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Wavelet Transforms: Practical Applications in Power Systems

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Abstract – An application of wavelet analysis to power system transient generated signals is presented in this paper. With the time-frequency localisation characteristics embedded in wavelets, the time and frequency information of a waveform can be presented as a visualised scheme. This feature is very important for non-stationary signals analysis such as the ones generated from power system disturbances. Unlike the Fourier transform, the wavelet transform approach is more efficient in monitoring fault signals as time varies. For time intervals where the function changes rapidly, this method can zoom in on the area of interest for better visualisation of signal characteristics.

Keywords: Wavelet transforms, Time-frequency localisation, High impedance faults, Voltage sag, Power quality

1. Introduction

The wavelet transform (WT) is a recently developed mathematical tool which can be used for signal processing with a wide variety of applications, e.g. acoustics, communications, transient analysis, medicine, etc. The main reason for this growing activity is the ability of the wavelet not only to decompose a signal into its frequency components, but also to provide a non-uniform division of the frequency domain, whereby it allows the decomposition of a signal into different levels of resolution. The basis function (mother wavelet) is dilated at low frequencies and compressed at high frequencies, so that large windows are used to obtain the low frequency components of the signal, while small windows reflect discontinuities [1]. This attribute to tailor the frequency resolution can greatly facilitate signal analysis and detection of signal features, which can be very useful in characterizing the source of the transients and /or the state of the post-disturbance system.

The WT normally uses both the analysis and synthesis wavelet pair. Synthesis is used when the waveform is to be reconstructed. In wavelet analysis, the original signal is decomposed into its constituent wavelet subbands or levels. Each of these levels represents that part of the original signal occurring at that particular time and in that particular frequency band. These individual frequency bands are logarithmically spaced rather than uniformly spaced as in Fourier analysis. This makes the decomposed signals possess a powerful time-frequency localization property, which is one of the major benefits provided by WT. The resulting decomposed signals can then be analyzed in both time and frequency domains.

The rest of this paper is organized as follows: Section 2 presents a discrete wavelet transform and multi-resolution analysis. Computer simulation of some power quality disturbances and wavelet analysis of the resulting signals are carried out in Section 3 to demonstrate their practical applications. Results and discussion is presented in Section 4, while Section 5 concludes the paper.

2. Discrete Wavelet Transform (DWT) and Multi-Resolution Analysis (MRA)

In order to take care of the resolution problem inherent in other signal processing tools, such as the Fourier transform, short-time Fourier transform, etc., wavelet analysis permits the use of long time intervals where more precise low-frequency information is required; and shorter regions where high frequency information is desired. In other words, it is possible to analyse a localised area of a larger signal with WT.

The wavelet transform is a mathematical tool that divides up data, functions or operators into different frequency components and then studies each component with a resolution matched to its scale [2]. Basically, wavelet transforms are divided into two, namely: Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). Since most operations are now performed using computers, which use digital forms of data, the latter is preferred by most researchers and is used in this study.

The DWT analyses the original signal at different frequency bands with different resolutions by decomposing the signal into a coarse approximation and detail information [3]. In doing this, the DWT employs two sets of functions called *Scaling functions* and *Wavelet functions*. These are respectively associated with high and low pass filters.

The objective of multi-resolution analysis (MRA) is to develop representation of a sophisticated signal, f(t) in terms of wavelet and scaling functions [2]. It is designed to produce good time resolution and poor frequency resolution at high frequencies and good frequency resolution and poor time resolution at low frequencies. The rationale behind this is that most signals encountered in practical

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applications have high frequency components for short durations and low frequency components for long durations. The schematic diagram of multi-resolution decomposition of a signal is illustrated in Fig. 1 where three levels of decomposition are obtained.

The scaling coefficients, otherwise known as approximation, are a low-resolution representation of the original signal, i.e. it is the high-scale, low frequency components of a signal. It is computed by taking the inner products of the function f(t) with the scaling basis $\phi_{j,k}$ as illustrated in eqn (1).

$$A_{j,k} = \langle f(t), \varphi_{j,k} \rangle = \int_{-\infty}^{\infty} f(t), \varphi_{j,k}(t)dt \tag{1}$$

