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WAVELET TRANSFORM IN THE DETECTION OF ELECTRICAL POWER QUALITY DISTURBANCES

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ABSTRACT

Disturbances in power quality usually produce continuity changes in the power signal. Wavelet transform is particularly useful in detecting discontinuities in signals, and this makes it appropriate for detection of disturbances in power quality. This study reviews various kinds of power quality disturbances with the goal of detecting them using wavelet transform. Two types of mother wavelets were used to process different power quality disturbance signals. The result shows clearly various forms of changes in amplitude and frequency of the signals.

Keywords: Power quality, wavelet transform, disturbance detection, amplitude- frequency, waveform distortion

1. Introduction

The interest in power quality has increased during the latest years. A power quality problem can be defined as “a problem due to frequency, voltage regulation, voltage dips, flicker, transients, harmonics, power factor and 3-phase imbalance” [1,2]. All machines affect the grid by the production of harmonics, voltage variations or by their power factors. At the same time the performance of the machines is affected by the power quality on the distribution network [3]. The number and usage of machines is increasing rapidly and thereby the power quality is being further affected. Machine drives can be disturbed by transients or other irregularities in the feeding voltage. The drives may as well disturb the network voltage by the production of harmonics, load changes and varying power factor [4]. The harmonic content and magnitude existing in any power system is largely unpredictable and their effects will vary widely in different parts of the same system due to varying effects of different frequencies. Since the distorted wave is in the supply system, harmonic effects may occur at any point on the system where the distorted wave exists. This occurrence is not limited to the immediate vicinity of the harmonic-producing device. When power is converted to direct current or some other frequency, harmonics will exist in any distorted alternating component of the converted power. Harmonics may be transferred from one circuit or system to another by direct connection or by inductive or capacitive coupling.

1.1 Types of Power Quality Disturbances

In an electrical power system, there are various kinds of power quality disturbances. IEEE defined power quality disturbances presented in this paper as organized into seven categories based on wave shape [5, 6, 7, 8, 9].

1. Transients
2. Interruptions
3. Sag/Undervoltage
4. Swell/Overvoltage
5. Waveform Distortion
6. Voltage Fluctuations
7. Frequency Variation

1.1.1 Transients

Potentially the most damaging type of disturbance, transients fall into two subcategories

i. impulsive

ii. oscillatory

i. Impulsive

Impulsive transients are sudden high peak events that raise the voltage and/or current levels in either a positive or a negative direction. These types of events can be categorized further by the speed at which they occur (fast, medium, slow). Impulsive transients can be very fast events (5 nanoseconds [ns] rise time from steady state to the peak of the impulse) of short-term duration (less than 50 ns). The impulsive transient is what most people are referring to when they say they have experienced a surge or a spike. Many different terms, such as bump, glitch, power surge, and spike have been used to describe impulsive transients.

ii. Oscillatory

An oscillatory transient is a sudden change in the steady-state condition of a signal's voltage, current, or both, at both the positive and negative signal limits, oscillating at the natural system frequency. In simple terms, the transient causes the power signal to alternately swell and then shrink, very rapidly. Oscillatory transients usually decay to zero within a cycle. This transient occurs when an inductive or capacitive load is turned off, such as a motor or capacitor bank.

1.1.2 Interruptions

An interruption is defined as the complete loss of supply voltage or load current. Depending on its duration, an interruption is categorized as instantaneous, momentary, temporary, or sustained. The causes of interruptions can vary, but are usually the result of some type of electrical supply grid damage, such as lightning strikes, animals, vehicle accidents, equipment failure, or a basic circuit breaker tripping.

1.1.3 Sag/Under Voltage

(i) Sag

Sag is a reduction of AC voltage at a given frequency for the duration of 0.5 cycles to 1 minute's time. Sags are usually caused by system faults, and are also often the result of switching on loads with heavy startup currents. Common causes of sags include starting large loads, remote fault clearing performed by utility equipment. Similarly, the starting of large motors of an industrial facility can result in significant voltage drop (sag)

(ii) Undervoltage

Undervoltages are the result of long-term problems that create sags. The term "brownout" has been commonly used to describe this problem, and has been superceded by the term undervoltage. Undervoltages can create overheating in motors, and can lead to the failure of non-linear loads such as computer power supplies. The solution for sags also applies to undervoltages. However, a UPS with the ability to adjust voltage using an inverter first before using battery power will prevent the need to replace UPS batteries as often. More importantly, if an undervoltage remains constant, it may be a sign of a serious equipment fault, configuration problem, or that the utility supply needs to be addressed.

