f_s=10000;$

TQWT with parameters Q=5, r=2.15, J=19 (These TQWT parameters are suitable for all the parameters shown in Equation (18)) is applied to Oscillatory Transient signal. Distribution of signal energy with respect subband is shown in Figure 8.b; Subbands of Signal is shown in Figure 8.c.By applying ITQWT on subband 20(most of the signal energy is concentrated on subband 20) we can extract fundamental component of a signal and it is shown in Figure 8.d.The Magnitude spectrum reconstructed fundamental component signal is shown in Figure 8.e.from which we can observe that the extracted fundamental component is a 50 HZ.sinsoidal signal

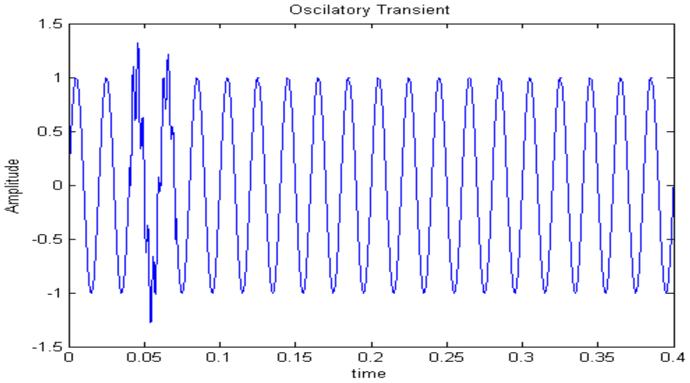

Figure 8. a. Oscilatory Transient Signal

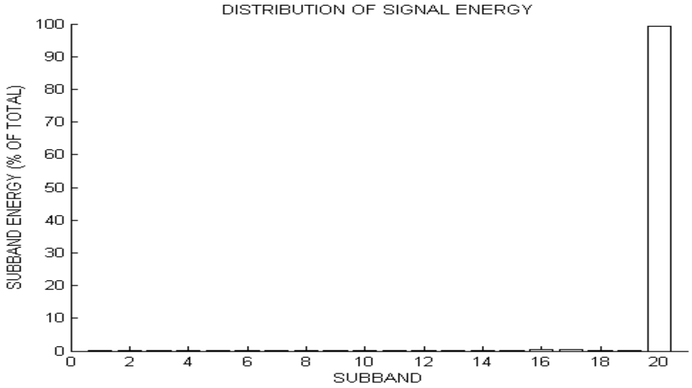

Figure 8. b. Distribution of Signal Energy

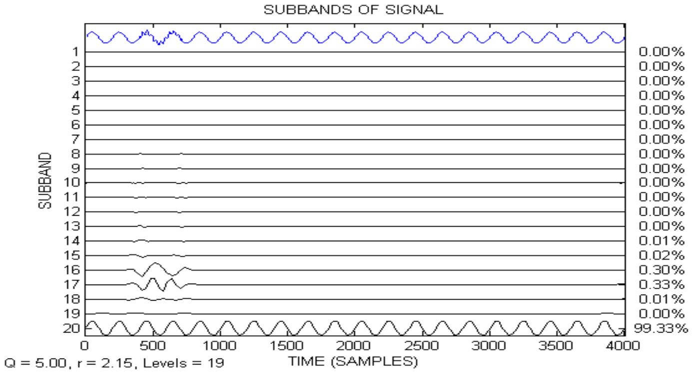

Figure 8. c. Subbands of Signal

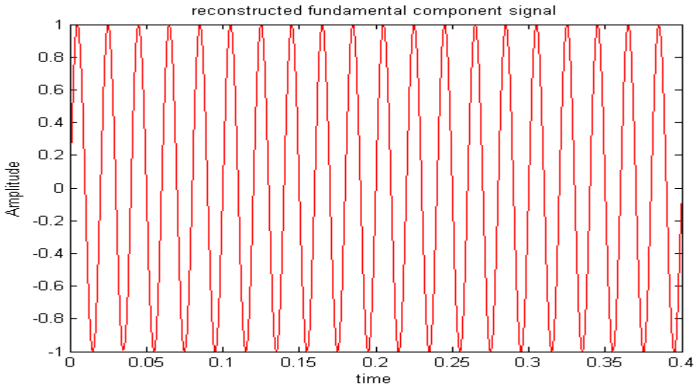

Figure 8. d. Reconstructed Fundamental Component Signal

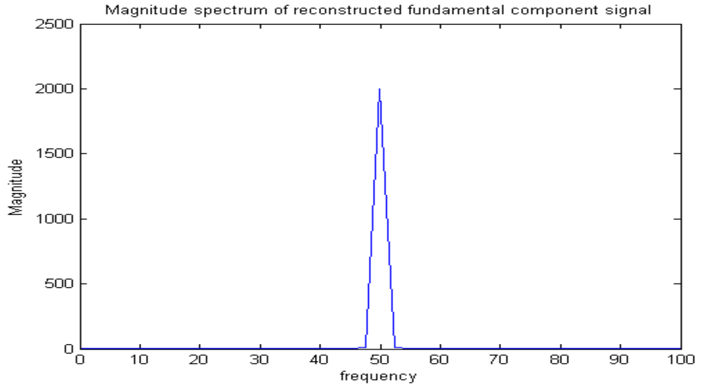

Figure 8. e. Magnitude Spectrum of Reconstructed Fundamental Component Signal

3.6. Harmonic PQD Event

