Identification of Fault Location in Multiple Transmission Lines by Wavelet Transform

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ABSTRACT
Distance protection is one of the most common methods used to protect transmission lines. Many techniques have been proposed to achieve accurate results. The main target of these techniques is to calculate impedance at the fundamental frequency between the relay and the fault point. This impedance is calculated from the measured voltage and current signals at the relay location. In addition to the fundamental frequency, the signals usually contain some harmonics and dc component, which affect the accuracy of the phasor estimation. Distance relays have experienced much improvement due to the adoption of digital relaying. Signal processing is one of the most important parts of the operation of the digital distance protection. Wavelets are recently developed mathematical tool for signal processing and the basic concept in wavelet transform (WT) is to select an appropriate wavelet function "mother wavelet" and then perform analysis using shifted and dilated versions of this wavelet. The WT uses short windows at high frequencies and long windows at low frequencies. Wavelet transform (WT) has the ability to decompose signals into different frequency bands using multi resolution analysis (MRA). It can be utilized in detecting faults and to estimate voltage and current of the fault signals without any DC offset in these signals, which are essential for transmission line distance protection. This paper presents a distance protection scheme for transmission lines based on analyzing the measured voltage and current signals using WT with MRA.

KEYWORDS: *Distance-protection relaying, multi-resolution analysis, power systems, wavelet transform (WT).*

I. INTRODUCTION.

This paper focuses the use of wavelet transform, a unified framework for analyzing power system fault identification in a multi-transmission line. Wavelet transform possesses excellent features such as a little wave, little in the sense of being of short duration with finite energy which integrates to zero [1]. Wavelet is well suited to wide band signals that are not periodic and may contain both sinusoidal and impulse components as it is typical for power system transients. In this paper, a new scheme is proposed for fast and reliable fault classification. The proposed method uses a wavelet-based scheme. Various transient system faults are modeled and a Wavelet based algorithm is used for classification of faults. Performance of the proposed scheme is evaluated using various fault types and encouraging results are obtained. It is shown that the algorithm is able to perform fast and correctly for different combinations of fault conditions, e.g. fault type, fault location, pre-fault power flow direction and system short circuit level [2 In power system, wavelet transforms (WTs) are better suited for the analysis of certain types of transient waveforms than the Fourier Transforms (FT) and Short-Time Fourier Transforms (STFT) approaches. A wavelet is described as a little wave, little in the sense of being of short duration with finite energy which integrates to zero, and hence if its suitability for transients. Power system transients, which often have an adverse effect on the normal operation of the system, are quite common like, lighting transients, transformer inrush currents, motor starting currents, capacitor and line-switching transients are just a few of the typical electromagnetic power system transients that occur in practice. Some of the methods employed for analysis of the transient phenomena at present are, transforming the data into the frequency domain via Fourier and STFT. These methods also have served the power engineering community. Fourier has a few drawbacks, they require periodicity in all the time functions involved and also location of transient in time axis is lost. STFT have the following drawbacks, they have the limitations of fixed window width and it will consume more time in transient location. If WTs are opted, they overcome the above discussed disadvantages, as wavelet transforms employ analysis functions that are both in time and frequency domain. It focuses on short-time intervals for high frequency components and long-time intervals for low frequency components. Wavelets have a window that automatically adapts to give appropriate resolution. In unsymmetrical faults only one or two phases are involved. In such fault the voltages and currents become unbalanced (unsymmetrical) and each phase is to be treated individually for calculation purposes. Most of the faults that occur are unsymmetrical faults. Since any unsymmetrical fault causes unbalanced currents to flow in the system, the unsymmetrical faults are analyzed using symmetrical components.

