Wavelet Based Analysis for Transmission Line Fault Location

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Abstract

This paper presents wavelet based analysis for transmission line fault location. Faults in power transmission lines cause transients that travel at a speed close to the speed of light and propagate along the line as traveling waves (TWs). Traveling wave theory is utilized in capturing the travel time of the transients along the monitored lines between the fault point and the protective relay. This will help in proposing an accurate fault location technique based on high frequency components of fault current. Time resolution for these components is provided by the wavelet transform.

This approach has the advantages of being independent of the fault impedance and fault inception angle. The application of the proposed technique for typical faults is illustrated using transient simulations obtained by MATLAB Simulink program.

Keywords: travelling waves, wavelet transform, fault location, MATLAB Simulink.

1. Introduction

An electric power system comprises of generation, transmission and distribution of electric energy. The rapid growth of electric power systems over the past few decades has resulted in a large increase of the number of lines which play an important role in electric power systems. Transmission lines subject to unexpected disturbances such as short circuit faults. Faults cause short to long term power outages for customers and may lead to significant losses especially for the manufacturing industry.

Once a fault occurs on such line, the relay must quickly isolate the faulted line. This ensures that the power system will not run into transient stability problems and no damage of the equipment due to the resulting electro dynamic and thermal stresses. The faster the fault clearing, the smaller is the disturbance on the system.

The most EHV protection algorithms are based on fundamental frequency components, whose performance are easily affected by some factors such as distributed capacitance, fault resistance, current transformer saturation and power swing, etc.

Distance relays, the primary EHV transmission line protection, operate on the impedance measured at the relay location. The fault distance can be estimated from the measured impedance of the transmission line at the power system frequency.

The impedance measurement used in distance protection schemes is not accurate for precise fault location as the error in the estimated fault location can be as high as 10% of line length (J. Rushton *et al.* 1972)

Various authors (M. S. Sachdev *et al.* 1985), (S. Sachdev *et al.* 1988), (M. M. Saha *et al.*1985) and (A.T. Johns *et al.* 1990) have proposed techniques whereby an improved estimate of the fault location can be achieved from the impedance measured by the protection relays.

These methods reportedly decrease the error in the fault location to around 1-6% of the line length.

In the last three decades interest has been expressed in the use of travelling wave based protection and fault location.

A technique proposed by (P.A. Crossley *et al.* 1983), the reflections of the travelling waves caused by the fault are analyzed to determine the time taken for the travelling waves propagating towards the fault point to return from being reflected at the fault point. A matched filter based on the initial surge to reach the relaying point is used to determine when the reflected surges return. The output of the matched filter produces a correlation function. This method has been tested and improved by (E. Shehab-Eldin *et al.* 1988) and (P. McLaren *et al.* 1985).

(C. Christopoulos *et al.* 1988) introduced the method of estimating the fault resistance from the correlation function to determine whether the reflected surge had been reflected from the fault point rather than from some other discontinuity on the transmission line.

In the majority of traveling waves methods, fault generated high frequency transients are utilized to determine fault location. Theses algorithms, despite the mentioned advantages, are sensitive to noises and faults occurred on the other lines, fault inception angle, reflected waves from other terminals, which are outside from the relay and fault point (Faybisovich V *et al.* 2008). In addition, these methods suffer from faults occurred close to the relay.

Techniques proposed by (Faybisovich V *et al.* 2008), (Styvaktakis E *et al.* 1999) and (Yongli L *et al.* 2004) utilize high frequency fault clearing transients instead of the fault generated transients to use advantages of the traveling wave methods whilst avoid their problems.

Examples of applying wavelet transform to analyze power system transients and extractions of their particular features are reported before by (C. Robertson *et al.* 1996).

The multi resolution property of the wavelet transform in time and frequency domain has been reported by (O.A.S Yaussef, 2003). The technique includes decomposition and reconstruction of the faulted signal to extract the low-frequency components and the fundamental frequency component of the signal, thus isolating the impulse and high frequency component using a small data window.