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (50Hz). Harmonics combine with the fundamental voltage or current and produce waveform distortion [1]. The equation for Harmonic type power Quality disturbance is given in Equation (19), and the parameters used in this equation are given in (20) [2]

$$h(t) = \alpha_1 \sin\left(\omega_b t\right) + \alpha_3 \sin\left(3\omega_b t\right) + \alpha_5 \sin\left(5\omega_b t\right) + \alpha_7 \sin\left(7\omega_b t\right) \tag{19}$$

Parameters $0.05 \le \alpha_3, \alpha_5, \alpha_7 \le 0.15$; $\sum\left(\alpha_i\right)^2 = 1; \omega_b = 2\pi.50;$ (20)

Harmonic type PQD signal is shown in Fig 9.a.for the parameters $f_s = 10000$; $\alpha = 0.5; \alpha_3 = \alpha_5 = \alpha_7 = 0.15;$ TQWT with parameters Q=5.2, r =1.9, J=19. (These TQWT Parameters are suitable for all the parameters shown in equation (20)) is applied to Harmonic type signal. Distribution of signal energy with respect subband is shown in Figure 9.b; Subbands of Signal is shown in Figure 9.c.By applying ITQWT on subband 20(most of the signal energy is concentrated on subband 20) we can extract fundamental component of a signal and it is shown in Figure 9.d.The Magnitude spectrum of reconstructed fundamental component signal is shown in Figure 9.e.from which we can observe that the extracted fundamental component is a 50 HZ. Sinusoidal signal