2.1 INTRODUCTION TO WAVELET TRANSFORMS

Wavelet transform is a powerful signal analysis tool that has been used successfully in many areas for than a decade. The Multi-Resolution Analysis (MRA) is one of the most active branches of the Wavelet Transforms. The main algorithm dates back to the work of Stephane Mallet in 1989 [3]. MRA provides an effective way to examine the features of a signal at different frequency bands. Hence, it is suited for the fault classification and location problems in the power system [4], [1]. The fundamental idea behind wavelets is to analyze according to scale. Wavelets are functions that satisfy certain mathematical requirements and are used in representing data or other functions. However, in wavelet analysis, the scale that we use to look at data plays a special role. Wavelet algorithms process data at different scales or resolutions. If we look at a signal with a large "window", we would notice gross features. Similarly, if we look at a signal with a small "window", we would notice small features. For many decades, scientists have wanted more appropriate functions than the sine's and cosines which comprise the basis of Fourier analysis, to approximate choppy signals. By their definition, these functions are non-local (and stretch out to infinity). They therefore do a very poor job in approximating sharp spikes. But with wavelet analysis, we can use approximating functions that are contained neatly infinite domains. Wavelets are well-suited for approximating data with sharp discontinuities. The wavelet analysis procedure is to adopt a wavelet prototype function, called an analyzing wavelet or mother wavelet. Temporal analysis is performed with a contracted, high-frequency version of the prototype wavelet, while frequency analysis is performed with a dilated, low-frequency version of the same wavelet. Because the original signal or function can be represented in terms of a wavelet expansion (using coefficients in a linear combination of the wavelet functions), data operations can be performed using just the corresponding wavelet coefficients, and if you further choose the best wavelets adapted to your data, or truncate the coefficients below a threshold, your data is sparsely represented. This sparse coding makes wavelets an excellent tool in the field of data compression.

2.2 Motivation to Use WT

The increasing complexity of the power systems, concomitant with a demand to drive the network harder without compromising on the quality of power supply, has meant that power engineers it continuously strive for a improved alternative methods of transient analysis, for the purposes of designing new equipment to efficiently and expeditiously deal with abnormal transient phenomena. In this respect, the present methods of transients analysis have limitations. For instance, a Fourier series requires periodicity of all the time functions involved, this effectively means that the basic functions (i.e. sine and cosine waves) used in Fourier analysis. Traditional Fourier analysis does not consider frequencies that evolve with time, i.e. non-stationary signal. Finally, certain adverse effect such as the Gibbs phenomenon and aliasing associated with the discrete FT (DFT) exists when analyzing certain waveforms. However, the drawback is the windowed FT (Also known as the short-time FT or STFT) has the limitations of the fixed window width which needs to be fixed a prior, this effectively means that it does not provide the requisite good resolution in both time and frequency, which is an important character for analyzing transient signals comprising both high and low-frequency components [5].

Wavelet analysis overcomes the limitations of the Fourier methods by employing analysis functions that are local both in time and frequency. The WT is well suited to wideband signals that are not periodic and may contain both sinusoidal and impulse components as is typical of fast power system transients. In particular, the ability of wavelets to focus on short-time intervals for high frequency components improves the analysis of signals with localized impulses and oscillation, practically in the presence of fundamental and low-order harmonics. In a sense, wavelets have a window that automatically adapts to give the appropriate resolution.

2.3 Basic Concepts of Wavelet Transforms

A wavelet is a waveform of effectively limited duration that has an average value of zero. Compare wavelets with sine waves, which are the basis of Fourier analysis. Sinusoids do not have limited duration they extend from minus to plus infinity, and where sinusoids are smooth and predictable, wavelets tend to be irregular and asymmetric. Fourier analysis consists of breaking up a signal into sine waves of various frequencies. Similarly, wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet. It also makes sense that local features can be described better with wavelets that have local extent [5]. The wavelet transform allows resolving the resolution problem encountered in STFT. The basic functions allow to trade off the time and frequency resolution in different ways. If a large region of low frequency signal is to be analyzed, a wide basis function will be used. Similarly, if a small region of high frequency signal is to be analyzed, a small basis function will be used. The basic functions of the wavelet transform are known as wavelets. There are a variety of different wavelet functions to suit the needs of different applications. In general, a wavelet is a small wave that has finite energy concentrated in time as shown in Figure 1. This is the characteristic about a wavelet that gives it the ability to analyze any time-varying signals.