Another approach using current travelling wave is utilized to detect the fault position in the transmission lines. The main principle of this method is to analyze the distribution of the modulus maxima of the wavelet transform of the current travelling wave. Detecting the fault position is achieved by identifying and comparing the position, amplitude and polarity of the modulus maxima of the wavelet transform (Dong Xinzhou *et al.*).

Another wavelet based multi-resolution analysis for fault location determination (D.Chanda *et al.* 2003). The three phase fault currents are processed through wavelet transform and Cubic interpolation technique is used for fault location determination. The effects of fault inception angle and resistance are examined with wide variations.

Another technique for fault location has been investigated on parallel transmission lines using wavelet (Hosung Jung *et al.* 2007). Using this technique, two parts for accurate, rapid fault detection and fault location estimation were proposed regardless of mutual coupling between parallel lines. The first part is fault detection and extraction of the fundamental signal using wavelet transform. The second part is fault location estimation using least square error method independent of fault resistance, and the remote in feed.

Another approach illustrates a procedure based on the continuous-wavelet transform (CWT) for the analysis of voltage transients due to line faults, and discusses its application to fault location in power distribution systems (A.Borghetti *et al.* 2006).

Another approach presents a fault location principle based on the double terminal methods of travelling wave using continuous wavelet transform (CWT) (Qin Jian *et al.*).

This paper presents an improved method to determine fault location on transmission line based on sampling of the fault current transients at the relay point. The main contribution of the paper is the use of time delay, not between the incident and reflected current waves, but instead, between the modal components of the current signal which are received at relay point due to fault in order to determine the exact location of the fault. The effect of fault inception angle and fault resistance on fault location accuracy is studied.

2. Calculation Algorithm

2.1 Travelling Wave Theory

This section describes the basics of travelling wave. Single phase transmission lines are considered only in describing the associated theory for simplicity.

When a fault occurs on a transmission line, voltage and current surges propagate away from the fault point in both directions. These surges reach other discontinuities on the transmission line and are reflected back towards the fault point.

This can be shown graphically by means of a lattice diagram such as that shown in Figure1. The backwards signal travelling wave f_b incident upon end S is given by (ignoring surges that may be transmitted through the fault point from end R)

$$\mathrm{f_b(t)} = \sum_{\mathrm{i}=0}^{\infty} \mathrm{a_i f_b(t-\tau_i)} \tag{1}$$

where $a_i = (\rho_f \rho_s)^i$, $\tau_i = (2i+1)T_a$, $f_b(t)$ is the backwards travelling wave caused by the occurrence of the fault, T_a is the time required for the travelling waves to propagate from the fault to end S,

$\rho_f = \frac{R_f - Z_0}{R_f + Z_0}$ is the fault reflection coefficient, R_f is fault resistance, Z_0 is surge impedance of line, $\rho_s = \frac{Z_s - Z_0}{Z_s + Z_0}$ is the reflection coefficient at end S and Z_s is impedance of sending end. One of the most important factors that affect estimation of arrival time is the fault inception angle and fault resistance. The fault initiated surge ΔV can be expressed as:

$$\Delta \mathrm{V} = \rho_\mathrm{f} \mathrm{V_{pf}} \tag{2}$$

where $\mathrm{V_{pf}}$ is the instantaneous value of the pre-fault voltage at the fault point. The value of $\mathrm{V_{pf}}$ depends on the instant of fault inception over the pre-fault voltage waveform. If the pre-fault voltage is close to zero (fault angle is close to zero or 180 °), the surge is so small to be detected.