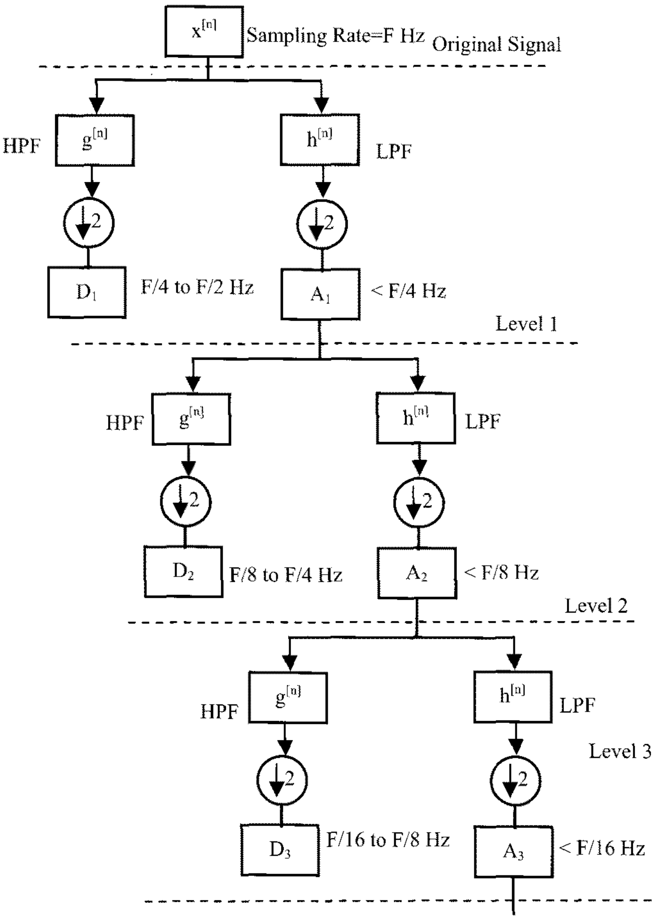


Fig. 1. Schematic Diagram of Multi-resolution Analysis of DWT Decomposition

KEY

(↓2) =Down Sampling by 2
LPF= Low Pass Filter
HPF= High Pass Filter
A=Approximation
D =Detail

Practically, this is obtained by passing the original signal through a low pass filter. On the other hand, the wavelet coefficients, also known as details, are defined as the low-scale, high frequency components of the original signal. In the application of the DWT in waveform realization, different WT coefficients are attained at different decomposition scales. Scale 1 (d1) is the shortest mother wavelet and contains the highest frequency information present in the input signal; scale 2 (d2) the next highest, and so on [4]. This is evident in Fig. 2 and can be computed by taking the inner products of the function, f(t) with the wavelet basis $\psi_{j,k}$ as presented in eqn (2).

$$D_{j,k} = \langle f(t), \psi_{j,k} \rangle = \int_{-\infty}^{\infty} f(t), \psi_{j,k}(t)dt \tag{2}$$

where j is the resolution level and k, the length of the filter vector.

The scale function $\phi_{j,k}$ (t) and wavelet function $\psi_{j,k}$ (t) are determined by the selection of a particular mother wavelet ψ (t) and eqns (3) and (4) respectively.

$$\varphi_{j,k}(t) = 2^{j/2}\varphi(2^j t - k) \tag{3}$$

$$\psi_{j,k}(t) = 2^{j/2}\psi(2^j t - k) \tag{4}$$

The effect of the decomposition scales is illustrated in Fig. 2 for three different scales of db4 on an input signal. The details and approximations of the original signal f (t) are obtained by passing it through a filter bank, which consists of low and high pass filters. The low pass filter removes the high frequency components, while the high-pass filter picks out the high-frequency contents in the signal being analyzed. The low-pass and the high-pass filters are determined by the scaling function and the wavelet function, respectively. The maximum number of wavelet decomposition levels for WT is determined by the length of the original signal, the particular wavelet being selected, and also, the level of detail required.