1.1.4 Swell/Overvoltage

i. Swell

A swell is the reverse form of a sag, having an increase in AC voltage for a duration of 0.5 cycles to 1 minute's time. For swells, high-impedance neutral connections, sudden load reductions, and a single-phase fault on a three-phase system are common sources.

The result can be data errors, flickering of lights, degradation of electrical contacts, semiconductor damage in electronics, and insulation degradation. Power line conditions, UPS systems, and ferroresonant "control" transformers are common solutions.

ii. Overvoltage

Overvoltages can be result of long-term problems that create swells. An overvoltage can be thought of as an extended swell. Overvoltages are also common in areas where supply transformer tap setting are set incorrectly and loads have been reduced. This is common in seasonal regions where communities reduce in power usage during off-season and the output set for the high usage part of the season is still being supplied even though the power need is much smaller. Overvoltage conditions can create high current draw and cause the unnecessary tripping of downstream circuit breakers as well as overheating and putting stress on equipment.

1.1.5 Waveform Distortion

There are five primary types of waveform distortion

i. DC offset
ii. Harmonics

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iii. Interharmonics
iv. Notching
v. Noise

i. DC Offset

Direct current (DC) can be induced into an ac distribution system, often due to failure of rectifiers within the many AC to DC conversion technologies that have proliferated modern equipment. DC can traverse the AC power system and add unwanted current to devices already operating at their rated level. Overheating and saturation of transformers can be the result of circulating dc currents. When a transformer saturates, it not only gets hot, but also is unable to deliver full power to the load, and the subsequent waveform distortion can create further instability in electronic load equipment.

ii. Harmonics

Harmonic distortion is the corruption of the fundamental sine wave at frequencies that are multiples of the fundamental .Symptoms of harmonic problems include overheated transformers, neutral conductors, and other electrical distribution equipment, as well as the tripping of circuit breakers and loss of synchronization on timing circuit that are dependent upon a clean sine wave trigger at the zero crossover point.

Harmonic distortion has been a significant problem with IT equipment in the past, due to nature of switch-mode power supplies (SMPS). These non-linear loads, and many other capacitive designs, instead of drawing current over each full half cycle, “slip” power at each positive and negative peak of the voltage wave.

iii. Interharmonics

Interharmonics is a type of wave form distortion that are usually the result of a signal imposed on the supply voltage by electrical equipment such as static frequency converters, induction motors and arcing devices. Cycloconverters (which control large linear motors used in rolling mill, cement, and mining equipment), create some of the most significant interharmonic supply power problems. These devices transform the supply voltage into an AC voltage of a frequency lower or higher than that of the supply frequency.

The most noticeable effect of interharmonics is in the graphics of display and incandescent lights, as well as causing possible heat and communication interference.

iv. Notching

Notching is a periodic voltage disturbance by electronic devices, such as variable speed devices, light dimmers and arc welders under normal operation. This could be described as a transient impulse problem, but because the notches are periodic over each ½ cycle, notching is considered a wave distortion problem. The usual consequences of notching are system halts, data loss, and data transmission problems.

v. Noise

Noise is unwanted voltage or current superimposed on the power system voltage or current waveform. Noise can be generated by power electronic devices, control circuits, arc welders, switching power supplies, radio transmitters and so on. Poorly grounded sites make the system more susceptible to noise. Noise can cause technical equipment problems such as data errors, equipment malfunction, long-term component failure, hard disk failure, and distorted video displays.

1.1.6 Voltage Fluctuations

A voltage fluctuation is a systematic variation of the voltage waveform or a series of random voltage changes, or small dimensions, namely 95 to 105% of nominal at a low frequency, generally below 25Hz.

Any load exhibiting significant current variations can cause voltage fluctuations. Arc furnaces are the most common cause of voltage fluctuation on the transmission and distribution system.

1.1.7 Frequency Variations

Frequency variation is extremely rare in stable utility power system, especially systems interconnected via a power grid. Where sites have dedicated standby generators or power infrastructure, frequency variation is more common especially if the generator is heavily loaded. Information technology (IT) equipment is frequency tolerant and generally not affected by minor shifts in local generator frequency. What would be affected would be any motor device or sensitive device that relies on steady regular cycling or power over time. Frequency variations may cause a motor to run faster or slower to match the frequency of power. This would cause the motor to run inefficiently and/or lead to added heat and degradation of the motor through increased motor speed and/or additional current draw.

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1.2 Problems of Signal Processing Techniques in PQ Disturbance

Various signal processing techniques used in power quality disturbances field are briefly discussed in the following subsections [10].