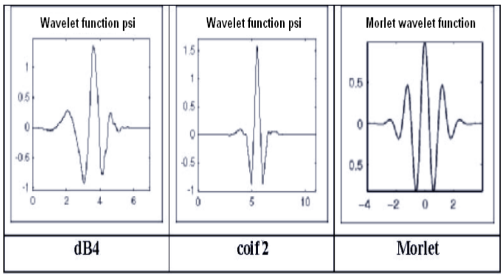


Fig. 1 Types of Wavelet

II. WAVELET FAMILIES

There are a number of basic functions that can be used as the mother wavelet for Wavelet Transformation. Since the mother wavelet produces all wavelet functions used in the transformation through translation and scaling, it determines the characteristics of the resulting Wavelet Transform. Therefore, the details of the particular application should be taken into account and the appropriate mother wavelet should be chosen in order to use the Wavelet Transform effectively. Figure 2 illustrates some of the commonly used wavelet functions. Haar wavelet is one of the oldest and simplest wavelet. Daubechies wavelets are the most popular wavelets. They represent the foundations of wavelet signal processing and are used in numerous applications.

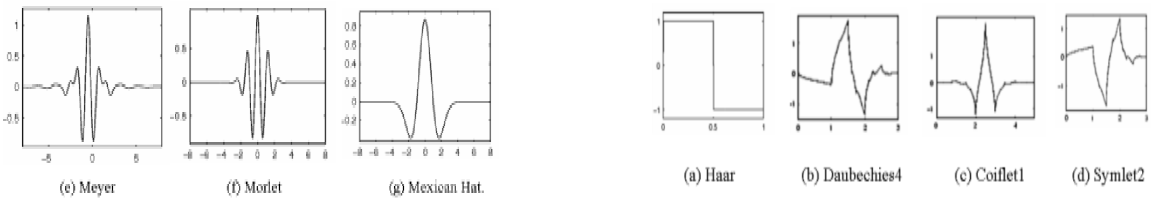


Fig. 2 Wavelet families

These are also called Maxflat wavelets as their frequency responses have maximum flatness at frequencies 0 and π. This is a very desirable property in some applications. The Haar, Daubechies, Symlets and Coiflets are compactly supported orthogonal wavelets. These wavelets along with Meyer wavelets are capable of perfect reconstruction. The Meyer, Morlet and Mexican Hat wavelets are symmetric in shape. The wavelets are chosen based on their shape and their ability to analyze the signal in a particular application.

3.1 Daubechies Family

The names of the Daubechies family wavelets are written dbN, where N is the order, and db is the "surname" of the wavelet. The db1 wavelet, as mentioned above, is the same as Haar wavelet. Here are the wavelet functions of the next nine members of the family. Figure 3 shows the members of the Daubechies family.

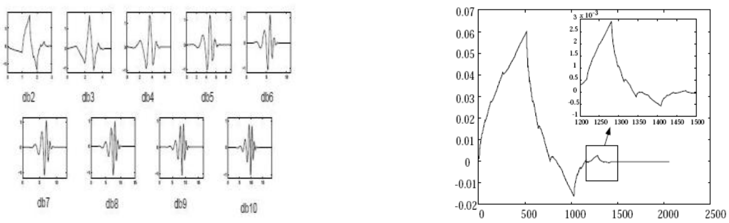


Fig. 3 Daubechies family wavelets

3.2 Continuous Wavelet Transform

The continuous wavelet transform was developed as an alternative approach to the short time Fourier transforms to overcome the resolution problem. The wavelet analysis is done in a similar way to the STFT analysis, in the sense that the signal is multiplied with a function, similar to the window function in the STFT, and the transform is computed separately for different segments of the time-domain signal. However, there are two main differences between the STFT and the CWT:

[1] The Fourier transforms of the windowed signals are not taken, and therefore single peak will be seen corresponding to a sinusoid, i.e., negative frequencies are not computed.