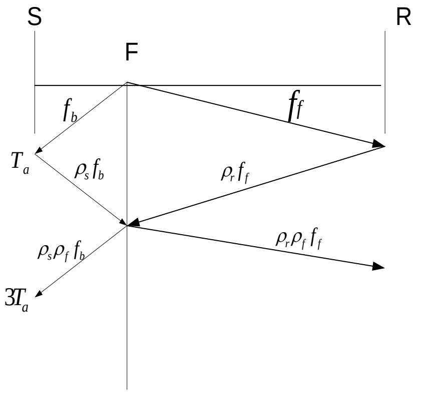

Figure1. Lattice Diagram

2.2 Modal Analysis

As poly phase transmission lines have significant electromagnetic coupling between the conductors, the voltage and current on a single conductor can't be directly treated as described previously. The modal decomposition, results in ground (mode 0) and aerial mode (mode 1&2), each mode has a particular speed and characteristic impedance. The coupled conductor voltages and currents are decomposed into a new set of modal voltages and currents. Each pair of modal voltages and currents can be treated independently of the other pairs in a similar manner to the single phase transmission line case. Three of the constant modal transformation matrices for perfectly transposed lines are the Clarke, Wedepohl and Karrenbauer transformations (E. Clarke, 1943), (P. Chowdhuri, 1996) and (A.T. Johns *et al.* 1995). Modal components will travel at different speeds along the faulted line near speed of light. Hence, the recorded fault transients at one end of the line will have time delays between their modal components. These delays can't be readily recognized unless the signals are further processed by appropriate transformations as discrete wavelet transform (DWT). The modal components can be obtained by

$$\mathrm{U_m} = \mathrm{T_u^{-1}}\mathrm{U}_p \tag{3}$$

$$\mathrm{I_m} = \mathrm{T_i^{-1}}\mathrm{I_p} \tag{4}$$

where U and I are the phase voltage and current components and the indices m and p are related to modal and phase quantities, respectively. T_u and T_i are the corresponding voltage and current transformation matrices.

Three modes are obtained from Clarke's transformation (two aerial and one ground mode).

Every of those modes are carrier some physical information. This is especially important for ground faults.

Clarke’s transformation for transforming the instantaneous phases current to modal component is used as follows

$$\begin{pmatrix} i_0 \\ i_{1m} \\ i_{2m} \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{5}$$

Where i_0 is the instantaneous ground mode current component, i_{1m} and i_{2m} are the instantaneous aerial mode current components for transposed lines.

2.3 *Wavelet Analysis*

Most of the signals in practice are time domain signals. But in many applications, the most distinguished information is hidden in the frequency content of the signal. Sometimes both frequency and time related information may be required. In such cases, wavelet transforms are used. Waveforms associated with the traveling waves are typically non-periodic signals that contain localized high frequency oscillations superimposed on the power frequency. The continuous wavelet transform (CWT) is defined as the sum over time of the signal multiplied by scaled, shifted versions of the wavelet function. The result of the CWT is many wavelet coefficients (WTCs), which are functions of scale and position.

Wavelet transform of sampled waveforms can be obtained by implementing the DWT.

Actual implementation of the DWT, involves successive pairs of high-pass and low-pass filters at each scaling stage of the wavelet transform. While, in principle any admissible wavelet can be used in the wavelet analysis, the Daubechies-3 wavelet is chosen as the mother wavelet in all the transformations. (Daubechies 1995), (MATLAB user’s guide) and (Fan YU *et al.* 2013)

2.4 *Proposed Algorithm*

Power system faults that occur along transmission lines initiate transient current waveforms. These transients travel along the lines and are reflected at the line terminals following the rules of Bewley’s Lattice Diagrams. Propagation of current signals along multiphase lines can be better observed by decomposing them into their modal components to obtain the ground and aerial mode signals which propagate with velocity near speed of light. This is why the propagation of modal components could be considered as travelling waves going back and forth with reflection coefficient as expressed by Equation (1). Hence, the recorded fault transients at one end of the line will have time delays between their modal components which can’t be readily recognized unless the signals are further processed by DWT, as described in the above section.

When the fault is ungrounded one, there is no reflection from far end and the wavelet coefficient (WTC) is insignificant for ground mode.

When the fault involves a connection to ground, then relay terminal signals may contain significant reflections from the far end bus in addition to the ones from the fault point. Also, depending on the location of the fault, the reflections from the far end may arrive before or after those reflected from the fault point.

The far end reflections will arrive later than the fault reflections if the fault occurs within half the length of the line, close to the relay location. The opposite will be true if the fault is situated in the second half of the line.

In the case of ground faults, it is observed that WTC contains the signatures of not only the reflections from the fault point, but also those from the far end bus. The former and the latter reflections can’t be distinguished and identified only based on the aerial mode but can be determined based also on the information provided by the ground mode at relay point.

