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Interpretation of Power Quality Disturbance Using Wavelet Transforms

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Abstract— ***A new method for detection of power quality disturbance is proposed: first, the original signals are de-noised by the wavelet transform; second, the beginning and ending time of the disturbance can be detected in time, third, determining the cause of power quality disturbances using Discrete Wavelet Transforms (DWT).In this paper, wavelet transform is proposed to identify the power quality disturbance at its instance of occurrence. Power quality disturbances like sag, swell, interruption, transients and harmonics are considered and are decomposed up to two levels using Db4 wavelet. Discrete Wavelet Transform (DWT) based signal processing technique has been applied to extract the features from the multiple Power Quality Disturbance (PQD) signals. The DWT uses a Multi Resolution Analysis (MRA) technique which decomposes the input signal into approximation and detail coefficients. The feature extraction is carried out in such a way to reduce the dimensions of input vector matrix for the classifiers. The features of energy value (EV) can be extracted from the detail coefficients.***

Keywords: Power Quality Disturbance (PQD), Multi Resolution Analysis (MRA), Daubechies (Db), Discrete Wavelet Transform (DWT).

1 INTRODUCTION

Power quality disturbances (PQDs) are generated with the growth of nonlinear loads, such as solid-state switching equipment, electronically switched devices, industrial rectifiers, and inverters. Warped voltage waveforms adversely affect electronic devices, such as electrical system failures, disk crashes, and microcontroller failures [1]. Therefore, it is essential to evaluate the power quality of the electric system by recognizing detailed disturbance events. By recognizing power quality events, an efficient strategy can be carried out to stabilize power grids. The patterns and the reasons for PQDs are multiple. For example, a short trouble may result in a voltage fluctuation, which creates sag or other events [2]. The use of DC–AC inverters may result in harmonics. High-power cost equipment may lead to voltage flickers. Transient and spike events may be caused by electric discharge or sudden switching-off with overrides [3]. The proposed method is based on five steps: analytical PQD signal generation, signal segmentation, feature Extraction. Different studies have been promoted for detecting power quality events. Most PQD detecting solutions are implemented with the following processes: feature extraction, feature dimension optimization, and pattern recognition. Feature extraction is essential for PQD classification. It is noted that features can be extracted directly from the original signal or the transformed formalization. In the pre-processing stage, many researchers have applied different feature extraction techniques for extracting the features. The various feature extraction methods include Fourier Transforms (FT), Discrete Fourier Transform (DFT), Short-Time Fourier Transform (STFT), Fast Fourier Transform (FFT), Wavelet Transform (WT), Discrete Wavelet Transform (DWT), Stockwell Transform (ST) and so on [6–8]. Fourier Transform (FT) is a simple technique for analysis, however it is not applicable for non-stationary signals [4]. Three variants of FT like DFT, STFT, FFT were generally used by the researchers for PQ detection in last two decades [5]. However, while using DFT and STFT, the transient nature of signals cannot be expressed clearly in a fixed window size. The FFT is similar to DFT in functionality, however with the latter, signal information like amplitude, frequency, and phases cannot be expressed correctly [9–11]. The series of Wavelet Transform (WT) can be used to overcome the shortcomings of DFT and STFT techniques. The WT offers frequency and time information of a signal simultaneously. This method is time consuming and is sensitive to the noisy environment [12,13]. The Stockwell Transform (ST) is a combination of WT and STFT which can be used to overcome the drawbacks of WT with the options of better extraction and characterization. A redundant representation of time–frequency domain is a major drawback of ST and also its processing time is more, if the sampling rate is high [14]. In WT series, the Discrete Wavelet Transform (DWT) is more popular and widely used for the PQ signal analysis in real time environment. One of the major concerns with DWT is the selection of mother wavelets for particular application [5]. However in literature, it is clear that the mother wavelet Daubechies-4 (db4) is more suitable and widely applied for PQ studies [15,16]. As compared to other signal processing methods, extraction of features can be achieved more accurately in minimum processing time by means of using DWT method. This is due to its filtering facility which filters the original signal from the noise signal more rapidly [17]. Therefore, in this study, DWT analysis has been adopted for extraction of features to train the classifiers. A power quality problem can best be described as any variations in the electrical power service, such as voltage dips, fluctuations, momentary interruptions, harmonics and transients, resulting in maloperation or failure of end-user equipment. Wavelet Transform provides the timescale analysis of the non-stationary signal. It decomposes the signal to time scale representation rather than time- frequency representation. Wavelet transform (WT) expands a signal into several scales belonging to different frequency regions by using translation (shift in time) and dilation (compression in time) of a fixed wavelet function known as Mother Wavelet. Wavelet based signal processing technique is one of the new tools for power system transient analysis and power quality disturbance classification and also transmission line protection. The Discrete Wavelet Transform and Multi Resolution Analysis (MRA) provides a short window for high frequency components and long window for low frequency components and hence provides an excellent time frequency resolution. This allows wavelet transform for analysis of signals with localized transient components. In this paper, a brief review about the DWT and MRA was dealt. With the help of MATLAB in a transmission line the disturbances were introduced for analysis. With the help of Daubechies as mother Wavelet decomposition was done using MATLAB-Wavelet Toolbox up to two level according to the accuracy of information obtained. Finally, the detection of voltage sag and voltage swell type of disturbances was done.