1. Although rms (Roots Mean Square) is not an inherent signal processing techniques, yet it is the most used tool. Rms gives a good approximation of the fundamental frequency amplitude profile of a waveform. A great advantage of this algorithm is its simplicity, speed of calculation and less requirement of memory, because rms can be stored periodically instead of per sample [11]. However, its dependency of window length is considered as a disadvantage. One cycle window length will give better results in terms of profile than a half cycle window. Moreover, rms does not distinguish fundamental frequency or noise components. On the other hand, rms voltage profiles are used for event analysis and automatic classification as proposed in [12]
2. A great quantity of work has been focused on the estimation of amplitude and phase of the fundamental frequency as well as its related harmonics. A primary tool for estimation of fundamental amplitude of a signal is the DFT (Discrete Fourier Transform) or its computationally efficient implementation called FFT (Fast Fourier Transform). FFT transforms the signal from time domain to the frequency domain. Its fast computation is considered as an advantage. With this tool, it is possible to have an estimation of the fundamental amplitude and its harmonics with a reasonable approximation. However, window dependency resolution is a disadvantage, e.g. the longer the sampling window, the better the frequency resolution. FFT performs well for estimation of periodic signals in stationary state; however it doesn't perform well for detection of suddenly or fast changes in waveform e.g. transients, voltage dips or interharmonics. In some cases, results of the estimation can be improved with windowing or filtering, e.g. hanning window, hamming window, low pass filter or high pass filter.
3. A combination of QMFs (Quadrature Mirrors Filters) arranged in binary trees is called filter banks. Filter banks have been used to study in more detail a specific sub band of the frequency spectrum. This technique was used in different application to detect rapid changes in the waveform or for estimation of specific sub-band components, e.g. harmonic contents between 500 to 1000 Hz, capacitor switching or transients.
4. A well known technique is the so-called Kalman filter. This technique is defined as a state space model for tracking amplitude and phase of fundamental frequency and its harmonics in real time under noisy environment, which was proposed in [13]. Since then, many applications have come up, including frequency estimation under distorted signals [14] detection of harmonics sources and optional localization of power quality monitors [15].
5. The use of wavelets was proposed to study power systems non-stationary harmonics distortion [16]. This technique is used to decompose the signal in different frequency sub-bands and study separately its characteristics.
6. STFT (Short Time Fourier Transform) is commonly known as a sliding window version of the FFT, which has shown better results in terms of resolution and frequency selectivity. However, STFT has a fixed frequency resolution for all frequencies, and has shown to be more suitable for harmonic analysis of voltage disturbances than binary tree filters or wavelets when applied to study voltage dip [17].

Latest advances in electrical power quality mitigation techniques are based on extraction of disturbances data instead of traditional methods. Hence time-frequency analysis is more suitable to detect disturbances from data. PQ disturbances also vary in a wide range of time and frequency, and (WT) wavelet transformation has unique ability to examine the signal in time and frequency ranges at the same time which makes WT a best suited tool for power quality disturbance [18-19].

Traditionally the Fourier transforms permits mapping signals from time domain to frequency domain by decomposing the signals into several frequency components. This technique is criticized in that the time information of transients is totally lost, although the accuracy of frequency components is high. Fourier transform does not fit the analysis of transients owing to the non-stationary property of its signals in both time and frequency domains. Wavelet transform generally offers this facility [20-24].

From the above literature survey [10- 24] it can be seen that majority of the papers presented the proposed use of WT, in which PQ disturbances have been defined into seven categories. This paper presents a software based novel approach for detection of PQ disturbances by amplitude and frequency analysis with wavelet transform.

2.0 Wavelet Transform

A wavelet is a wave-like oscillation with amplitude that starts out at zero, increases, and then decreases back to zero. It can typically be visualized as a "brief oscillation" like one might see recorded by a seismograph or heart monitor. Wavelets can be combined, using a "shift, multiply and sum" technique called convolution, with portions of an unknown signal to extract information from the unknown signal. A wavelet transform is the representation of a function by wavelets. The wavelets are scaled and translated copies (known as "daughter wavelets") of a finite-length or fast-decaying oscillating waveform (known as the "mother wavelets"). WT have advantages over traditional Fourier transforms for representing functions that have discontinuities and sharp peaks, and for accurately deconstructing and reconstructing finite, non-periodic and/or non-stationary signals. WT is a transform which is capable of providing the time and frequency information simultaneously, hence giving a time-frequency representation of the signal. They are classified into discrete wavelet transforms (DWTs) and continuous wavelet transforms (CWTs). Both DWT and CWT are continuous-time (analog) transforms. They can be used to represent continuous-time (analog) signals. CWTs operate over every possible scale and translation whereas DWTs use a specific subset of scale and translation values or representation grid.