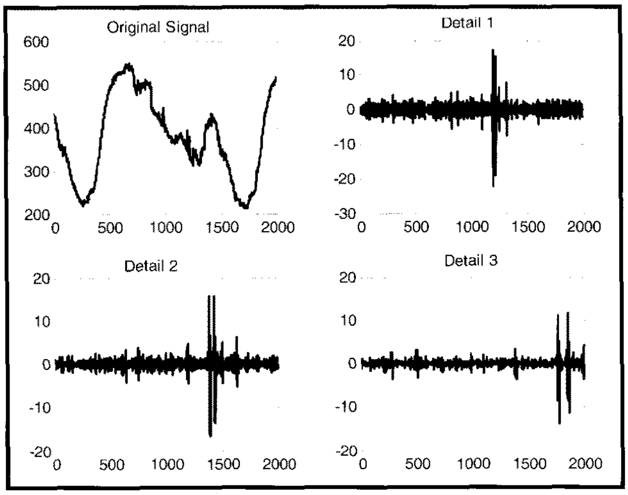


Fig. 2. Different Decomposition Scales of Daubechies Wavelet

In wavelet analysis, narrow wavelets are used to analyse high frequency, short-term effects such as fast transients and momentary outages. However, wide wavelets are used to identify low frequency effects, an example of which is flicker. Signal processing uses exclusively orthogonal wavelets. The non-redundant representation and perfect reconstruction of the original signal can only be realized through compactly supported orthogonal wavelets. Those used most frequently for signal processing are Daubechies (db), biorthogonal (bior), Coiflets (coif), Morlet (morl) and Symlets (smy) wavelets [4]. These wavelets exhibit different attributes and performance criteria when applied to specific applications, such as detection of transients, signal compression and de-noising.

3. Wavelet Transform Applications in Power Systems

There are many potential applications for WT in power systems, e.g. for differential transformers protection, fault detection, detection of power quality disturbances, analysis of partial discharge phenomenon in gas insulated substations, etc. However, due to brevity of space, this paper will deal with only a few illustrative problems, namely: power system protection/fault detection and detection of power quality disturbances.

3.1 High-Impedance Faults (HIFs) Detection

High-impedance faults (HIFs) are faults that cannot be easily detected or cleared by modern protective devices, the reason being that, when HIFs occur, they do not produce enough fault current to be detectable by conventional over current relays and fuses. These faults often occur when an overhead conductor breaks and falls on a high impedance surface such as an asphalt road, sand, grass or tree. When this type of fault happens, energized high-voltage conductors may fall within reach of people who are then exposed to the danger of electrocution. In addition, arcing that often accompanies such faults poses a fire hazard. Hence, there is need for immediate detection and clearance of high impedance faults. Unfortunately, the decision is not that simple.

A lot of research has been carried out in relation to the detection of HIFs. The most common detection scheme involves the adjustment of overcurrent protective devices such as overcurrent relays, reclosers, fuses, etc. [5]. Usually, time overcurrent devices are set to operate at 125 – 200 % of the maximum load the device carries. The drawback of this technique is that while these devices must interrupt fault currents, they must also carry normal and emergency load currents. In the same vein, a type of ground relay has been developed in anticipation of detecting low current faults [6] that phase relays cannot detect. Even though ground relays are able to detect many low current faults, they are still unable to detect a large number of very low current faults [7], such as HIFs. Several other new detection methods have been proposed recently, such as artificial neural network technology [8], third harmonic current angle method [9], the fractal technique [10], etc. Each of these techniques could improve fault detection, but then each has its own drawbacks.

From the point of view of signal processing, however, wavelet transforms can be applied to high-impedance fault generated signals [4, 11] to bring out characteristics that could allow for its detection. This is implemented in this paper. In this technique, data generated from HIF simulation are analysed using wavelet analysis. The method is able to discriminate between high-impedance faults and normal switching events, as demonstrated in [12].

The choice of mother wavelet plays a significant role in detecting and localising different types of fault transients. For example, db4 and db6 are better for short and fast transients while for slow transient disturbances, db8 and db10 are particularly good [13]. It is for this reason that Duabechies (db4) mother wavelet is chosen in this particular application. In this study, an HIF due to a downed conductor is simulated at point A on an 11 kV radial distribution feeder shown in Fig. 3. The fault current on the affected phase recorded at the relaying point and its d1 coefficients (i.e. level 1 decomposition of the signal) are presented in Figs. 4 (a) and (b) respectively. The HIF detection shown in Fig. 4 (c) is based on summating the D1 coefficients – the output of the DWT – presented in Fig. 4(b), over a one-cycle window. The whole process is based on a moving window approach whereby the one-cycle window is moved continuously by one sample [4], taking the sampling frequency to be 6 kHz of the power frequncy.