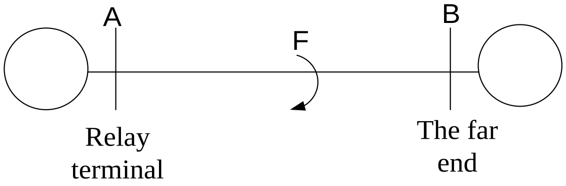

Figure2. Studied System

It can be easily verified by using the lattice diagram method.

A lattice diagram illustrating the reflection and transmitted of traveling waves initiated by the fault transient is shown in Figure3. and Figure4.

A single phase to ground fault is assumed to occur at point F. Aerial mode is considered only. The travel times from the fault to bus A and bus B are designated by T_1 and T_2 respectively.

The arrival time of the first transient peak depends on the velocity of the line and the fault distance and independent of the type of fault.

If the fault is determined to be in the near half of the line, then τ will simply be the time interval between the first two peaks of the aerial mode at the relay point.

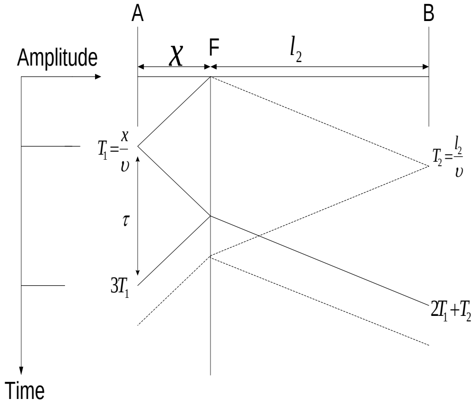

Figure3. Bewelly Lattice Diagram for Single Line to Ground Fault within Half of the Line near Relay Terminal.

$\tau = 3T_1 - T_1 = 2(x/\upsilon)$

The fault location can be determined by

$$x = (\upsilon\tau/2) \tag{6}$$

Where x is the distance to the fault, υ is the wave velocity of aerial mode, and τ is the time delay between two consecutive peaks of the DWT in aerial mode.

If the fault is suspected to be in the second half of the line, then

$\tau = 2T_2 = 2(l - x/\upsilon)$

$$x = l - (\upsilon\tau/2) \tag{7}$$

The proposed method calculates the fault location based on the sampled current signals at the relay point. The main idea is to utilize the inherent time delay between the different modal current components received at relay point due to fault. The exact location of the fault is determined based on the DWT of the aerial mode (mode 2).

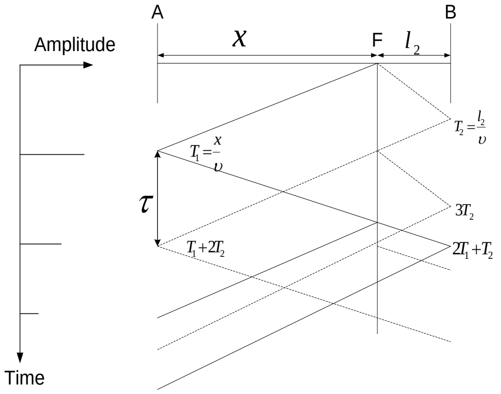

Figure4. Bewelly Lattice Diagram for Single Line to Ground Fault within Half of the Line at Far End.

The steps of the method proposed are given below:

- Simulation of the system to calculate different fault current.
- Transform the three phase current signals into their modal component by Clarke's transformation matrix.
- Decompose the modal signals using the DWT and obtain the wavelet coefficients (WTC) for ground mode and aerial mode using db-3 as mother wavelet function.
- If the ground mode WTC is zero, then the fault is identified as ungrounded one, and the distance to fault is given by Equation (6).
- If the ground mode WTC isn't zero, then calculate the travel time delay τ_m, between the first peak of ground and aerial modes
- if $\tau_m > \tau_{l/2}$, then the distance to fault is determined by Equation (7).

  where $\tau_{l/2}$ is the time delay between first peak of ground and aerial modes when the fault is located at the center of the line.
- if $\tau_m < \tau_{l/2}$, then the distance to fault is determined by Equation (6).