[2] The width of the window is changed as the transform is computed for every single spectral component, which is probably the most significant characteristic of the wavelet transform.

a. Mathematically, the continuous wavelet transform (CWT) of a given signal x(t) with respect to a mother wavelet g(t) is generically defined as shown in Equation 1.

$$CWT(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} x(t)g(\frac{t-b}{a})dt \qquad (1)$$

Where 'a' is the dilation of scale factor and 'b' is the translation factor, and both variables are continuous. It is apparent from Equation (1) that the original one-domain signal x(t) is mapped to a new time-dimensional function space across scale 'a' and translation 'b' by the wavelet transforms (WT). A WT coefficients CWT (a,b) at particular scale and translation represents how well the original signal x(t) and scaled and translated mother wavelet match. Thus, the set of all wavelet coefficients CWT (a,b) associated with a particular signal are the wavelet representation of the original signal x(t) with respect to the mother wavelet g(t).

The parameter scale used in wavelet transformation is similar to the scale used in the maps. At high scale, the wavelet seeks for global information or low frequency information about the signal. At low scale, the wavelet seeks for detailed information or high frequencies information about the signal.

3.3 Discrete Wavelet Transform

The foundations of the DWT go back to 1976 when Croiser, Esteban, and Galand devised a technique to decompose discrete time signals [2]. Analogous to the relationship between continuous Fourier transform and discrete Fourier transform, the continuous wavelet transform has digitally implementable counterpart called the discrete wavelet transform and is defined as

$$DWT\ (a,b) = \frac{1}{\sqrt{a^m}}\sum_{n} x(n)g(\frac{k - nb_o a_o^m}{a_o^m}) \qquad (2)$$

Where 'a' and 'b' are the scaling and translation parameters. Where as $a=a_o^m$ and $b=nb_o\ a_o^m$ giving rise to a family of dilated mother wavelet, i.e. daughter wavelet. Scaling gives the DWT logarithmic frequency coverage in contrast to the uniform frequency coverage of, say, the windowed-DFT (i.e. WDFT). The DWT output can be represented in a two-dimensional grid in a manner similar to the WDFT but with very different divisions in time and frequency.

III. MULTI-RESOLUTION AND WAVELET DECOMPOSITION

The Wavelet represents a powerful signal processing with a wide variety of applications:

Acoustics, communications, transient analysis, medicine etc. the main reason for this growing activity is the ability of the wavelet transform not to be decompose a signal into its frequency components, but also unlike the Fourier transforms to provide a non-uniform division of frequency domain [5]. Whereby it focuses on short time Fourier intervals for the high frequency components and long intervals for low frequencies. This attribute to tailor the frequency resolution can be greatly facilitate signal analysis and the detection of the signal features, which can be very useful in characterizing the sources of the transients and or the state of the post disturbance system. The wavelet transforms normally uses both the analysis and synthesis wavelet pair. Synthesis is used for wavelet reconstruction. The original signal is decomposed into its constituent wavelet sub bands or levels. Each of these levels represents that part of original signal occurring at the particular time and in that particular frequency band. These individual frequency bands are logarithmically spaced rather than uniform spaced as in the Fourier transforms. The decomposed signal posses a powerful property which is one of the major benefits provided by the WT. The resulting decomposed signal can be analyzed in both time and frequency domains. Multi-resolution analysis is a procedure to obtain low-pass approximates band-pass details from original signals [2]. An approximates is a low resolution representation of a original signal, while a detail is the difference between two successive low-resolution representations of the original signal.