2. Power Quality Disturbance Signals Stimulation Using MATLAB

2.1 Power Quality Disturbances

For the power quality analysis, detection and classification of the disturbance is very important. For this purpose, the different power quality disturbances are recorded and later used for the analysis purpose. So, the first step in PQ analysis is generation of disturbance signal. The PQ disturbances are generated as per the definition and parameters defined by IEEE 1159 and IEC 61000 standard. Table 1 classifies different PQ disturbances.

TABLE 1. Power Quality disturbances

Name of Disturbance	Category	Duration	Magnitude
Short duration Sag	Instantaneous Momentary Temporary	0.5-30 cycle 30 cycle-3 sec 3 sec-1 min	$0.1pu - 0.9pu$ $0.1pu - 0.9pu$ $0.1pu - 0.9pu$
Swell	Instantaneous Momentary Temporary	0.5-30 cycle 30 cycle-3 sec 3 sec-1 min	$1.1pu - 1.8pu$ $1.1pu - 1.8pu$ $1.1pu - 1.8pu$
Interruption	Instantaneous Momentary	0.5-3sec 3sec-1min	$< 0.1pu$ $< 0.1pu$
Transients (Oscillatory)	Low Frequency<5KHz Medium Frequency 5-500KHz High Frequency 0.5-5MHz	$03 - 50ms$ $20\ \mu s$ $5\ \mu s$	$0 - 4\ pu$ $0 - 8\ pu$ $0 - 4\ pu$
Harmonics	0-100 harmonic		$0 - 20\ \%$

2.1.1 Voltage Sag: Voltage sag is the most common type of disturbance occurring in power system. A sudden reduction in magnitude is called voltage sag or dip. Voltage sag is defined as reduction in current or voltage amplitude from 0.9pu to 0.1pu. Duration of voltage sag may be from half cycle to one minute. The main cause of voltage sag are switching on of heavy load, large induction motor starting or transformer energization. Different kinds of faults like line to ground, double line to ground causes voltage sag.

2.1.2 Voltage Swell: Voltage swell is rise in voltage magnitude. It is defined as rise in current or voltage amplitude from 1.1pu to 1.8pu and remains from half cycle to 1 minute. The rise in magnitude is due to switching off heavy load, due to large capacitor bank or due to asymmetrical faults.

2.1.3 Over Voltage or Under Voltage: These disturbances are similar to voltage swell and voltage sag but the time duration is longer than 1 minute.

2.1.4 Transients: These are momentary disturbances which have very short time duration. These are mainly due to switching events or due to environmental effects. These are further classified as impulse or oscillatory.

2.1.5 Interruption: Interruption is just complete loss of power. If the amplitude of voltage or current goes below 0.1pu, for half cycle to 1 minute duration, this is called interruption.

2.1.6 Harmonics: Harmonics are distortion in sinusoidal frequency which is integral multiple of a fundamental signal frequency. Power electronic devices or non-linear loads are the main causes of harmonics.

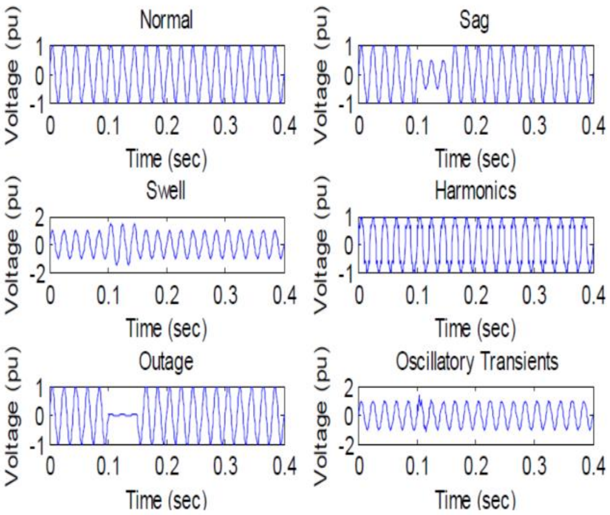

Fig 1 Power Quality Disturbance Signal

3. PROPOSED METHODOLOGY FOR DETECTION OF PQDS

The steps involved during the process of detection and classification of PQDs is shown in the form of block diagram of Fig. 2. Also, the brief explanations of steps are given as below:

3.1 Data Acquisition (Step-1): Proposed model is simulated in Matlab under various PQDs, and the disturbed voltage signal is stimulated by MATLAB and used for further process.

3.2 Feature Extraction (Step-2): The features can be extracted by means of processing the input time-varying voltage signal with the help of DWT technique. The DWT analysis is useful to extract the wavelet transform coefficients (detailed and approximation) from the signals of different PQ events. From the extracted coefficients that features of energy values are evaluated to learn the classifiers.

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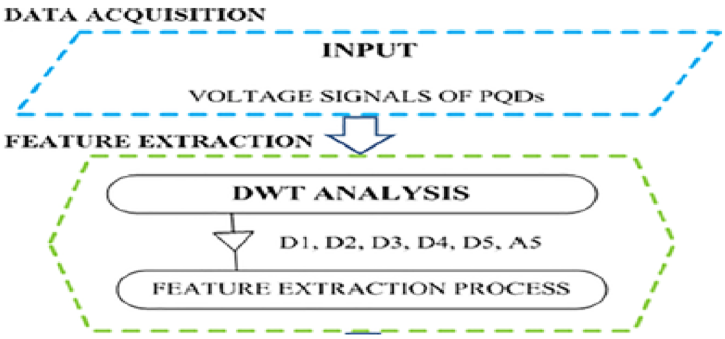

Fig 2 Proposed methodology for detection of PQDs

4. WAVELET TRANSFORMS

Fourier Transforms gives information about the frequency contents of the signal. But it doesn't give information about the time of occurrence of the frequency. Hence suitable for stationary signal analysis where frequency component doesn't vary with time. A wavelet is a transient signal that can be defined as an oscillatory function, or a non-stationary signal which has a zero mean, and decays quickly to zero. The wavelets are functions that satisfy certain mathematical requirements and are used in representing data or other functions. The fundamental idea behind wavelets is to analyse according to scale. The wavelet transform procedure is to adopt a wavelet prototype function, called an analysing wavelet or mother wavelet. Frequency analysis is performed with contracted, high frequency version of the prototype wavelet and a dilated, low frequency version of the prototype wavelet Figure 3.

Fig 3 Wavelet Transform

Other applied fields that are making use of wavelets are astronomy, acoustics, nuclear engineering, sub band coding, signal and image processing neurophysiology, music magnetic resonance imaging, speech discriminations, optics earthquake predictions, radar, human vision, and in pure mathematics applications such as solving partial differential equations. The wavelet transforms, as frequencies increases, the time resolution increases; likewise, as frequency decrease, the frequency resolution increases. Thus a certain high frequency component can be located more accurately in time then a low frequency component can be located more accurately in the time a low frequency component and a low frequency component can be located more accurately in frequency compared to high frequency component. The extensive use of the wavelet transform in various fields is due to its variety of properties

5. SCALING AND SHIFTING

Scaling a wavelet simply means stretching (or compressing) it. The parameter scale in the wavelet analysis is similar to the scale used in maps. As the case of maps, high scales corresponding to a non-detailed global view, and low scales correspond to a detail view. Similarly, in terms of frequency, low frequencies correspond to global information of the signal, whereas high frequencies correspond to detailed information of hidden pattern in the signal. To go beyond colloquial descriptions such as "stretching", we introduce the scale, often denote by the letter α.

