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Detection and Location of Faults in Three Phase Underground Power Cables by Wavelet Transform

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Abstract
Estimation and d termination of fault in an underground cable is very important in order to clear the fault quickly and to restore the supply with minimum interruption. This paper presents determination and location of fault in underground cables by wavelet transform as it is one of the most efficient tools for analyzing non stationary signals and it has been widely used in electrical power systems .The high voltage power cable 220KV,100 km is modeled in MAT LAB simulink using simpower system tool box. Mexican Hat wavelet transforms is used to extract the signals and the waveforms are shown .The simulation results shows that wavelet method is efficient and powerful to estimate the faults when they occurs in the underground cables.
Keywords: *Underground cable, Fault Location, Wavelet Transform, power system disturbances, Mexican hat, travelling*

1. Introduction

In the modern electrical power systems of transmission and distribution systems, underground cable is used largely in urban areas and compared to overhead lines, fewer faults occur in underground cables. However if faults occur, it's difficult to repair and locate the fault. Faults that could occur on underground cables networks are single phase-to-earth (LG) fault; and three phase-to-earths (LLLG) fault [1]. The single line to earth fault is the most common fault type and occurs most frequently. Fault detection and location based on the fault induced current or voltage travelling waves has been studied for years together. In all these techniques, the location of the fault is determined using the high frequency transients [1]. . Fault location based on the travelling waves can generally be categorized into two: single-ended and double ended. For single-ended, the current or voltage signals are measured at one end of the line and fault location relies on the analysis of these signals to detect the reflections that occur between the measuring point and the fault. For the double-ended method, the time of arrival of the first fault generated signals are measured at both ends of the lines using synchronized timers [2]

2. Wavelet Transform

It is clear that any non-stationary signal can be analyzed with the wavelet transforms. Time – frequency analysis of non-stationary signals indicates the time instants at which different frequency components of the signal come into reckoning. One direct consequence of such a treatment will be the possibility to accurately locate in time all abrupt changes in the signal and estimate their frequency components as well. It is in this very application that we are interested in here, i.e. to locate low magnitude abrupt changes in the neutral current waveforms of a power transformer. In this context, we can visualize the neutral current as a non-stationary signal whose properties change or evolve in time, when there is a fault. This is particularly so when there is a momentary short circuit between adjacent turns due to high stresses.

The wavelet transform is similar to the Fourier transform (or much more to the windowed Fourier transform) with a completely different merit function. The main difference is this: Fourier transform decomposes the signal into sines and cosines, i.e. the functions localized in Fourier space; in contrary the wavelet transform uses functions that are localized in both the real and Fourier space. Generally, the wavelet transform can be expressed by the following equation:

$$F(a,b) = \int_{-\infty}^{\infty} f(x)\varphi * (a,b)(x)dx \quad (1)$$

where the * is the complex conjugate symbol and function ψ is some function. This function can be chosen arbitrarily provided that obeys certain rules. As it is seen, the Wavelet transform is in fact an infinite set of various transforms, depending on the merit function used for its computation. This is the main reason, why we can hear the term "wavelet transforms" in very different situations and applications. There are also many ways how to sort the types of the wavelet transforms. Here we show only the division based on the wavelet orthogonality. We can use *orthogonal wavelets* for discrete wavelet transform development and *non-orthogonal wavelets* for continuous wavelet transform development. These two transforms have the following properties:

The discrete wavelet transform returns a data vector of the same length as the input is. Usually, even in this vector many data are almost zero. This corresponds to the fact that it decomposes into a set of wavelets (functions) that are orthogonal to its translations and scaling. Therefore we decompose such a signal to a same or lower number of the wavelet coefficient spectrum as is the number of signal data points. Such a wavelet spectrum is very good for signal processing and compression, for example, as we get no redundant information here. The continuous wavelet transforms in contrary returns an array one dimension larger than the input data. For a 1D data we obtain an image of the time-frequency plane. We can easily see the signal frequencies evolution during the duration of the signal and compare the spectrum with other signals spectra. As here is used the non-orthogonal set of wavelets, data are correlated highly, so big redundancy is seen here. This helps to see the results in a more humane form.