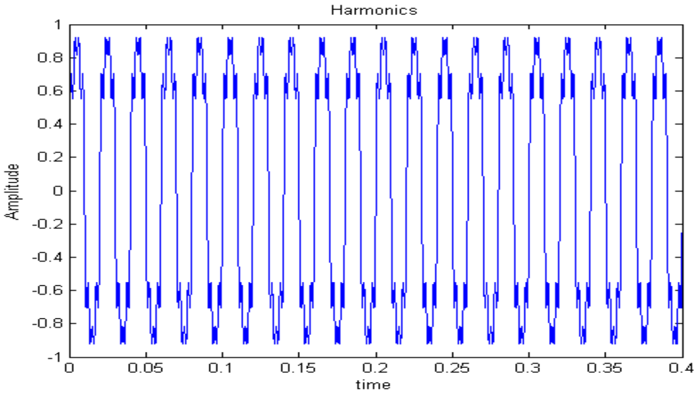

Figure 9 .a. Hamonics Signal

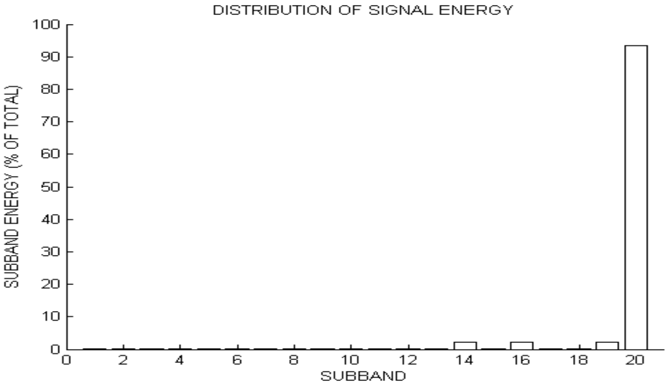

Figure 9. b. Distribution of Signal Energy

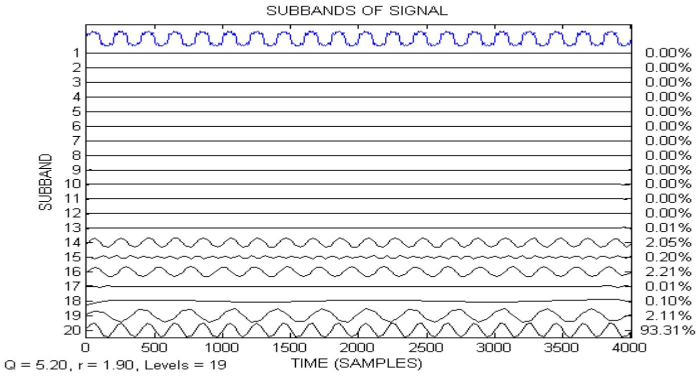

Figure 9. c. Subbands of Signal

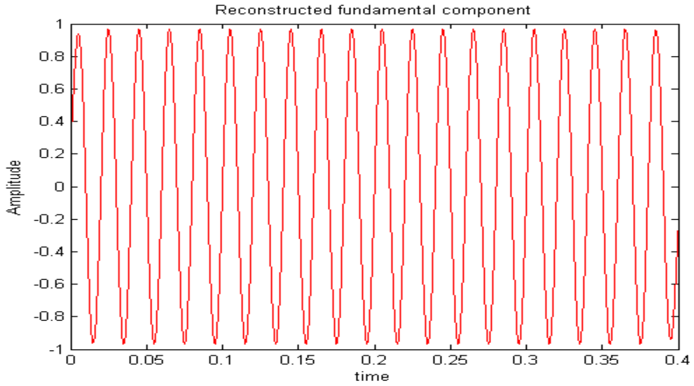

Figure 9. d. Reconstructed Fundamental Component Signal

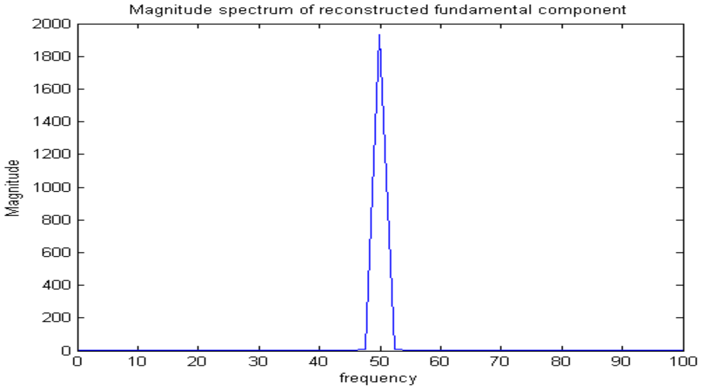

Figure 9 .e. Magnitude Spectrum of Reconstructed Fundamental Component

3.7. Sag+Harmonic PQD Event

The equation for Sag with Harmonic type power Quality disturbance is given in Equation (21), and the parameters used in this equation are given in (22) [1]

$$h(t)=\left[1-\alpha\left(u\left(t-t_1\right)-u\left(t-t_2\right)\right)\right]\left[\alpha_1\sin\left(\omega_b t\right)+\alpha_3\sin\left(3\omega_b t\right)+\alpha_5\sin\left(5\omega_b t\right)\right] \quad (21)$$

Parameters

$$0.1<\alpha\leq 0.9; T\leq t_2-t_1\leq 9T; 0.05\leq\alpha_3,\alpha_5\leq 0.15; \sum\left(\alpha_i\right)^2=1; \omega_b=2\pi.50; T=1/50\,, \quad (22)$$

Sag with Harmonic type PQD signal is shown in Figure 10.a.for the parameters $\alpha=0.9;\alpha_3=\alpha_5=\alpha_7=0.15;t_1=0.05;t_2=0.15;\ f_s=10000;$ TQWT with parameters Q=4.5, r =3, J=29 (These TQWT parameters are suitable for all the parameters shown in Equation (22)) is applied to Sag+Harmonic type signal. Distribution of signal energy with respect subband is shown in Figure 10.b; Subbands of Signal is shown in Figure 10.c.By applying ITQWT on subband 30(most of the signal energy is concentrated on subband 30) we can extract fundamental component of a signal and it is shown in Figure 10.d. From which we can observe that the extracted fundamental component is sag type of signal. The Magnitude spectrum of reconstructed fundamental component signal is shown in Figure 10.e.