2.1 Continuous Wavelet Transform

All the wavelet functions used in the transformation are derived from mother wavelet through translation (shifting) and scaling (dilation or compression). The CWT is as expressed in Equation (1), where *x (t)* is the signal to be analyzed and *Ψ (t)* is the mother wavelet or the basis function.

$$X_{WT}(t,s)=\frac{1}{\sqrt{|s|}}\int x(t).\psi(t)\times\left(\frac{t-\tau}{s}\right)dt \qquad (1)$$

The mother wavelet used to generate all the basic functions is designed based on some desired characteristics associated with that function. The translation parameter τ relates to the location of the wavelet function as it is shifted through the signal. Thus, it corresponds to the time information in the Wavelet Transform. The scale parameter is defined as |1/f|, where f is the frequency of the information. Scaling either dilates (expands) or compresses a signal. Large scales (low frequencies) dilate the signal and provide detailed information hidden in the signal, while small scales (high frequencies) compress the signal and provide global information about the signal. Notice that the WT merely performs the convolution operation of the signal and the basis function. The above analysis becomes very useful as in most practical applications, high frequencies (low scales) do not last for a long duration, but instead, appear as short bursts, while low frequencies (high scales) usually last for entire duration of the signals.

2.2 **Discrete wavelet transform**

The continuous wavelet transform was developed as alternative approaches to the short time Fourier transform to overcome the resolution problem. The important point to note here is the fact that the computation is not a true continuous wavelet. From the computation at finite number of location, it is only a discretized version of the continuous wavelet. Note, however, that this is not discrete wavelet transform (DWT). These days, computers are used to do almost all computations. It is evident that neither the FT, nor STFT, nor the CWT can be practically computed by using analytical equations, integrals, etc. It is therefore necessary to discretize the transforms. As the discretized CWT enables the computation of the continuous wavelet transform by computers, it is not a true discrete transform. As a matter of fact, the wavelet series is simply a sampled version of the CWT, and the information it provides is highly redundant as far as the reconstruction of the signal is concerned. This redundancy, on the other hands, requires a significant amount of computation time and resources. The discrete wavelet transform DWT provides sufficient information both for analysis and the synthesis of the original signal, with a significant reduction in the computation time. The DWT is considerably easier to implement when compared to the CWT.

Wavelet analysis deals with expansion of functions in term of a set of basic functions like Fourier analysis. However, wavelet analysis expands functions not in terms of trigonometric polynomials but in terms of wavelets, which are generated in the form of translations and dilations of a fixed function called mother wavelet. Comparing with FT, wavelet can obtain both time and frequency information of signal, while only frequency information can be obtained by Fourier transform [21, 23, 24, 25, 26].

The signal can be represented in terms of both the scaling and wavelet functions as follows:

$$f(t)=\sum_n c_j(n)\varphi(t-n)+\sum_n\sum_{j=0}^{j=1} d_j(n)2_2^1\psi(2^j t-n) \qquad (2)$$

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where c_j is the j level scaling coefficient, d_j is the j level wavelet coefficient, $\varphi(t)$ is the scaling function, $\Psi(t)$ is wavelet function, J is the highest level of wavelet transform, and t is time.

Each level is created by scaling and translation operations in a special function called mother wavelet. A mother wavelet is a function that oscillates, has finite energy and zero mean value. Wavelet theory is expressed by continuous wavelet transformation as:

$$CWT_{\psi} x(a,b) = W_x(a,b) = \int_{-\infty}^{\infty} X(t)\psi_{a,b}(t)dt \quad (3)$$

where $\psi_{a,b}(t) = |a|^{1/2}\psi(\frac{t-b}{a})$, a (scale) and b (translation) are real numbers.

Equation (3) has great theoretical interest for the development and comprehension of its mathematical properties. However, its discretization is necessary for practical applications. For discrete-time systems, the discretization process leads the time discrete wavelet series as:

$$DWT_{\psi} x(m,n) = \int_{-\infty}^{\infty} X(t)\psi_{m,n}(t)dt \quad (4)$$

$$\psi_{m,n}(t) = a_0^{-m/2}\psi(\frac{t-nb_0a_0^m}{a_0^m}) \quad (5)$$

where $a = a_o^m$ and $b = nb_oa_o^m$.

DWT provides a time and frequency representation of the recorded power quality signals. This is a very attractive feature in analyzing time series because time localization of spectral components can be obtained. Classical methods of signal processing depend on an underlying notion of stationary, for which methods such as Fourier analysis are very well adapted. In power quality researches, however, more properties other than stationary are required, and thus the DWT application is more appropriate than Fourier transform. The goal of multi resolution analysis (MRA) is to develop representation of a signal at various levels of resolution. MRA is composed of two filters in each level which are low pass and high pas filter. MRA can detect, diagnose defects, and provide early warning of power quality problems. Power quality problems are characterized by their maximum amplitudes, crest voltages, RMS, frequency, statistics of wavelet coefficients, instantaneous voltage drops, number of notches, duration of transients, etc. These characteristics are unique identifying features for different power quality problems and introduced signal processing tools in power quality analysis [21, 23, 24, 25, 26].