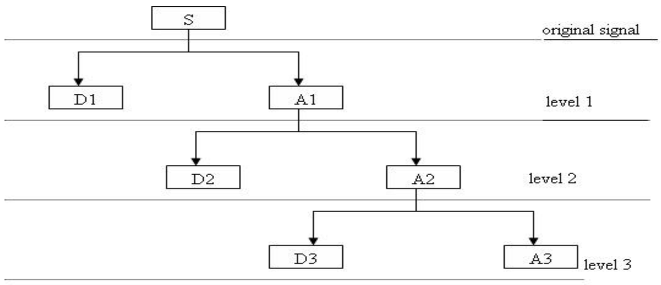


Fig. 4 Multi-Resolution and Wavelet Decomposition

An approximation contains the general trend of the original signal while a detail embodies the high-frequency content of the original signal. Approximation and detail are obtained through a succession of convolution processes. The original signal is divided into different scales of resolution, rather than different frequencies, as in the case of Fourier analysis. The algorithm of multi-resolution decomposition id illustrated in Figure 4, where three levels of decomposition are taken as an example of illustration**.** The details and approximations of the original signal S are obtained by passing through a filter bank, which consists of low-pass and high-pass filter. A low-pass filter picks out high frequency contents in the signal being analyzed. With reference to Figure 3, the multi-resolution decomposition procedures are defined as:

Dj(n) = ∑h(k)Aj-l(n-k) (3)

Aj(n) = ∑L(k)Aj-l(n-k) (4)

Where l and h are low-pass and high-pass filter vectors, respectively Dj, Aj are detail and approximation at resolution j, j=1,2,……..,j respectively, Aj-1 is the approximation of the level immediately above level j, k=1,2,…….,k where k is length of the filter vector.

To have a non-redundant representation and unique representation and unique reconstruction of the original signal, orthogonal filter banks are required. WT and multi-resolution decomposition are closely related. Also, as shown in Figure 3, wavelet decomposition is accomplished by including down-sampling operations into the multi-resolution analysis. The maximum number of wavelet decomposition levels for WT is determined by the length of original signal, the particular wavelet being selected, and the level of detail required. The low-pass and high-pass filter is determined by the scaling function and wavelet function respectively. Signal processing uses exclusively orthogonal wavelets [1]. The non-redundant representation and perfect reconstruction of the original signal can only realize through compactly supported orthogonal wavelets. The ones that are frequently used for signal processing are daubechies, morlets, and coiflets and symlets. The wavelets exhibit different attributes and performance criterion when applied to specific applications, such as detection of transients, signal compression and denoising.

4.1 IMPLEMENTATION OF DWT

The interchange of the variables n, k and rearrangement of the Equation (2) gives.

$$DWT\,(m,n) = \frac{1}{\sqrt{a^m}} \sum_n x(n) g(a_o^{-m} n - b_o k) \qquad (5)$$

On closer observation of this equation, we notice that there is a remarkable similarity to the convolution equation for the finite impulse response (FIR) digital filters, namely

$$y(n) = \frac{1}{c} \sum x(k) h(n-k) \qquad (6)$$

where h(n-k) is the impulse responses of the FIR filter.

By comparing Equation (5) and Equation (6), it is evident that the impulse response of the filter in the DWT equation is

$$g(a_o^{-m} n - b_o k) \qquad (7)$$

Therefore mentioned characteristic feature of the DWT is very different from the WDFT. The DWT is thus very effective in isolating the highest frequency band at precisely the quarter cycle of its occurrence while the 50Hz power frequency is fully preserved as a continuous magnitude. This simple example clearly explains the multi-resolution attributes of the wavelet transforms in analyzing a non-stationary transient signal comprising both high and low-frequency components.