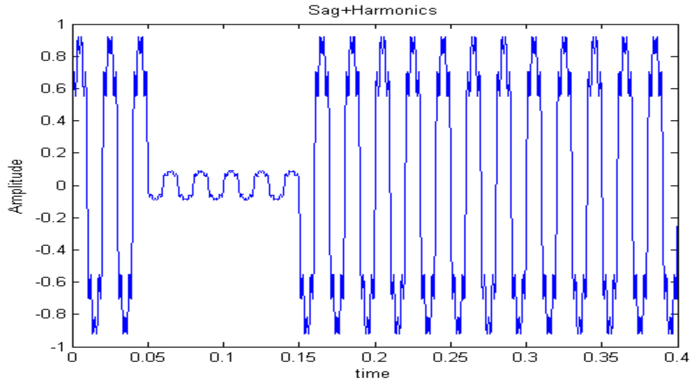

Figure 10. a. Swell+Harmonics Signal

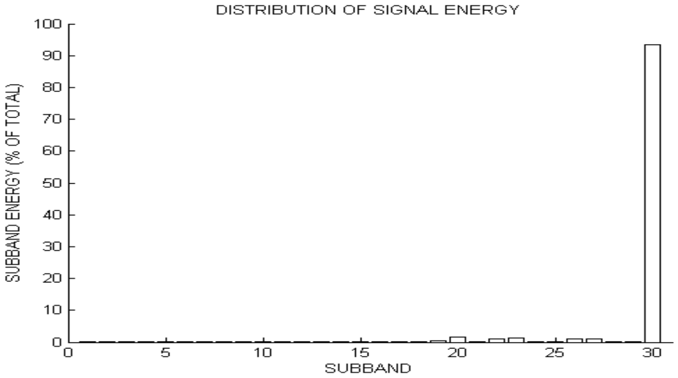

Figure 10. b. Distribution of Signal Energy with Respect to Subbands

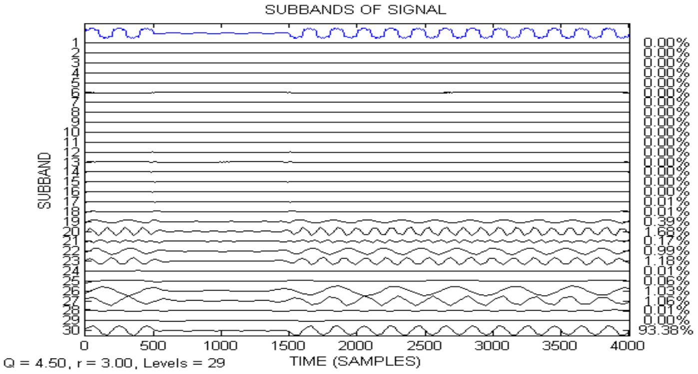

Figure 10. c. Subbands of Signal

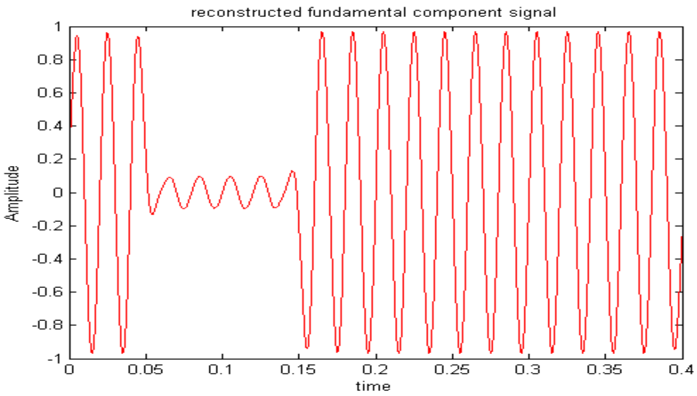

Figure 10. d. Reconstructed Fundamental Component Signal

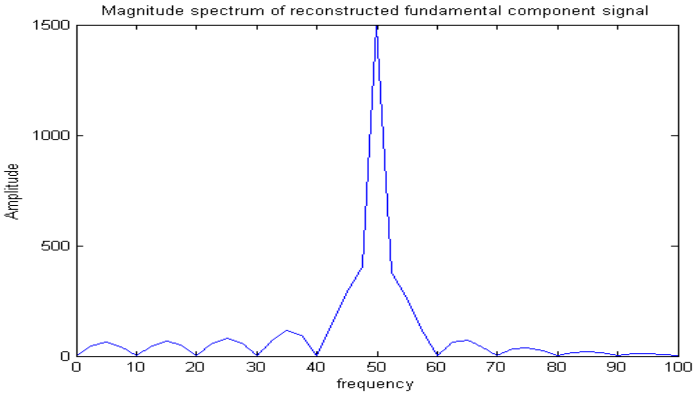

Figure 10. e. Magnitude Spectrum of Reconstructed Fundamental Component Signal

3.8. Swell +Harmonic PQD Event

The equation for Swell with Harmonic type power Quality disturbance is given in equation (23), and the parameters used in this equation are given in (24) [2]

$$h(t)=\left[1+\alpha\left(u\left(t-t_1\right)-u\left(t-t_2\right)\right)\right]\left[\alpha_1\sin\left(\omega_b t\right)+\alpha_3\sin\left(3\omega_b t\right)+\alpha_5\sin\left(5\omega_b t\right)\right] \tag{23}$$

Parameters

$$0.1<\alpha\le 0.8; T\le t_2-t_1\le 9T; 0.05\le\alpha_3,\alpha_5\le 0.15; \sum\left(\alpha_i\right)^2=1; \omega_b=2\pi.50; \tag{24}$$