2.1 Discrete Wavelet Transform

The wavelet transform can be accomplished in two different ways depending on what information is required out of this transformation process. The first method is a continuous wavelet transform (CWT), where one obtains a surface of wavelet Coefficients, CWT(b,a), for different values of scaling 'a' and translation 'b', and the second is a Discrete Wavelet Transform (DWT), where the scale and translation are discredited, but not are independent variables of the original signal. In the CWT the variables 'a' and 'b' are continuous. DWT results in a finite number of wavelet coefficients depending upon the integer number of discretization step in scale and translation, denoted by 'm' and 'n'. If a_0 and b_0 are the segmentation step sizes for the scale and translation respectively, the scale and translation in terms of these parameters will be

$$a = a_0^m \text{ and } b = b_0 a_0^m$$

$$\psi_{b,a}(t) = 1/\sqrt{a\psi}(t - b/a$$

The above presented equation represents the mother wavelet of continuous time wavelet series. After discretization in terms of the parameters, a_0, b_0, 'm' and 'n', the mother wavelet can be written as:

$$\psi'_{b,a}(m,n) = 1/\sqrt{a_0}\Psi(t - \frac{nb_0 a_0^m}{a_0^m})$$

$$\psi'_{b,a}(m,n) = a_0^{m/2}\psi(ta_0^{-m} - nb_0)$$

After discretization, the wavelet domain coefficients are no longer represented by a simple 'a' and 'b'. Instead they are represented in terms of 'm' and 'n'. The discrete wavelet coefficients DWT (m, n) are given by equation:

$$DWT(m,n) = a_0^{m/2} \int_{-\infty}^{+\infty} f(t)\psi(ta_0^{-m} - nb_0)dt$$

The transformation is over continuous time but the wavelets are the transformation is over continuous time but the wavelets are represented in a discrete fashion. Like the CWT, these discrete wavelet coefficients represent the correlation between the original signal and wavelet for different combinations of 'm' and 'n'.

2.2 Continuous Wavelet Transform (CWT)

The continuous wavelet transform (CWT) was developed as an alternative approach to short time Fourier transform (STFT). The continuous wavelet transform is defined as follows:

$$CWT(b,a) = \int f(t)\psi_{b,a}^*(t)\, dt$$

Where * denotes complex conjugation. This equation shows how a function $f(t)$ is decomposed into a set of basic functions $\psi b, a(t)$, called the wavelet, and the variables 'a' and 'b', scale and translation, are the new dimensions after the wavelet transform.

The inverse wavelet transform of the above is given as

$$f(t) = \iint CWT(b,a)\, \psi_{b,a}(t) dbda$$

The wavelets are generated from a single basic wavelet $\psi\ (t)$, so-called mother wavelet, by scaling and translation:

$$\psi_{b,a}(t) = 1/\sqrt{a}\psi(t - b/a)$$

In above equation, 'a' is the scale factor, 'b' is the translation factor and the factor $1/\sqrt{a}$ is for energy normalization across the different scales.

There are some conditions that must be met for a function to qualify as a wavelet:

- Must be oscillatory
- Must decay quickly to zero (can only be non-zero for a short period of the wavelet function).
- Must integrate to zero (i. e., the dc frequency component is zero)

These conditions allow the wavelet transform to translate a time-domain function into a representation that is localized both in time (shift or translation) and in frequency (scale or dilation). The time-frequency is used to describe this type of multi resolution analysis. The selection of the mother wavelet depends on the application. Scaling implies that the mother wavelet is either dilated or compressed and translation implies shifting of the mother wavelet in the time domain.

The most important properties of wavelets are the admissibility and the regularity conditions and these are properties, which gave wavelets their name. It can be shown that square integrable function $\psi(t)$ satisfying the admissibility condition, $\int \frac{|\psi(\omega)|^2}{|\omega|} d\omega < +\infty$ can be used to first analyze and then reconstruct a signal without loss of information. $\psi(\omega)$ stands for the Fourier transform of ψ(t). The admissibility condition implies that the Fourier transform of $\psi(t)$ vanishes at the zero frequency, i.e. $|\psi(\omega)|^2_{\omega=0} = 0$.This means that wavelets must have a band-pass like spectrum. This is a very important observation, which has been used to build efficient wavelets transform. A zero at the frequency (m) also means that the average value of the wavelet in the time domain must be zero, $\int \psi(t) dt = 0$

As can be seen from the above derived mathematical expression, the wavelet transform of a one-dimensional function is two-dimensional; the wavelet of a two-dimensional function is four dimensional, the time-bandwidth product of the wavelet transform is the square of the input signal and for most practical applications this is not a desirable property. Therefore, one imposes some additional conditions on the wavelet functions in order to make the wavelet transform decrease quickly with decreasing scale 'a'. These are the reliability conditions and they state that the wavelet function should have some smoothness and concentration in both time and frequency domains. Regularity is complex concept.