6. SHIFTING

Shifting a wavelet means delaying its onset. Mathematically, delaying a function f(t) by k represented by f (t-k). Discrete Wavelet Transform (DWT) & Multi- Resolution Analysis (MRA). Wavelets have been applied successfully in a wide variety of research areas such as signal analysis, image processing, data compression, de-noising and numerical solution of differential equations. In recent years, wavelet analysis techniques have been proposed extensively in the literature as a new tool for fault detection, localization and classification of different power system transients. In this paper we present the wavelet-multi-resolution analysis as a new tool for extracting the distortion features. The MRA is a tool that utilizes the DWT to represent the time domain signal f (t) can be mapped into the wavelet domain and represented at different resolution levels in terms of the following expansion coefficients,

$$C_{signal} = [C_0 | d_0 | d_1 | \text{---} \, d_{f-n} | \,] \qquad (1)$$

Where, d_i, represent the detail coefficients at different resolution levels, and C_0, presents the last approximate coefficients. Wavelet transform can be achieved by convolution and decimation. The detail coefficients d_j and the approximated coefficients c_j can be used to reconstruct a detailed version D and an approximated version A_1, of signal f (t) at that scale. Effectively the wavelet coefficients $h_0(n)$ and the scaling function coefficients h (n) will act as high pass and low pass digital filters respectively. The frequency responses $H_0(\omega)$ and $H_1(\omega)$ of the mother wavelet Daubechies (Db4) and its scaling function are shown in Figure 4. These two functions divide the spectrum of the input signal f (t) equally. Decimation (or down sampling) is an efficient multi-rate digital processing technique for changing the sampling frequency of a signal in the digital domain and efficiently compressing the data. As indicated in Figure 4 the sampling rate compression and data reduction in detail coefficients are achieved by discarding every second sample resulting from convolution process. Since half of the data is discarded (decimation by 2), there is a possibility of losing information (aliasing); however, the wavelet and the scaling function coefficients ($h_1(n)$ and $h_0(n)$) will act as digital filters that limit the band of the input C_{j+1} and prevent aliasing.

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Fig 4 Comparison between Sinusoidal wave and a Wavelet

5. DAUBECHIES FAMILY WAVELETS

As per IEEE standards, Daubechies wavelet transform is very accurate for analysing Power Quality Disturbances among all the wavelet families, for transient faults. The names of the Daubechies family wavelets are written as Db_N, where N is the order, and db the "surname" of the wavelet. (Figure 5)

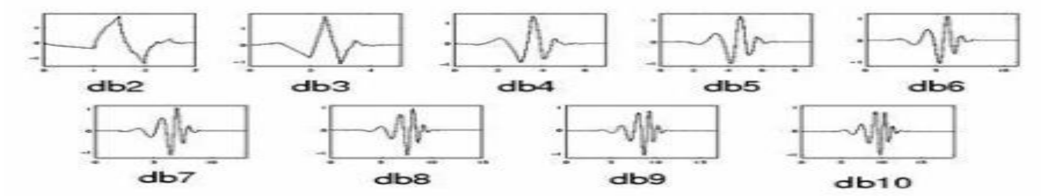


Fig 5 Daubechies family wavelets

where a and b are the scaling and translational parameters respectively, h is the mother wavelet function. Although, the CWT is useful to overcome the problem of resolution in Short Time Fourier Transform (STFT), but it has the limitations of low redundancy during reconstruction of signal and also less feasible for the real time applications. This is overcome by the discrete WT (DWT) that can be defined using wavelet function ψ(t) as [40,41],

$$DWT(m,n) = \left[1/\sqrt{a_o^m}\, \sum_k f(k)\, h\left({n - k b_o a_o^m}/{a_o^m} \right) \right] \quad (3)$$

where scaling and translation parameters are replaced by the functions of m and n integers, i.e,. $a = a_o^m$ and $b = kb^0 a_0^m$, respectively, whereas *f(k)* is the discrete points of continuous time signal *f(t)*, and h is the mother wavelet function. The DWT uses a Multi Resolution Analysis (MRA) technique which decomposes the input test signal into approximation and detail coefficients. The MRA can be applied for decomposing of PQD signals, because of its advantages of using less memory and easy implementation. Also, it is useful to decompose the signals at various resolution levels. The MRA can be implemented by the set of filter banks as shown in Fig. 6.