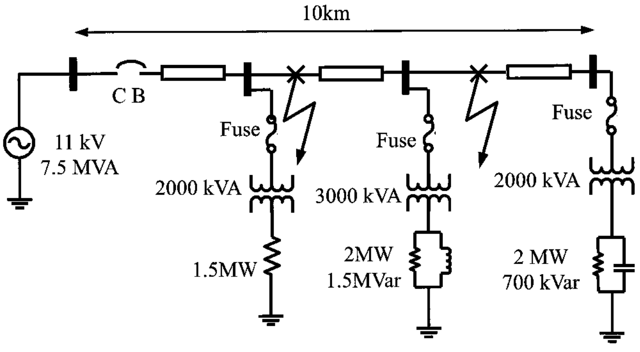


Fig. 3. One-line Diagram of the Case Study Distribution Feeder

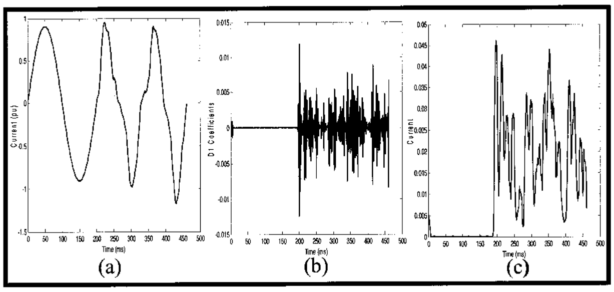


Fig. 4. HIF Current Waveform, D1 Coefficients and its Detection

3.2 Detection of Power Quality Disturbances

There are quite a number of different definitions of power quality, depending on one's frame of reference. However, the authors of this paper subscribe to the definition given by Roger, et al [14] as "any power problem manifested in voltage, current, and frequency deviations that result in failure or misoperation of customer equipment". Instances of degradation in power quality arise when wave shapes are irregular, voltage is poorly regulated, harmonics and flicker are present or there are momentary events that distort the usually sinusoidal waveforms of the electric supply. This is one of the main problems faced by manufacturing industries in most countries today. Power quality problems interrupt sensitive manufacturing processes and result in very expensive consequences to these companies. In view of this, there is a serious need to detect and mitigate these problems in power systems.

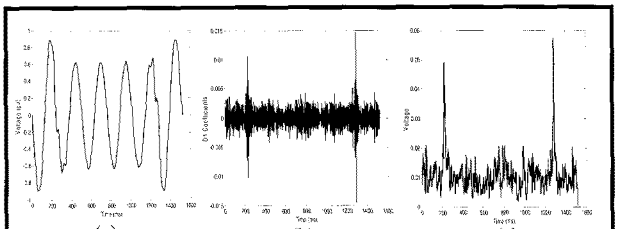
Since there are many forms of disturbance that can occur in power systems, in order to improve the electric power quality, sources of disturbances must be known and controlled. Typical examples of power quality disturbances are: voltage sags, voltage swell, outage, very short duration fault impulse, harmonic distortion, switching transients, notching, etc. In order to minimize their adverse impact on both the quality of power supply and customer equipment, new techniques are needed. Before this can be done, the disturbance must first be localised and detected. This can be achieved using a powerful signal analysis tool such as WT [15-18] that can analyse different power quality problems simultaneously in both time and frequency domains. In this study, power quality disturbances with deviations of voltage from its ideal waveform, harmonic distortion, and switching transient are considered. These are the most common power quality disturbances in power systems.

1) Voltage sag disturbance detection: Voltage sags are the most common power problems encountered in power systems [19]. Sags are a short-term reduction in voltage, usually between 80 and 85 % of the nominal voltage that can last from a few milli seconds to a few cycles [20]. They can be characterised by their depth and duration on the electric power network. Possible causes of this type of power quality problem include short circuit faults, large electric motors starting, turning on of heavy equipment, capacitor switching, etc. Voltage sag with a 30% drop or more is considered severe [21], as can cause malfunction of certain loads at other customers on the same feeder. Sags can occur on multiple-phase or on a single phase, and are often accompanied by voltage swells on other healthy phases.

Because of the increased use of sensitive electronic equipment, voltage sag is having a more extensive impact on customers than before. As a consequence, monitoring and assessing the system performance at both transmission and distribution voltage levels is becoming increasingly important. Voltage sag can have effects similar to those of a power surge, such as flickering lights, memory loss and data errors in computer application systems. This has lead to a number of methods for detecting voltage sags in power systems. Current techniques in use include supply peak values monitoring, application of the Fourier transform to each phase [22], numerical matrix sag detection method [20] and application of wavelet analysis technique [15, 16, 23]. This method is adopted in this study.