2.3 Mother Wavelet

For practical applications, and for efficiency reasons, one prefers continuously differentiable functions with compact support as mother (prototype) wavelet (functions). However, to satisfy analytical requirements (in the continuous WT) and in general for theoretical reasons, one chooses the wavelet functions from a subspace of the space $L^1(\mathbb{R}) \cap L^2(\mathbb{R})$. This is the space

of measurable functions that are absolutely and square integrable:

$$\int_{-\infty}^{\infty} |\psi(t)|\, dt < \infty \text{ And}$$

$$\int_{-\infty}^{\infty} |\psi(t)|^2\, dt < \infty$$

Being in this space ensures that one can formulate the conditions of zero mean and square norm one:

$\int_{-\infty}^{\infty} \psi(t)\, dt = 0$ is the condition for zero mean, and

$\int_{-\infty}^{\infty} |\psi(t)|^2\, dt = 1$, is the condition for square

norm one. For ψ to be a wavelet for the continuous

wavelet transform, the mother wavelet must satisfy an admissibility criterion in order to get a stably invertible transform. For the discrete wavelet transform, one needs at least the condition that the wavelet series is a representation of the identity in the space $L^2(\mathbb{R})$. Most constructions of discrete WT

make use of the multiresolution analysis, which defines the wavelet by a scaling function. This scaling function itself is solution to a functional equation.

In most situations it is useful to restrict ψ to be a continuous function with a higher number *M* of vanishing moments, i.e. for all integer *m* < *M*

$$\int_{-\infty}^{\infty} t^m \psi(t)\, dt = 0$$

The mother wavelet is scaled (or dilated) by a factor of *a* and translated (or shifted) by a factor of *b* to give:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)$$

For the continuous WT, the pair (a, b) varies over

the full half-plane $R_+ \times R$; for the discrete WT this

pair varies over a discrete subset of it, which is also called *affine group*.These functions are often incorrectly referred to as the basis functions of the (continuous) transform. In fact, as in the continuous Fourier transform, there is no basis in the continuous wavelet transform. Time-frequency interpretation uses a subtly different formulation.

2.4 Mexican Hat Wavelet Transform

Wavelets equal to the second derivative of a Gaussian function are called Mexican Hats (MH). They were first used in computer vision to detect multi scale edges. The MH Wavelet family is given by the following equation

$$\psi(t) = (1 - 2t^2)e^{-t^2}$$

This is obtained by taking the second derivative of the Gaussian function

3. Estimation and Determination of Fault Location

By comparing the transient signals at all phases the classification of fault can be made .If the transient signal appears at only one phase then the fault is single line to ground fault The transient signals generated by the fault is no stationary and is of wide band of frequency, when fault occurs in the network, the generated transient signals travels in the network. On the arrival at a discontinuity position, the transient wave will be partly reflected and the remainder is incident to the line impedance. The transient reflected from the end of the line travels back to the fault point where another reflection and incident occur due to the discontinuity of impedance. To capture these transient signals wavelet analysis can be used. The fault location can be carried out by comparing the aerial mode wavelet coefficient to determine the time instant when the energy of the signal reaches its peak value. The distance between the fault point and the bus of the faulted branch is calculated as follows consider a three phase cable line of length X connected between bus A and bus B, with a characteristic impedance Zc and traveling wave velocity of v. If a fault occurs at a distance X_2 from bus A, this will appear as an abrupt injection at the fault point. This injection will travel like a wave "surge" along the line in both directions and will continue to bounce back and forth between fault point, and the two terminal buses until the post-fault steady state is reached. The distance to the fault point can be calculated bu using travelling wave theory. Let t_1 and t_2 corresponds to the times at which the modal signals wavelet coefficients in scale 1, show their initial peaks for signals recorder at bus A and bus B. the delay between the fault detection times at the two ends is $t_1 - t_2$ be determined. When td is determined we could obtain the fault location from bus A According to:

$$X_2 = X - (t_1 - t_2)\, V/2 \qquad (5)$$

Or from bus B

$$X_1 = X - (t_2 - t_1)\, V/2 \qquad (6)$$

$$D = \frac{Lt - v(Ta - Tb)}{2} \qquad (7)$$

The v is assumed to be 1.8182x105 miles/sec, Sampling time is 10 us and the total line length is

100km. Where X_1 and X_2 is the distance to the fault, td is the time difference between two consecutive peaks of the wavelet transform coefficients of the recorded current and v is the wave propagation velocity.

3.1 Method of simulation

Initially, 220KV KV, 100 km is designed using mat lab Simulink with 7.0 versions and response of the complete system is evaluated for different faults. Wavelet transform effectively acts as a band pass filter which extracts a band of high frequency transient current signals from the faulted cable. The total length of the cable considered is 100 km. Results from simulations are obtained with Wavelet Mexican hat wavelet .The travelling wave velocity of the signals is 1.8182×10^5 km/s, and sampling time of 10µs is used and the fault is at 10km length is considered.Fig 1 depicts the single line diagram of the simulated system which is 220KV, 100km underground power cable. In this work the fault distance has been estimated as per the equation 7, where *Lt – Total length of the cable velocity of travelling wave, Ta – time of fault detected at sending end and Tb – time of fault detected at receiving end of the cable.*