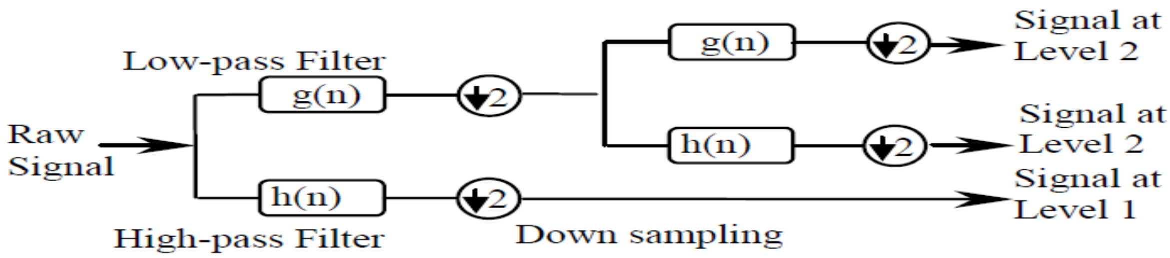


Fig 6 Decomposition of signal in to 2 level using MRA based on DWT

Assume that the input time domain signal f (n) is passed through the set of Low Pass (LPF) and High Pass filter (HPF) banks at each level with decimation of 2. The HPF provides high frequency component of detail coefficient (D1) and LPF provides low frequency component of approximation coefficient (A1) at first level of process. During this process, the frequency band is same for both high and low pass filters and the sampling frequency is divided by two after decomposition in each cycle. Then the output of LPF (A1) is decomposed further level to get the two components of coefficients ((A2) and (D2)) in next stage. This process is repeated until the desired level of decomposition is achieved [19,20]. In DWT method of analysis, the accuracy of signal detection is mainly based on the choice of mother wavelet. In general, many types of mother wavelet families like Harr, Daubechies, Coiflet, and Symmlet wavelets are available. Among that, Daubechies (db) wavelet is widely used for power system applications; because it is more flexible to detect low amplitude, short duration, fast oscillating and decaying signals. The wavelet filter Daubechies 4 (db4) is one of the best choices as a mother wavelet for analysing of PQ disturbances, since it has larger energy contents, shorter filter length, shorter computational time and more suitable for real time applications [21]. Therefore, in this study, mother wavelet of db4 has been used for PQ analysis.

8. FEATURE EXTRACTION:

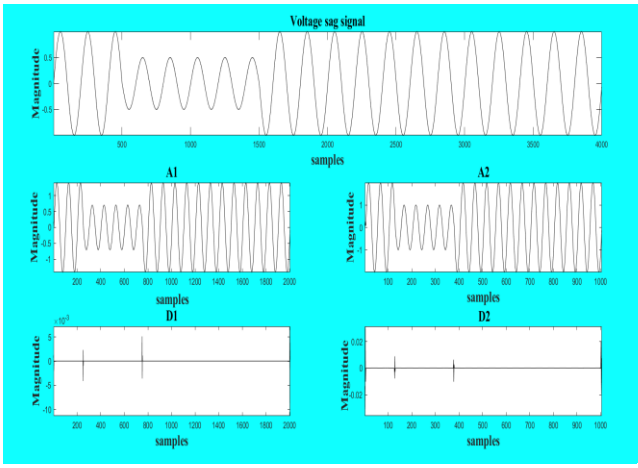
The feature extraction is carried out in such a way to reduce the dimensions of input vector matrix for the classifiers. The features of energy value (EV) can be extracted from the detail coefficients which is given in the equation (3) [22] as below:

$$EV = 1/N\left[\sum_{j-1}^{N} 1\left(D_{ij}^{2}\right)\right] \qquad (4)$$

where Mean $\mu i = 1/N\left[\sum_{j=1}^{N} D_{ij}\right]$, i = 1,2,3…. L (level of decomposition), N is the number of samples in each decomposed signal. The features like EV are the primary source of information for the classifiers to identify the type of PQD in the network.

9. RESULTS AND DISCUSSION:

Several types of mother wavelet have been applied on power quality signals for comparison purposes. It was concluded that the choice of mother wavelet has an important effect on the results. Although, there is no mother wavelet that can give best results on all the power quality disturbances, the Daubechies family db4, in general, has the clearest detection of changes in the energy of the distorted signals over the most decomposition bands. In this paper volage sag signal and voltage swell signal is decomposed 2 levels using MRA based on DWT of sag signal and energy distribution of voltage sag signal