2.5 *Effect of Fault Type*

The proposed algorithm is capable to find the location of the various types of the faults occurred, including single line to ground, double line to ground, double line and three phase faults. Table3. confirms the accuracy of the proposed algorithm in predicting the fault location for different types of the faults occurred on the transmission line.

2.6 *Effect of Fault Inception Angle*

Many traveling wave-based fault location algorithms suffer from the fault inception angle (Costa FB *et al.* 2012). To evaluate the influence of the fault inception angle on the accuracy of the proposed algorithm, simulations for grounded fault (single line to ground fault) and ungrounded fault (three-phase fault) occurring in 100 km distance from relay point with different fault inception angles are carried out and the obtained results are shown in Table4. It is clear that the inception angle of the fault has no significant effect on the accuracy of the algorithm.

2.7 *Effect of Fault Resistance*

About 80% of the transmission line faults are single phase to ground fault (Heine P *et al.* 2003) where one of the conductors is short circuited to the ground without or via a fault resistance. Majority of the fault location algorithms are influenced by the fault resistance. Therefore, it is essential to study the effect of fault resistance on the accuracy of the proposed algorithm. To evaluate the influence of the fault resistance, simulation results for single line to ground faults occurring in 100 km distance from relay point with different fault resistances are presented in Table5. It is clear that the fault resistance does not have appreciable effect on the accuracy of the proposed algorithm.

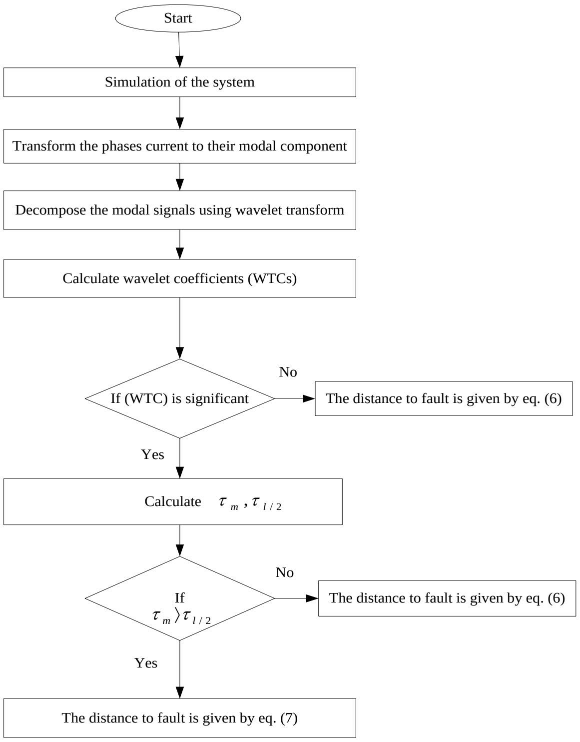

Figure5. Flow Chart of the Methodology

3. Studied System

Table1. Line Data

L_0 (H/km)	1.63e-3
L_1 (H/km)	0.9337e-3
C_0 (F/km)	7.751e-9
C_1 (F/km)	12.74e-9
Length	200km
$v_1 = \frac{1}{\sqrt{L_1 C_1}}$	289942.32km/s
$v_0 = \frac{1}{\sqrt{L_0 C_0}}$	281341.43Km/s

Table2. Source Data

Supply Voltage	500KV
Frequency	50Hz
Supply Resistance	0.5Ω
Supply Inductance	0.3mH
Fault Time	0.003s
Sampling Time	8*10^(-8) s

<u>For symmetrical fault at 120km from relay point</u>

The WTCs of the ground mode are found to be insignificant; hence this type of fault is classified as short circuit (ungrounded). Therefore, based on Equation (6), the fault location can be calculated using the time difference between two consecutive peaks of the DWT in aerial mode.