In this study, voltage sag caused by a three-phase short circuit fault at point B on the 11 kV radial distribution system, shown in Fig. 3, is initiated and simulated at the 200th milli-sec. This fault was allowed to last for a period of 1000 ms before cleared. The resulting voltage waveform obtained at the customer side is as presented in Fig. 5 (a). The corresponding d1 wavelet decomposition is shown in Fig. 5 (b). It is seen from the latter that the DWT picks up the higher frequency components present at the start and end of the disturbance, whereas it is insensitive to the steady-state voltage. This enables the disturbance occurrence from Fig. 5 (c) to be well visualised.

As mentioned earlier in the application of DWT waveform realization, different WT coefficients are attained at different decomposition scales. Also, it should be noted that the choice of appropriate mother wavelet is crucial when using WT. An extensive series of studies relating to voltage sag problems reveal that Daubechies db6 (which is classed as a medium wavelet) is ideally suited for solving voltage sag problems [13]; hence its use in this study.



(a) (b) (c)

Fig. 5. Voltage sag Waveform, D1 Coefficients and its Detection

2) Harmonic current detection: The objective of the electric utility supply is to deliver stable voltage and undistorted waveform at fairly constant magnitude throughout its system. This objective, however, is hampered by harmonic currents produced by some non-linear loads, such as adjustable speed drives (ASDs), UPSs, arc furnace loads, computers, copiers, etc., on the system. The currents from these appliances result in distorted voltages and currents that can adversely impact the performance of the power system and the facilities it feeds. Some of the problems caused by the presence of harmonic currents include increased transmission losses, premature failure of electronic devices, equipment overheating, communication interference, fuse and circuit breaker mis-operation, equipment malfunction, etc. Clearly, there is a need to mitigate this menace from power systems. To adequately deal with harmonics in power systems, it is important to detect them promptly and precisely.

Of the aforementioned non-linear loads, arc furnace loads are notorious as sources of harmonics on power systems. They are used for the melting and refining of materials in steel plants. There are three distinct stages in the operation of an electric arc furnace [21]. In the first stage, the electrodes are lowered in order to make the electric arc strike, followed by the heat supplying stage by the arc for the melting operation. Lastly, additives are added to the melt to refine the material in the third stage. Among these stages, the first and the second generate very high current that contains distortions in the waveforms.

The arc furnace system depicted in Fig. 6 can be used for the study of harmonic analysis. As shown in the figure, the arc furnace load is connected to the network via a step down transformer. This type of load is chosen in this study because of its notorious nature as a harmonic source in power systems. The system is simulated using MATLAB's Power System Blockset [24] and the obviously distorted arc furnace current waveform measured at busbar 2 (load bus) is as shown in Fig. 7 (a).

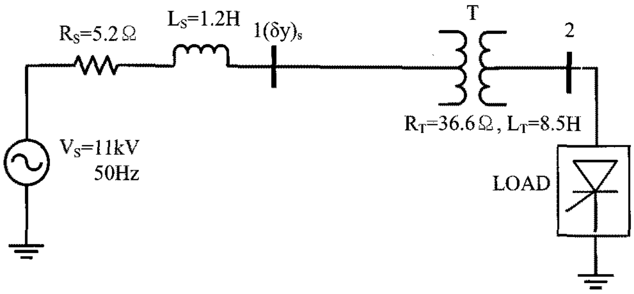


Fig. 6. One-Line Diagram of Arc Furnace System

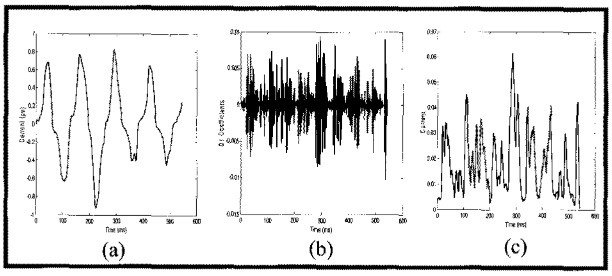


Fig. 7. Load Current with Harmonics, D1 Coefficients and its Detection

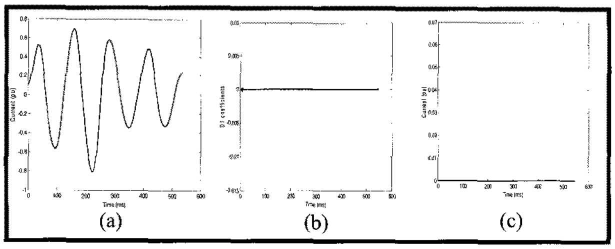


Fig. 8. Denoised Load Current, D1 Coefficients and its Detection

The d1 coefficients and detection result of the resulting harmonic current are plotted in Figs. 7 (b) and (c) respectively. The detection procedure in this paper becomes more convincing when Fig. 7 is compared with Fig. 8.