Swell with Harmonic type PQD signal is shown in Fig.11.a.for the parameters $\alpha=0.5; \alpha_3=\alpha_5=\alpha_7=0.15; t_1=0.05; t_2=0.15; f_s=10000;$ TQWT with parameters Q=4.5, r = 3, J=29 (These TQWT parameters are suitable for all the parameters shown in Equation (24) is applied to Swell+Harmonic type signal. Distribution of signal energy with respect subband is shown in Figure 11.b; Subbands of Signal is shown in Figure 11.c.By applying ITQWT on subband 30(most of the signal energy is concentrated on subband 30) we can extract fundamental component of a signal and it is shown in Figure 11.d. From which we can observe that the extracted fundamental component is swell type of signal. The Magnitude spectrum of reconstructed fundamental component signal is shown in Figur 11.e.

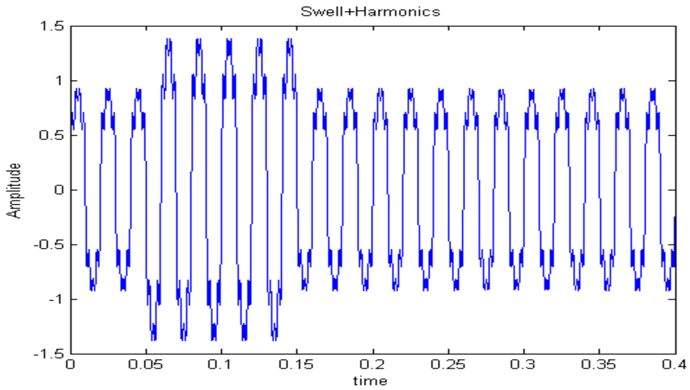

Figure 11. a. Swell+Harmonics Signal

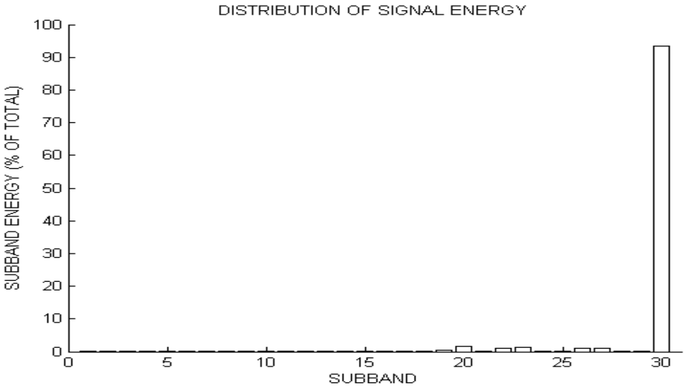

Figure 11. b. Distribution of Signal Energy with Respect to Subbands

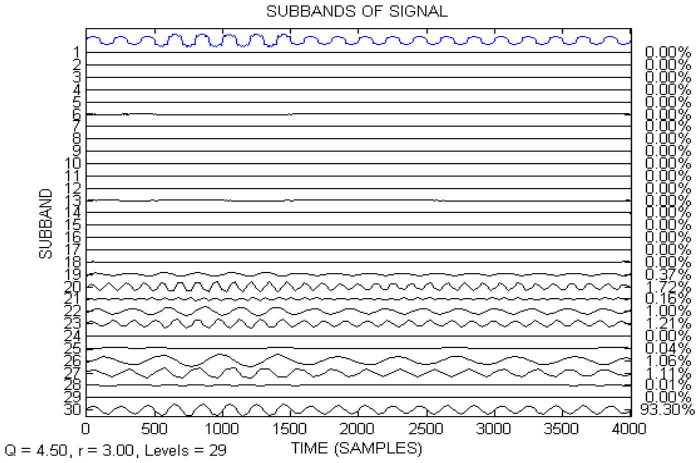

Figure 11. c. Subbands of Signal

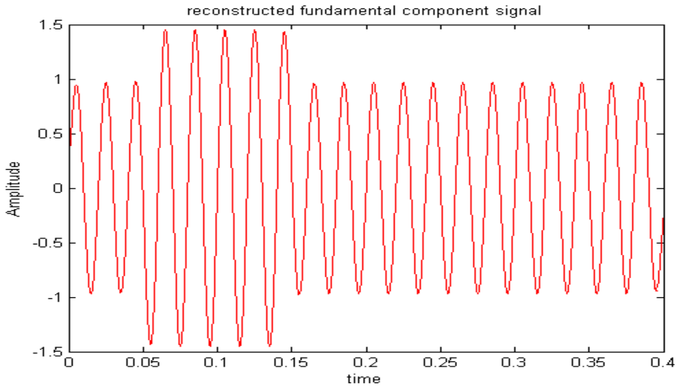

Figure 11. d. Reconstructed Fundamental Component Signal

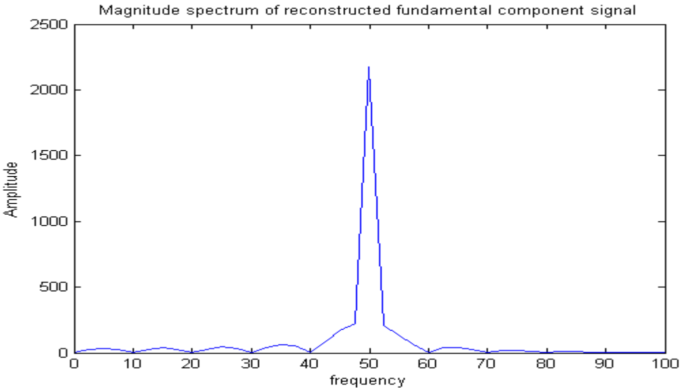

Figure 11. e. Magnitude Spectrum of Reconstructed Fundamental Component Signal

3.9. Notch PQD Event