2.3 **Multi Resolution Analysis (MRA) and Decomposition**

Discrete wavelet transform is the basic tool for feature extraction. DWT is the discrete counterpart of the CWT [27]. The CWT of a continuous time signal $x(t)$ is defined as:

$$CWT_{\psi} x(a,b) = \int_{-\infty}^{\infty} X(t)\psi_{a,b}(t)dt \quad (6)$$

where a, b C R, a≠0

$$\psi^*{}_{a,b}(t) = \frac{1}{\sqrt{a}}\psi^*(\frac{t-b}{a}) \quad (7)$$

The function $\Psi(t)$ is the mother wavelet, and the asterisk denotes a complex conjugate, a and b are the scaling and translating parameters respectively. The sampled signal $k(x)$ is used to replace the CWT of $t(x)$ such that:

$$DWT\psi x(m,n) = \sum_k X_k\psi^* m,n(k) \quad (8)$$

$$\psi^*{}_{m,n}(k) = \frac{1}{\sqrt{a_0^m}}\psi^*(\frac{k-nb_0a_0^m}{a_0^m}) \quad (9)$$

Both the scaling factor a_0^m and the shifting factor $nb_0a_0^m$ are functions of the integer parameter m, where m and n are scaling and sampling numbers respectively and m = 0, 1, 2 … by selecting $a_0 = 2$ and $b_0 = 1$. A representation of any signal $x(k)$ at various resolution levels can be developed by using the MRA. It is implemented by a set of successive filter banks with the low pass filter $h(n)$ and its dual high pass filter $g(n)$ [28]. The approximation and the detail coefficients are obtained from the input sequence *cj-I (n)*.

$$cj(n) = \sum_k h(k-2n)cj - I(k) \quad (10)$$

$$dn(n) = \sum_k g(k-2n)cj - I(k) \quad (11)$$

where cj represents the coefficients of the approximate signal at level j, and dj represents the detailed coefficients of the signal at level j.

2.4. **Choice of Mother Wavelet for analysis**

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Two mother wavelets, namely haar and dmey at level 5 were chosen for the wavelet analysis of the signals. Haar is more suited to the analyses of changes in amplitude, while dmey is suitable for the analyses of changes in the frequency of the signal.

3.0 Applications and Results.

The signals were simulated in Matlab and processed with wavelet toolbox in Matlab 7.2, using Haar, and dmey mother wavelets at level 5. The following series of diagrams (Figures **1**-**7**) shows the fifth level approximation and first to fifth level details of application of wavelet transform in processing signals for different types of power quality disturbances. The diagrams on the left are for Haar mother wavelet, while those on the right are for dmey mother wavelet. The time (point) of occurrence of the disturbances are markedly shown by both approximation and detail results at all levels. Amplitude changes are shown in the diagrams for Haar mother wavelet, while that of dmey shows changes in frequency with higher frequency disturbances such as noise appearing in the early details of dmey mother wavelet transform. Each type of disturbances thus can be detected by combining the results for both mother wavelets and interpreted by a human expert. However it is desirable to process the obtained wavelet transform results further with artificial intelligence techniques such as Artificial Neural Network (ANN), Neurofuzzy, and hybrid systems to automate the process.

4.0 Conclusion

This study has reviewed various forms of electrical power quality disturbances with the aim of detecting them using wavelet transform approach. Wavelet transform is useful in the identification of variation or discontinuities in signals. The diagrams of wavelet transform of signals for different kind of disturbances shows clearly the peculiarities of each kind of disturbances. Though the kind of disturbance can be determined by human experts from the diagram, further work is required to automate this detection process in an on-line, real-time, low-cost system. Therefore it is necessary to process the results of the wavelet transform further with artificial intelligent systems such as Artificial Neural Network, Neurofuzzy system, hybrid intelligent systems etc.