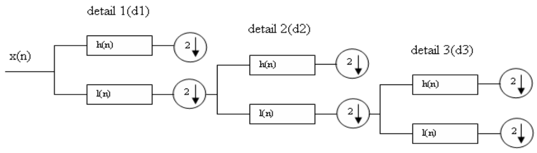


Fig. 5 Implementation of the Discrete Wavelet Transform

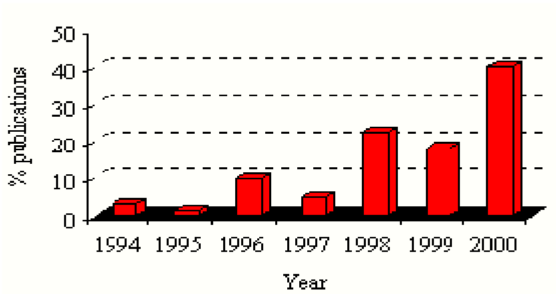
By selecting $a_{=2}$ and b_o=1, the CWT can be implemented by using a multi-stage filter with the mother wavelet as the low-pass filter l(n) and its dual as the high-pass filter h(n), as shown in Figure 5. As evident from the example considered, down sampling the output of the low-pass filter l(n) by factor 2(2) effectively scales the wavelet by a factor of 2 for the next stage, thereby simplifying the process of dilation.

$$h[l-1-n] = (-1)^n l(n) \tag{8}$$

Where l is the filter length. Note that the filter length are 'odd index' alternated reversed versions of each other, and the low-pass to high-pass conversion is provided by the $(-1)^n$ term, filters satisfying this condition are commonly used in signal processing, and they are known as the 'quadrature mirror filters'. The implementation of the DWT with a filter bank is computationally efficient. The output of the high-pass filter in Figure 5 gives the detailed version of the high-frequency component of the signal. As can be seen, the low-frequency component is further split further to get the other detail of the input signal.

4.2 APPLICATIONS OF WAVELET TRANSFORMS IN POWER SYSTEM

Wavelet transform has received great attention in power community in the last years, because are better suited for the analysis of certain types of transient waveforms than the other transforms approach. The aim of this paper is to provide a descriptive overview of the wavelet transform applications in power systems to those who are novel in the study of this subject. A specific application of wavelet MRA in transmission line fault detection, classification, and location is discussed briefly in the following sections. The wavelets were first applied to power system in 1994 by Robertson [6] and Ribeiro. From this year the number of publications



in this area has increased as Figure 6 shows.

Fig. 6 Evolution of Wavelet Publications in Power Systems

The main focus in the literature has been on identification and classification methods from the analysis of measured signals, however, few works use wavelet transform as an analysis technique [7] for the solution of voltages and currents which propagate throughout the system due, for example, a transient disturbance popular wavelet transform applications in power systems are the following:

- Power system protection
- Power quality
- Power system transients
- Load forecasting
- Power system measurement

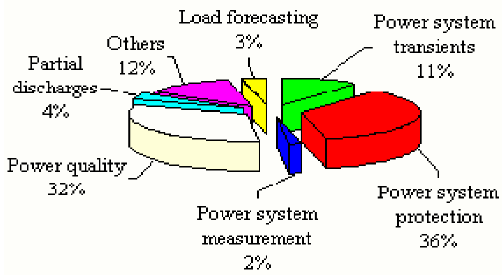


Fig. 7 Percentage of Wavelet Publications in Different Power System Areas

Figure 7 shows the percentage of publications in each area; the areas in which more works have been developed are the protection and power quality field [8]. The goal in each of the above is to "reduce the large volume of transient signal data to a much smaller and higher quality information packet to archive or actively distribute to the power system" [9]. The result is to enhance the value of transient data from digital recording equipment through increased use of day-to-day transient event monitoring.

IV. MATLAB SIMULATION

A simulation model is developed for the system shown in figure 8 using simulink.