Notching is a switching or other disturbance of the normal power voltage waveform, lasting less than 0.5 cycles which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to 0.5 cycles [1]. Notching is caused by the normal operation of power electronics devices when current is commutated from one phase to another. The equation for Notch type power Quality disturbance is given in equation (25), and the parameters used in this equation are given in (26) [2]

$$h(t)=\sin\left(\omega_b t\right)-sign(\sin\left(\omega_b t\right))\left\{\sum_{n=0}^{9} k\left[u\left(t-\left(t_1+0.02n\right)\right)-u\left(t-\left(t_2+0.02n\right)\right)\right]\right\} \qquad (25)$$

Parameters $0.1 \le k \le 0.4; 0 \le t_1, t_2 \le 0.5T; 0.01T \le t_2 - t_1 \le 0.05T$ (26)

Notch PQD signal is shown in Figure 12.a.for the parameters

$k = 0.4; t_1 = 0.0029; t_2 = t_1 + 0.0005; f_s = 10000;$

TQWT with parameters Q=6, r=3, J=31 (These TQWT parameters are suitable for all the parameters shown in Equation (26))is applied to Notch signal, Distribution of signal energy with respect subband is shown in Figure 12.b; Subbands of Signal is shown in Figure 12.c.By applying ITQWT on subband 32(most of the signal energy is concentrated on subband 32) we can extract fundamental component of a signal and it is shown in Figure 12.d.The Magnitude spectrum of reconstructed fundamental component signal is shown in Figure 12.e.from which we can observe that the extracted fundamental component is a 50 HZ. Sinusoidal signal