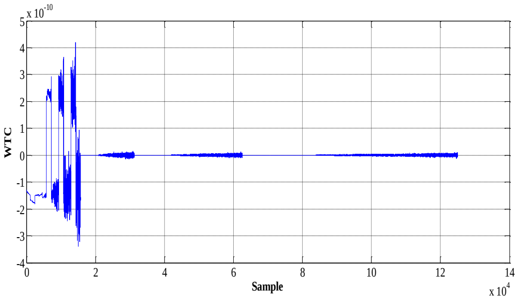

Figure6. Wavelet Coefficients for Ground Mode Signal

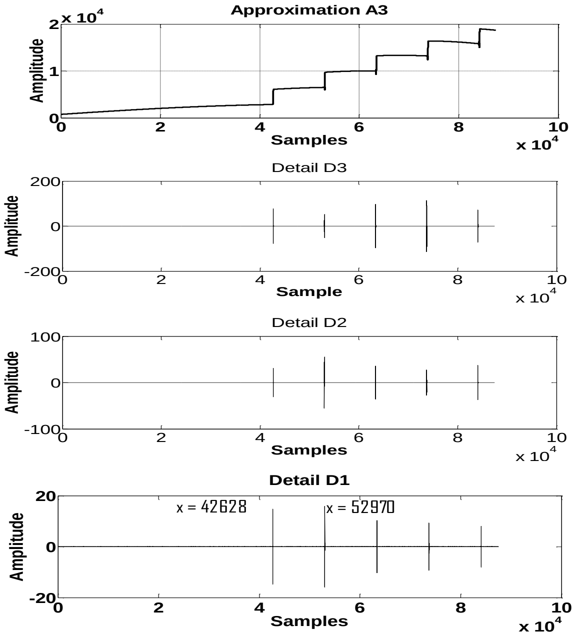

Figure7. DWT Decomposition for Aerial Mode Signal

$$x = \frac{289942.3 * (52970 - 42628) * 8 * 10^{\wedge}(-8)}{2} = 119.94km$$

For single line to ground fault at 120km

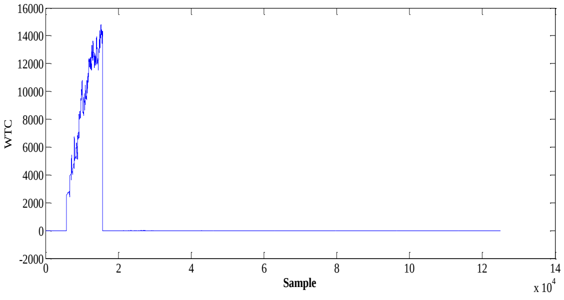

Figure8. Wavelet Coefficients for Ground Mode Signal

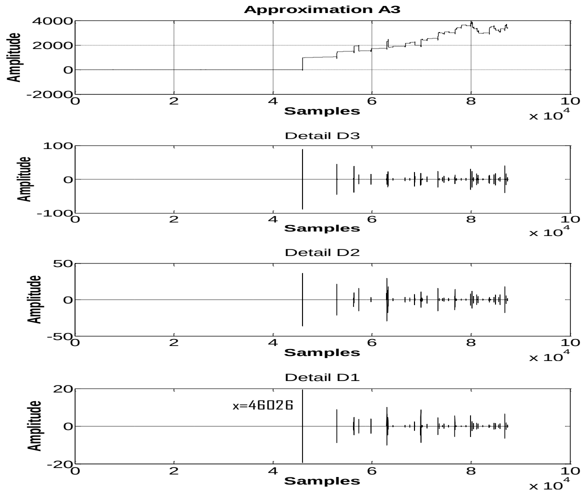

Figure9. DWT Decomposition for Ground Mode Signal

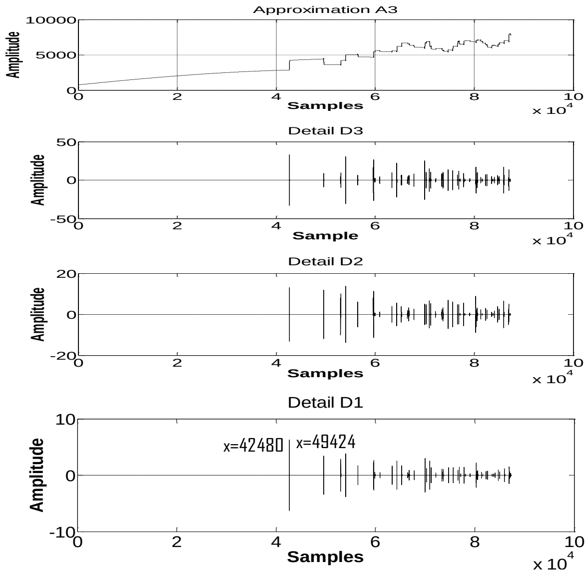

Figure10. DWT Decomposition for Aerial Mode Signal

$$\tau_m = (46026 - 42480) * 8 * 10^{-8} = 0.28\text{ms}$$

$$\tau_{l/2} = 0.21\text{ms}$$

$$x = 200 - \frac{289942.3 * (49424 - 42480) * 8 * 10^{-8})}{2} = 119.46km$$

$$\text{Error (\%)} = \frac{\text{Actual length} - \text{calculated length}}{\text{line length}} * 100 \ = \frac{120 - 119.46}{200} = 0.27\%$$

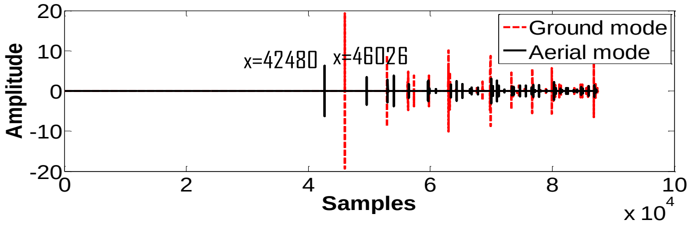

Figure11. DWT Level 1 for both Ground Mode and Aerial Mode

4. Result

Table3. Result of Different Fault Location Calculation

Fault Type / Fault Location	Single Line to Ground Fault		Double Line Fault	
	Calculated Distance	Error %	Calculated Distance	Error %
40 km	39.6 km	0.2%	39.6 km	0.2%
80 km	80.37 km	-0.18%	80.37 km	-0.18%
120 km	119.46km	0.27%	119.94 km	0.028%
160 km	160.42km	-0.21%	159.54 km	0.23%
200 km	200.3 km	-0.15%	200.3 km	-0.15%

Fault Type / Fault Location	Double Line to Ground Fault		Symmetrical Fault	
	Calculated Distance	Error %	Calculated Distance	Error %
40km	39.6km	0.2%	39.6km	0.2%
80km	80.37km	-0.18%	80.37 km	-0.18%