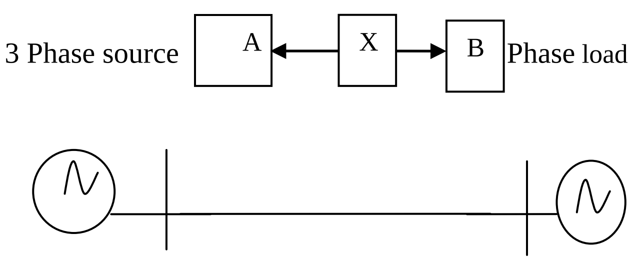

Fig.1. Three - Phase underground cable Transmission line

3.2 Algorithm of Evaluation

In this paper the authors select all the possible cases to illustrate the performance of the proposed technique under fault conditions. First LG fault is selected as simulation case and fault locations are tabulated along with % error to compare the deviation from the actual values using continuous wavelet transform Mexican hat similarly for simulation and their results are tabulated. LLLG faults selected. The results obtained by Mexican hat wavelet transform are tabulated in table 3 and Table 4. Since the impedance of the total line length is a known quantity, the distance to the fault will be obtained proportional to the imaginary component of the measured impedance. The overall flowchart of the proposed algorithm is shown in

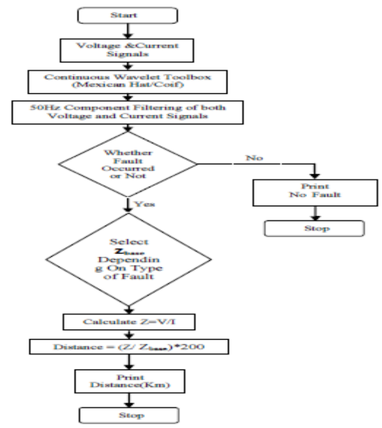

Fig.2.The overall flowchart of the proposed algorithm

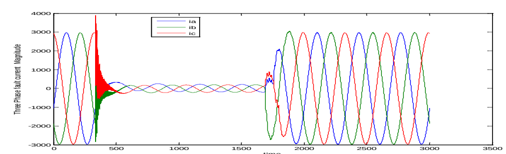

Fig.3.Three Phase current for LLLG fault at 10 km

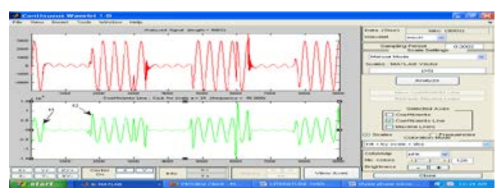

Fig.4.Three Phase current for LLLG fault at 10 km (Mexican Hat)

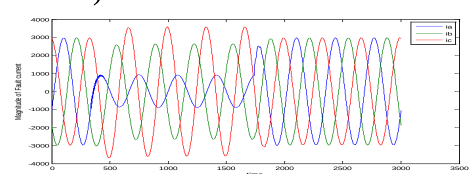

Fig.5.TSingle Phase current for LG fault at 10 km

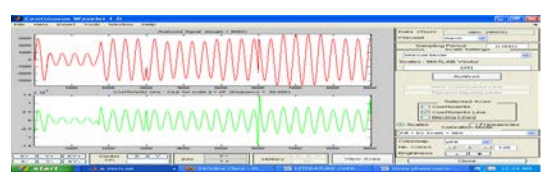

Fig.6.Single Phase current for LLG fault at 10 km (Mexican Hat)

Table1: Percentage of error by Conventional method-Lg fault

LG Fault		
Actual Distance (km)	Conventional Method (kM)	%Error in (km)
10	12.34	-23.4

Table1: Percentage of error by Mexican Hat-LG fault

LG Fault		
Actual Distance(km)	Estimated Distance(KM) Mexican Hat	%Error in km
10	10.24	-2.4

Table-3 Table1: Percentage of error by Conventional method-LLLG fault

LLLG Fault		
Actual Distance (km)	Conventional Method (km)	%Error in (km)
10	11.92	-19.2

Table4 Table1: Percentage of error by Mexican Hat – LLLG fault

LLLG Fault		
Actual Distance (km)	Estimated Distance(KM) Mexican Hat	%Error in (km)
10	10.81	-8.1

4. Conclusions

In this paper First 220kV, 100 km underground power cable is designed using mat lab Simulink with 7.0 versions and response of the complete system is evaluated for different faults. Initially the fault distance is estimated for both LG fault and LLG faults and the results are shown in table 1 and table2.In the second stage the fault distance is evaluated with Mexican hat wavelet transform and the results are given in table 3 and table4. As a result, it is found that the percentage of error given by the wavelet transform is very less and there by the accuracy of detection of fault in ug cables by using wavelet transform if more there by we can come to conclusion that the application of the discrete wavelet transform (DWT) based on traveling wave is a good choice in power system.

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