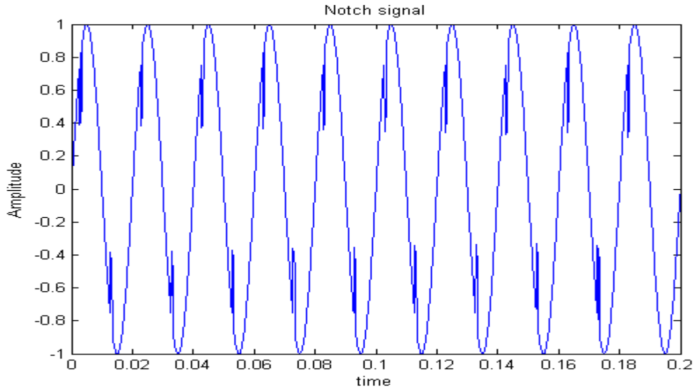

Figure 12. a. Notch Signal

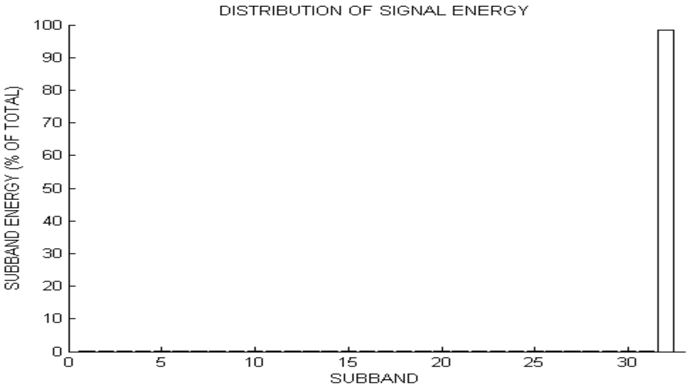

Figure 12. b. Distribution of Signal Energy with Respect to Subbands

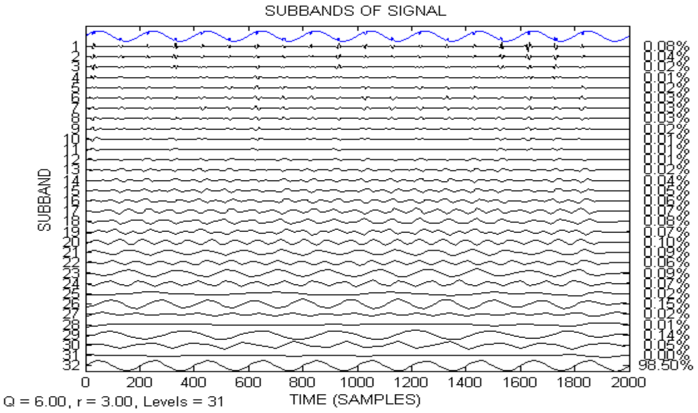

Figure 12. c. Subbands of Signal

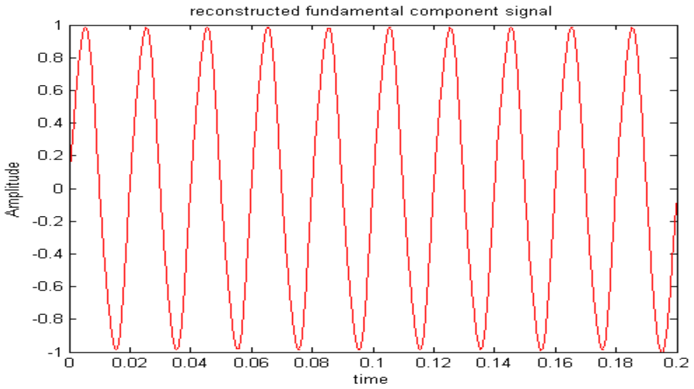

Figure 12. d. Reconstructed Fundamental Component Signal

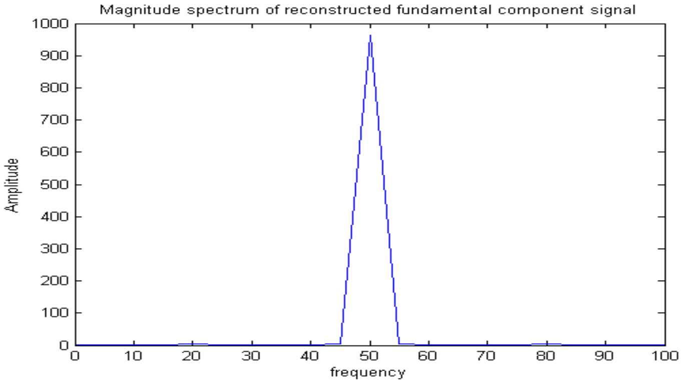

Figure 12. e. Magnitude Spectrum of Reconstructed Fundamental Component Signal

3.10. Spike PQD Event

Spikes are short duration non stationary noise signals whose amplitude at temporal instant cannot be predicted. Spikes are observed as impulses superimposed to the fundamental frequency. These are caused by load turning on and off, equipment faults, effect of discharging of stored energy when turned off, lightning, *etc.*, [1]

The equation for Spike type power Quality disturbance is given in equation (27), and the parameters used in this equation are given in (28) [2]

$$h(t)=\sin\left(\omega_b t\right)+sign(\sin\left(\omega_b t\right))\left\{\sum_{n=0}^{9} k\left[u\left(t-\left(t_1+0.02n\right)\right)-u\left(t-\left(t_2+0.02n\right)\right)\right]\right\} \tag{27}$$

Parameters

$$0.1\le k\le 0.4; 0\le t_1,t_2\le 0.5T; 0.01T\le t_2-t_1\le 0.05T; \omega_b=2\pi.50; T=1/50 \tag{28}$$

Spike PQD signal is shown in Fig.13.a.for the parameters

$$k=0.4; t_1=0.0029; t_2=t_1+0.0005; f_s=10000;$$

TQWT with parameters Q=5.2, r=2, J=19 (These TQWT parameters are suitable for all the parameters shown in equation (28))is applied to Spike signal, Distribution of signal energy with respect subband is shown in Figure 13.b; Subbands of Signal is shown in Figure 13.c.By applying ITQWT on subband 20(most of the signal energy is concentrated on subband 20) we can extract fundamental component of a signal and it is shown in Figure 13.d.The Magnitude spectrum of reconstructed fundamental component signal is shown in Figure 13.e.from which we can observe that the extracted fundamental component is a 50 HZ. Sinusoidal signal.