3) Capacitor Switching Transient: Energization of utility shunt capacitors is a normal operation in power systems. These capacitors are switched into the system for power factor correction, and voltage regulation improvement. However, this event constitutes some power quality disturbances in power systems. Some of the bad effects of shunt capacitor switching include false operation of the protective devices, equipment damage, etc. Fig. 9 (a) presents the voltage waveform of a slow capacitor switching, whose circuit is energised at 295th ms. The D1 coefficients as a result of wavelet analysis, and the switching transient detection are presented in Figs. 9 (b) and (c) respectively. The data for Fig. 9 (a) is obtained from the simulation carried out in [12] using MATLAB software.

Energizing transients can be controlled by using pre-insertion devices such as pre-insertion resistors or reactors. The resistance value considered to be optimum for controlling capacitor energization transients is approximately equal to the characteristic impedance of the charging loop [25].

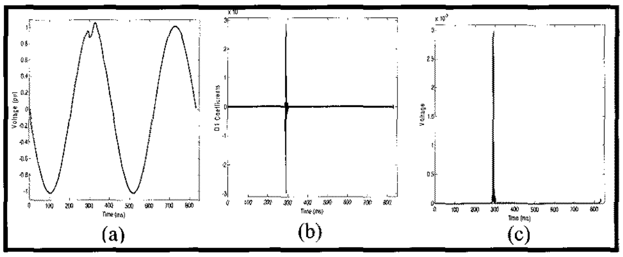


Fig. 9. Voltage Waveform of a Slow Capacitor Switching Disturbance, D1 Coefficients and its Detection

4. Results and Discussion

Looking at Fig. 4(a), one hardly notices any difference, apart from the wave shape of the signal, between pre and post HIF fault. Whereas the difference is better visualised after the fault current signal was decomposed using the DWT as in Fig. 4(b). The detection procedure is better appreciated in Fig. 4(c), the fault current magnitude of which could be used as a criterion for its detection.

In the same vein, the voltage sag experienced on the 11 kV distribution feeder shown in Fig. 5(a) could easily be detected with the use of a DWT, as evidenced in Figs. 5(b) and 5(c). It is seen from these figures that the DWT only picks up the higher frequency components at the start and end of the disturbance, while it is insensitive to steady state voltage. It is worth mentioning that this method has been applied to detect voltage swell as well, though it is not presented in the literature.

Harmonic distortion detection is equally possible using a DWT as depicted in Fig. 7(c) with the same procedure as in HIF detection. The fundamental current is typified in Fig. 8(a) after extracting the noise components of the original signal, which demonstrates the effectiveness of WT as a denoising tool. It is seen in Fig. 8(c) that when a wavelet analysis is carried out on the fundamental current, the current magnitude is virtually zero, which is expected anyway since WT will only pick the high frequency components of the signal, which in this case has already been removed. This could be used as a criterion to differentiate between fundamental current and its harmonics while developing appropriate algorithms for the detection scheme.

Lastly, the detection of a slow capacitor switching transient disturbance experienced on the system at the switching instant, shown in Fig. 9, follows the same detection procedure described earlier. The result obtained is quite interesting since WT clearly figures out the transient disturbance.

5. Conclusion

This paper presented the use of wavelet transform as a signal analysis tool and multi-resolution analysis vis-à-vis their applications in power systems. The study involved computer simulation of some power quality disturbances on power systems, and DWT analysis of the resulting current and voltage waveforms to detect the various types of power quality problems under consideration. With the time-frequency localisation characteristics embedded in wavelets, the time and frequency information of fault generated signal waveforms can be presented as a visualized scheme. This feature of WT comes from its ability to separate power quality problems which overlap in both time and frequency domains. The method was tested with data generated from various computer simulations carried out in this study, and was found to provide satisfactory results in detecting various power quality disturbances.

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