Fig. 8 schematic diagram of power system

[1] Generator ratings: 240 KV, 60Hz.
[2] Transmission line parameters:

R	0.01844 (Ω/km)
L	3.73e-3 (H/km)
C	5.08e-9 (F/km)
Z1 & Z2	(8.05+j110.66) Ω
Z0	(79.19+j302.77) Ω
Z_L	(4.15+j84.6) Ω

5.1 The phase currents and voltages for the simulation model without fault

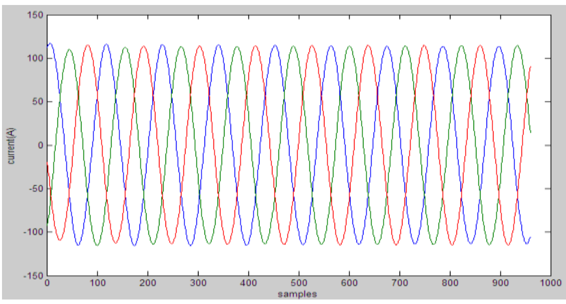


Fig. 9 Healthy phase current signal

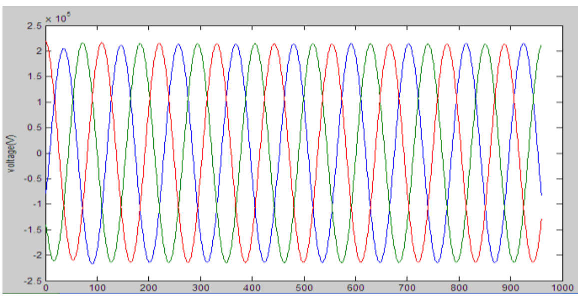


Fig. 10 Healthy phase voltage signals

5.3 Phase currents and voltages of the simulation model with L-G fault are shown below

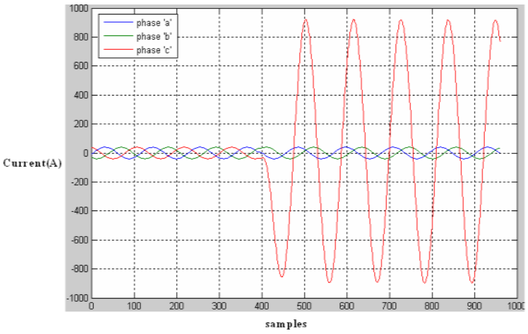


Fig. 11 current waveforms for an L-G fault

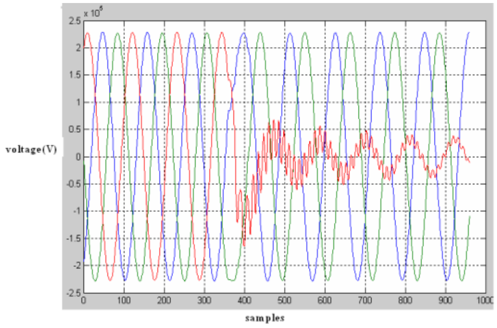


Fig. 12 Voltage waveforms for L-G fault

VI. RESULTS AND DISCUSSIONS

6.1 Wavelet distance protection algorithm.

In order to investigate the applicability of the proposed wavelet transform distance protection algorithm, a simulation of transmission line model is developed. Fault simulations were carried out using MATLAB. The three phase current and voltage signals are sampled at 960Hz (16 samples/fundamental power cycle). These signals are then filtered using the pre-band-pass filters to attenuate the dc component. The output filtered signals are the input to the proposed wavelet distance protection algorithm.

6.2. Analysis of L-G fault.

The simulated fault signals are being analyzed through the Wavelet transform using MATLAB wavelet toolbox as follows. Three phase current and voltage signals[10] Figure 8 are loaded to the multisignal analysis1-D in the wavelet toolbox main menu.

The proposed technique is divided into two sections

6.2.1 Fault detection.

The first section is detection of the fault by observing the output of the high pass filter details of the first decomposition level. This decomposition level has the ability to detect any disturbances in the original current waveform. The loaded current signals (Figure 8) are decomposed at one level with the db1 wavelet.