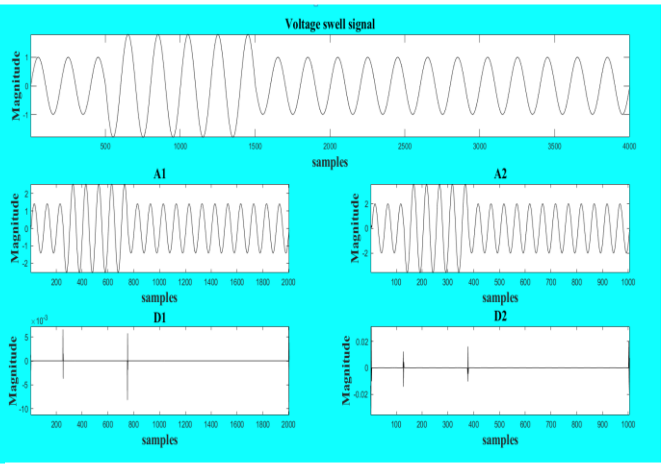
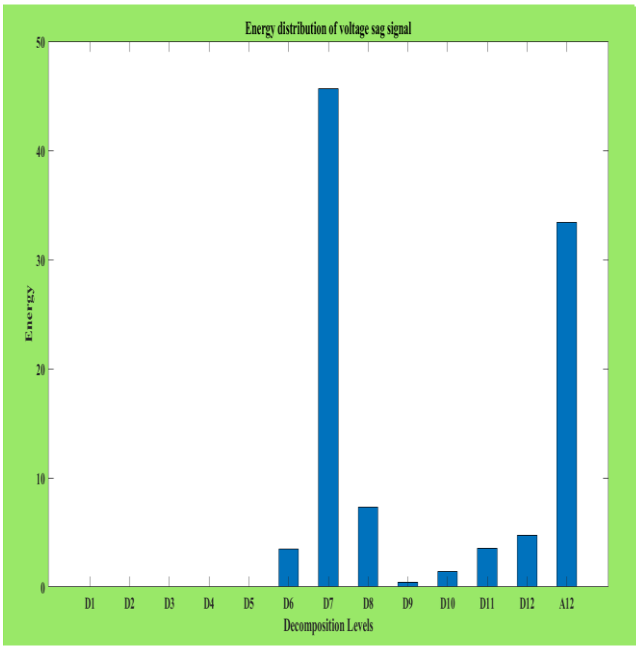


Fig 7 Decomposition of a sag signal into 2 levels using MRA based on DWT of sag signal

Fig 9 Decomposition of a swell signal into 2 levels using MRA based on DWT of sag signal



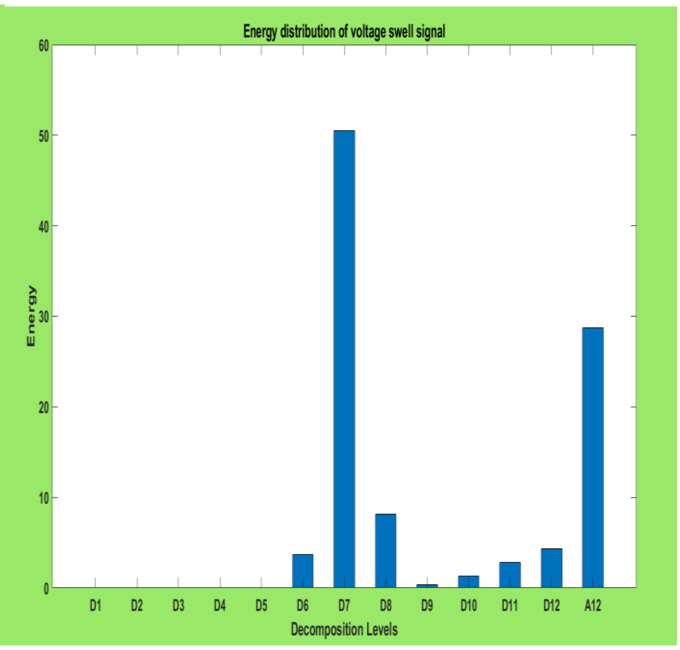


Fig 8 Energy distribution of voltage sag signal

Fig 10 Energy distribution of voltage swell signal.

Wavelet transform is achieved by convolution and decimation. The detail coefficients D_i where i=1,2 and the approximated coefficients c_j can be used to reconstruct a detailed version D and an approximated version A_1, of signal f (t) at that scale. Effectively the wavelet coefficients $h_0(n)$ and the scaling function coefficients h (n) will act as high pass and low pass digital filters respectively. The frequency responses $H_0(\omega)$ and $H_1(\omega)$ of the mother wavelet Daubechies (Db4) and its scaling function are shown in Figure 7,9. These two functions divide the spectrum of the input signal f (t) equally. Decimation (or down sampling) is an efficient multi-rate digital processing technique for changing the sampling frequency of a signal in the digital domain and efficiently compressing the data. As indicated in Figure 7,9 the sampling rate compression and data reduction in detail coefficients are achieved by discarding every second sample resulting from convolution process. Since half of the data is discarded (decimation by 2). The wavelet and the scaling function coefficients (h_1(n) and h_0(n)) will act as digital filters that limit the band of the input and prevent aliasing.

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