120km	119.94km	0.028%	119.94 km	0.028%
160km	159.54km	0.23%	159.54 km	0.23%
200km	200.3km	-0.15%	200.3 km	-0.15%

Table4. Effect of Fault Inception Angle Variation on Fault Location Calculation

Fault Distance=100Km				
Inception Fault Angle (degree)	Calculated Distance (Km)			
	Ungrounded Fault	Error %	Grounded Fault	Error %
5^0	99.55 km	0.22%	99.56 km	0.22%
20^0	99.56 km	0.22%	100.76 km	-0.38%
40^0	100.76 km	-0.38%	101.97 km	-0.98%
60^0	99.56 km	0.22%	99.56 km	0.22%
80^0	99.56 km	0.22%	99.55 km	0.22%
90^0	99.56 km	0.22%	100.76 km	-0.38%

Table5. Effect of Fault Resistance Variation on Fault Location Calculation

Fault Distance=100Km		
Fault Resistance (Ω)	Calculated Distance (km)	Error (%)
5	99.56Km	0.22%
15	99.56Km	0.22%

20	99.56Km	0.22%
25	99.56Km	0.22%
50	99.56Km	0.22%
75	99.56Km	0.22%
100	99.56Km	0.22%

5. Conclusion

This paper presents a fault locator algorithm that uses single ended recordings of the fault current signals.

- A method is proposed for fault location based on the behavior of the fault current initiated traveling waves after being decoupled into their modal components and then transformed into the time frequency domain using the DWT.
- The accuracy of the proposed method for different types of fault is satisfactory with maximum error of 0.23%.
- The fault inception angle has no significant effect on the accuracy of the algorithm with maximum error not exceeding 0.98%.
- The fault resistance has no significant effect on the accuracy of the algorithm with maximum error of 0.22%.

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