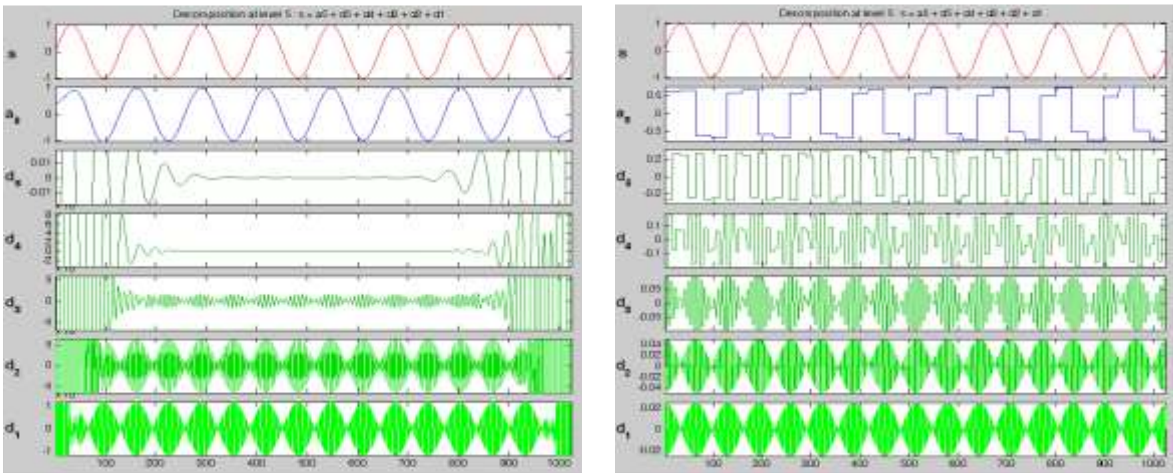

Figure 1: Normal signal detection using Haar, and dmey mother wavelets at level 5

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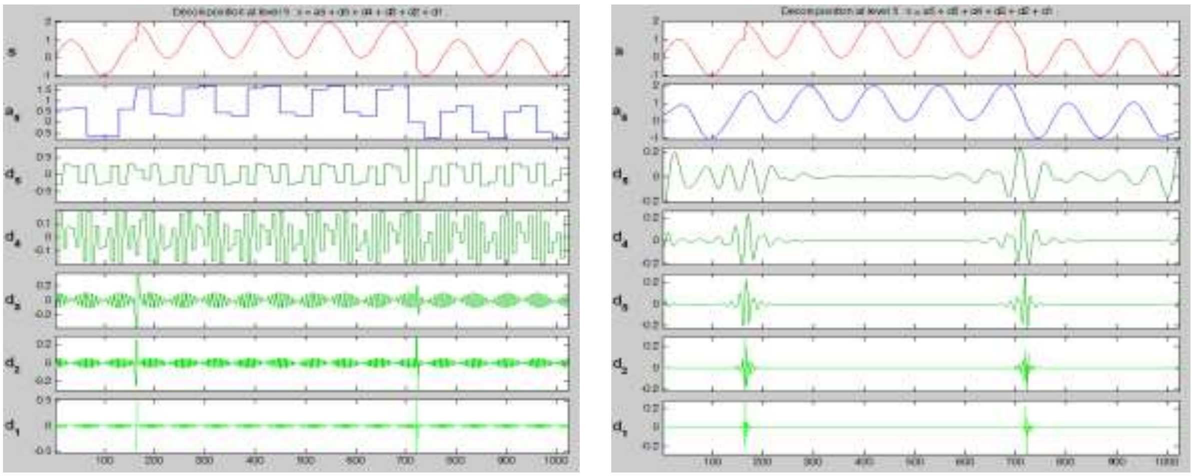

Figure 2: Signal with DC Offset disturbances detection using Haar, and dmey mother wavelets at level 5