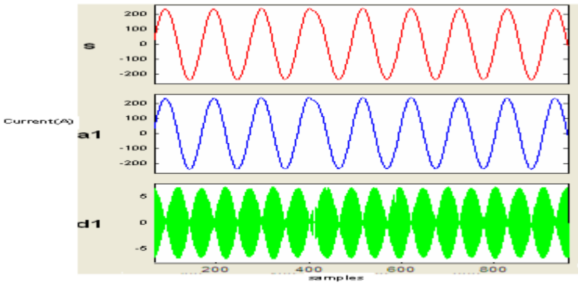


Fig. 13 First level decomposition of phase 'a'

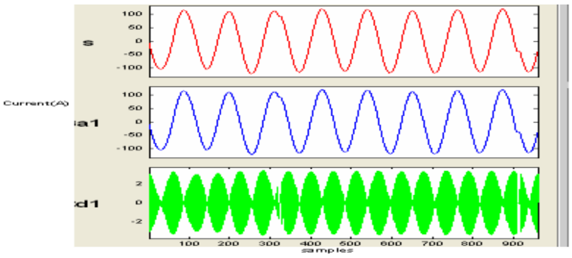


Fig. 14 First level decomposition of phase 'b'

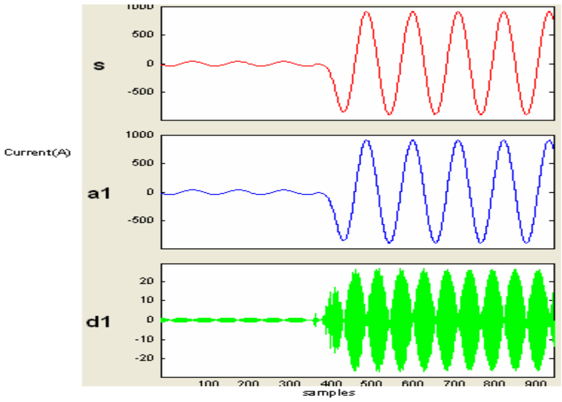


Fig. 15 First level decomposition of phase ‘c’

6.2.2 Estimation of current and voltages.

The second section of the algorithm is the estimation of the fundamental frequency voltage and currents. It can be done by observing the output of the low-pass filter at the fourth decomposition level (A4). The fourth level of decomposition gives good approximation of the phasors. At this level the High frequencies in the signal are eliminated by the high-pass filters of the first, second and third decomposition levels and DC component has already been eliminated by pre-band-pass filtering the signal. The estimation of phasors is based on capturing the peak value of each signal (magnitude).The three phase current and voltage signals are decomposed by the db4 wavelet.

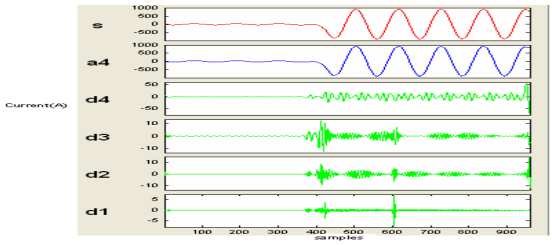
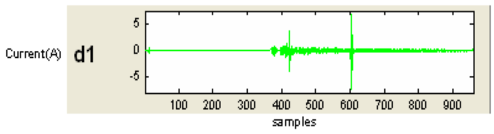


Fig. 16 4-levels of decomposition of phase ’c’

6.2.3 Fault distance measurement



No of samples : 182
Simulation time : 0.22 sec
Time interval between two peaks : 0.22/182
: 1.208 m sec
Traveling wave velocity : 1.82 x 10^5 miles/sec
Fault distance D = (v*Td)/2
= 109.89 miles
= 175.83Km.

VII. CONCLUSIONS

The present work proposed an efficient wavelet based transmission line distance protection. It has the ability of detecting faults and to estimate the voltages and currents of signals without any DC offset in the signals, which are fundamental for distance protection. This wavelet based technique allows decompose the signal into frequency bands (multi-resolution) in both time and frequency allows accurate fault detection as well as estimation of fault signal currents and voltages at the fundamental frequency. Various faults on the transmission line can be identified and cleared within one cycle according to the fault location.

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