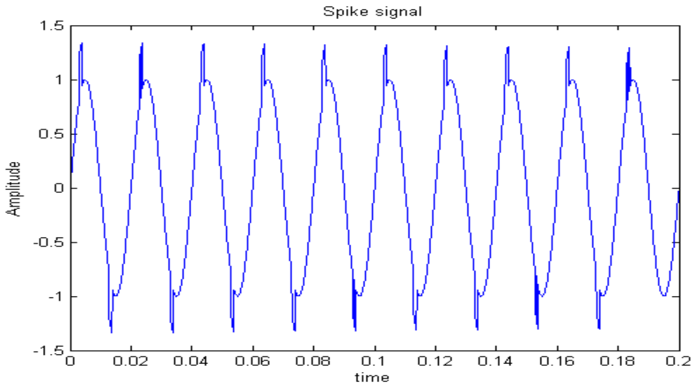

Figure 13. a. Spike Signal

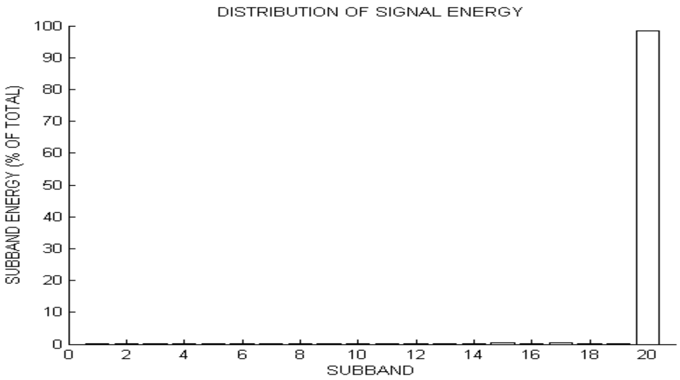

Figure 13. b. Distribution of Signal Energy with Respect to Subbands

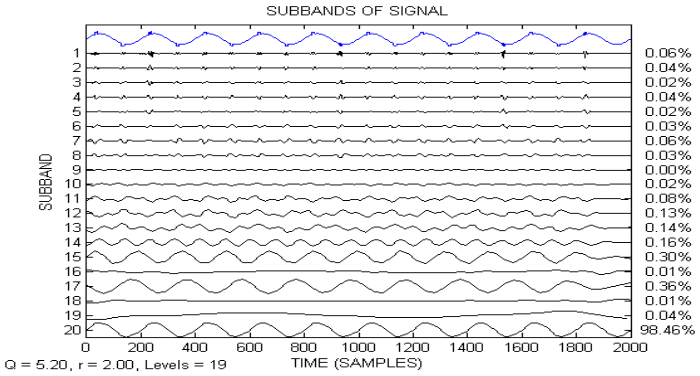

Figure 13. c. Subbands of Signal

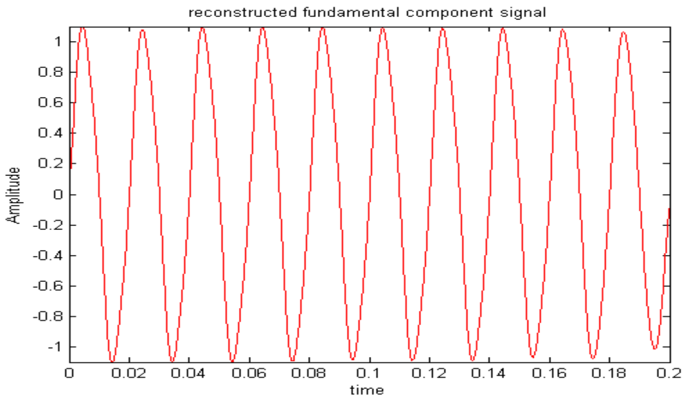

Figure 13. d. Reconstructed Fundamental Component Signal

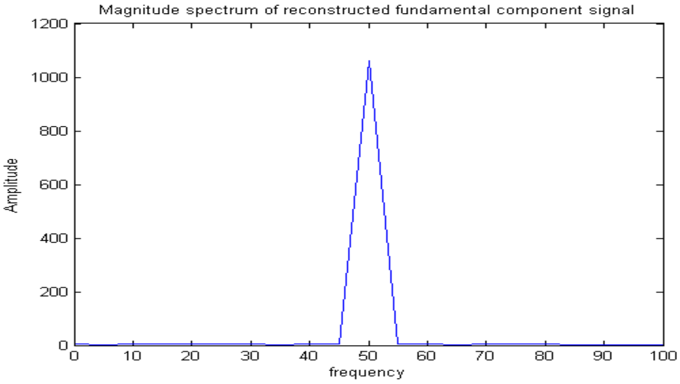

Figure 13. e. Magnitude Spectrum of Reconstructed Fundamental Component Signal

4. Conclusions

In this paper, a novel approach for extraction of fundamental frequency component in power system is discussed. In this method, the fundamental frequency component of the signal is extracted using Tunable-Q Wavelet Transform. To show the effectiveness of the proposed method, ten types of PQ events such as voltage sag, swell, interruption, harmonic, sag with harmonics and swell with harmonics, notch etc are discussed and deliberated.

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