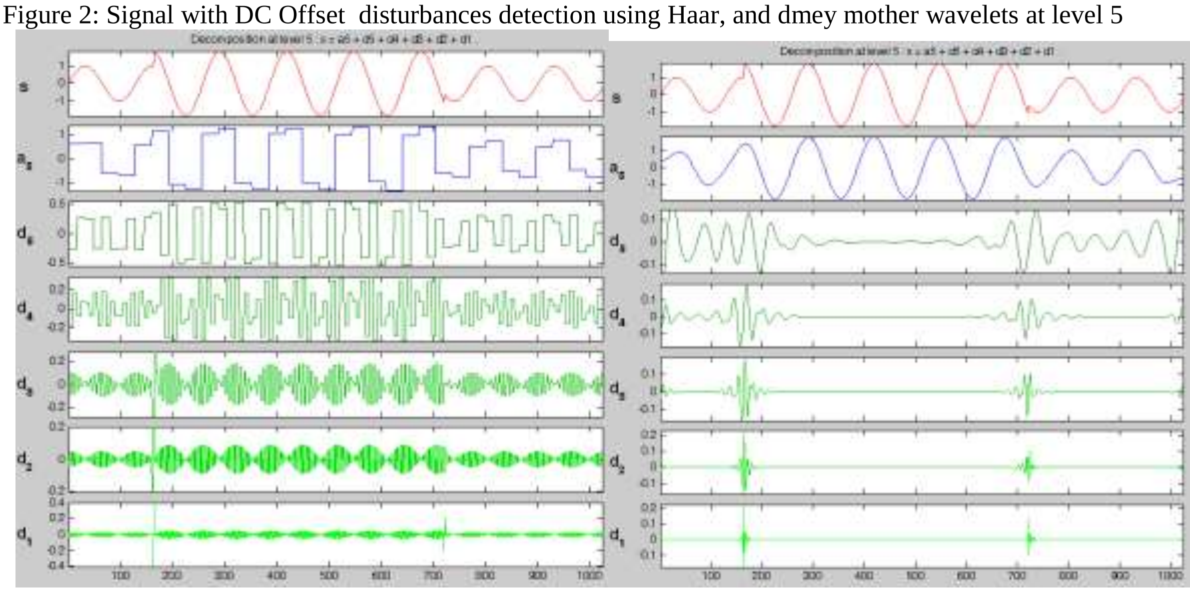

Figure 3: Signal with Swell disturbances detection using Haar, and dmey mother wavelets at level 5

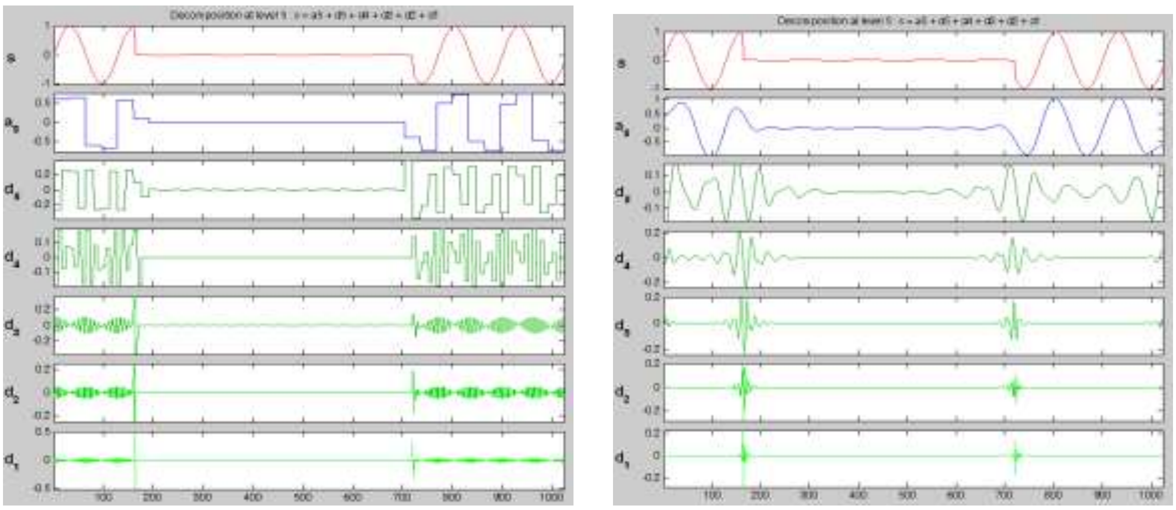

Figure 4: Interruption signal PQ disturbances detection using Haar, and dmey mother wavelets at level 5

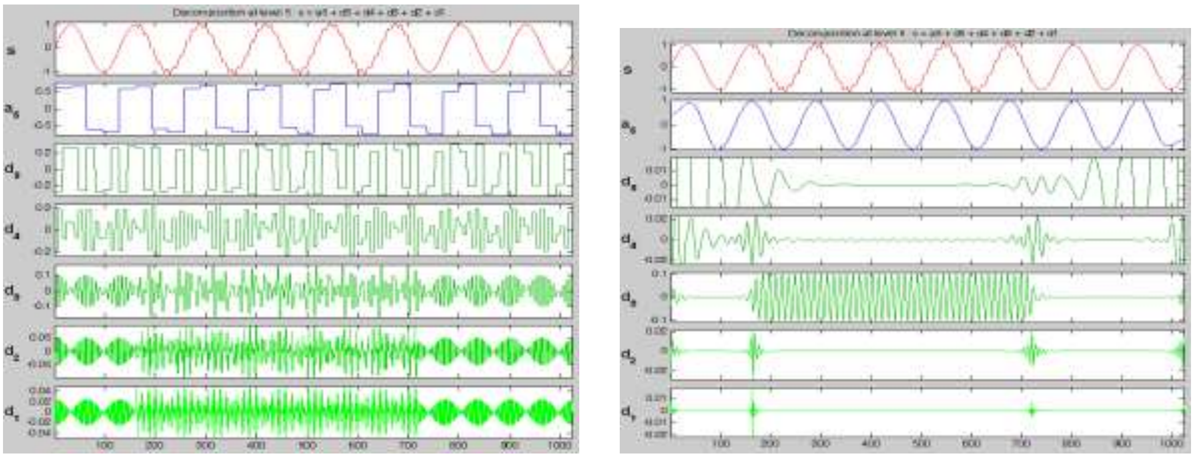

Figure 5: Signal with Harmonic disturbances detection using Haar, and dmey mother wavelets at level 5

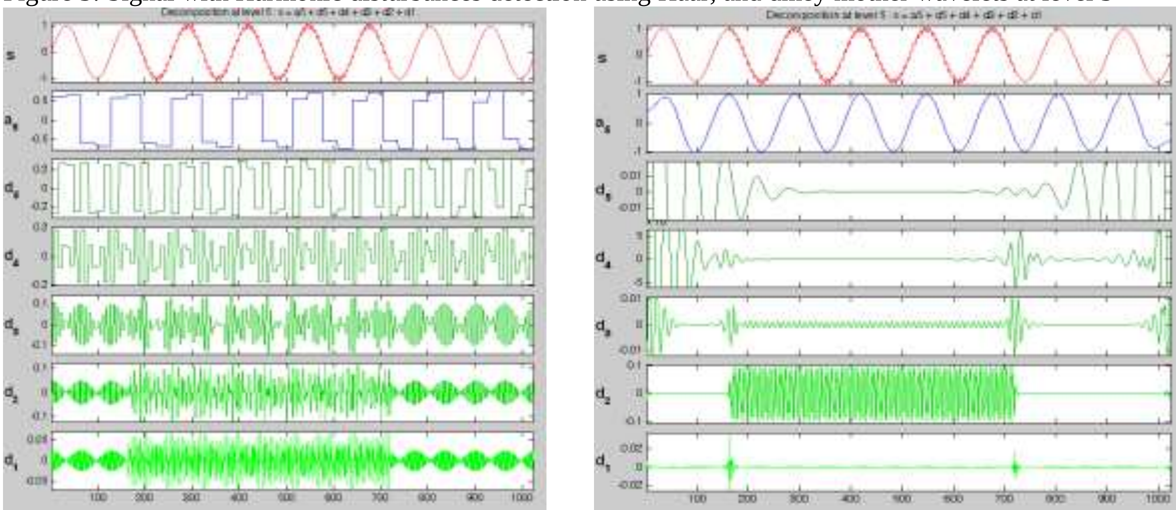

Figure 6: Noise signal PQ disturbances detection using Haar, and dmey mother wavelets at level 5

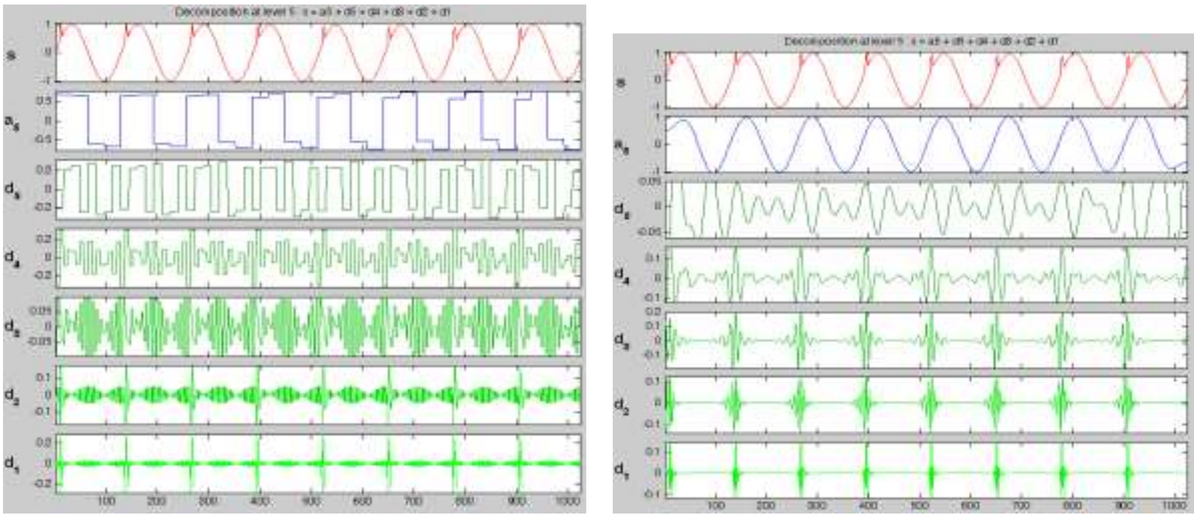

Figure 7: Signal with noisy periodic notching disturbances detection using Haar, and dmey mother wavelets at level 5

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