Wavelet Transform Based Algorithm for High-Impedance Faults Detection in Distribution Feeders

Mudathir Funsho Akorede
Electrical Engineering Department, University of Ilorin, Ilorin, Nigeria
E-mail: makorede@ieee.org

James Katende
Electrical & Information Engineering Department, Covenant University, Otta, Nigeria
E-mail: sempa54@yahoo.com

Abstract

This paper presents a wavelet transform based technique for high-impedance faults detection in power distribution feeders. In this study, accurate electrical models for a HIF and capacitor switching event on a power network are developed and simulated using MATLAB. The analysis of the resulted fault signals, using the Discrete Wavelet Transform (DWT) yields single-phase current and voltage in the low frequency range, which are fed to a classifier for pattern recognition. The classifier algorithm in this paper is based on a moving window approach whereby the one-cycle window of the DWT output is moved continuously by one sample. The algorithm when tested with data obtained from various computer simulations carried out in this study, produced impressive results in HIF detection and discrimination. The major contribution of this work is that it is able to determine the magnitude of the fault current, which many earlier researchers did not consider in their works.

Keywords: High Impedance Faults, Wavelet Transforms, Detail Coefficients, Pattern Classifier, Distribution Feeder

1. Introduction

High-impedance faults (HIFs) are defined as undesirable electrical contacts between a bare energized conductor and a non-conducting foreign object. Non-conductors present high impedances to current flow due to their material. A typical HIF normally occurs when a conductor physically breaks and falls on a high impedance surface such as an asphalt road, sand, grass or a tree. This type of fault is a serious threat to both human life and the environment. Another common type of HIF is when the conductor does not break, but comes in contact with non-conducting grounded objects either through a failure of the conductor mounting system, insulation failure, or inadvertent contact with some external elements such as a tree limb, vegetation, a wall, etc. (Aucoin, 1985). These faults will usually exhibit the same arcing signature as a broken conductor lying on the ground.

Majority of HIFs occur at distribution voltages of 15 kV and below, with the problem becoming worse at the lower voltages (Report, 1996). When a HIF occurs in a distribution system, it produces little or no fault, due to the fault high impedance, when compared with the load current. This makes it difficult for the conventional over-current relays, especially earth fault relays, to detect it. Another
prominent feature of HIFs is that they exhibit random behaviour with unstable and wide fluctuations in current levels. The fault signals are also rich in harmonics and have high frequency components as a result of arcing (Stoupis, et al, 2004, Aucoin, 1982).

As a matter of necessity, the nature of HIFs has been a subject of study and research since the early 1970’s (Report, 1996) with the hope of finding some characteristics in the current or voltage waveform that would make practical detection possible. This search has resulted in the development of several techniques for detection of HIFs. The most popular detection technique involves the adjustment of overcurrent protective devices (Detection, 1989), but this design has led into several unexpected service interruptions since the electric current level resulting from HIFs cannot be differentiated from other non-fault events in the power system. A type of ground relay was developed for detecting abnormal ground currents (Carr, 1981). The deficiency of this, however, is that it is not reliable for heavily unbalanced loads and multi-grounded systems.

Recently, the concept of intelligent computing was applied to detection of HIFs. In particular, artificial neural network technology has been applied to HIF detection through the Electromagnetic Transient Programme (EMTP) generated signals (Ebron, 1990). Also, based on changes in harmonic currents of feeders, several algorithms were suggested. Among these are the third harmonic current method (Uriarte, 2003), the fractal technique (Mamishev, 1999), nearest neighbour rule approach (Lai, 2006), and decision tree-based method (Sheng, 2004). Of course each of these techniques could improve fault detection, but then, each has its drawbacks. However, from a signal processing point of view, HIF generated signals are found to present time-varying characteristics. On the basis of this, the signal processing technique using the wavelet transform approach (Huang, 1999, Kim, 2001) can be employed in detecting HIFs. This is the technique employed in this study since it is more efficient in monitoring time-varying fault signals. Further, the algorithm developed in this study is capable to determine the magnitude of the fault current, which was not considered in many earlier works.

The structure of the rest part of this paper is presented as follows: Section 2 gives the theoretical background of wavelet transforms as a signal analysis tool, especially when compared with other existing tools; while Section 3 is dedicated to modelling and simulations of high impedance fault and capacitor switching event on the 11 kV case study power distribution feeder. The implementation of wavelet analysis on the signals generated from the simulations is carried out in Section 4 for pattern recognition, and Section 5 draws the conclusion of the study.

2. Wavelet Transform and Multi-Resolution Analysis
The wavelet transform is a recently developed mathematical tool that provides a non-uniform division of data or signal, into different frequency components, and then studies each component with a resolution matched to its scale (Huang, 1999). It is often used in the analysis of transient signals because of its ability to extract both time and frequency information simultaneously, from such signals. The comparison of the WT with the Fourier transforms (FT) and why it is preferred to the FT has been documented in (Polikar, 1994).

Multi-resolution Analysis (MRA) is an alternative approach used to analyse signals to overcome the time and frequency resolution problems, since these problems persist regardless of the transform employed. MRA analyses the signal at different frequencies with different resolutions. It does not resolve every spectral component of the signal equally. It is designed to produce good time resolution and poor frequency resolution at high frequencies and vice versa. The rationale behind this is that the signals that are encountered in practical applications have high frequency components for short durations and low frequency components for long durations.

In DWT, a time scale representation of a digital signal is obtained using digital filtering techniques, developed by Mallat in 1988 (Wavelet, 2004). DWT uses filters of different cut-off frequencies to analyse the signal at different scales. The signal is passed through a series of high pass filters to analyse the high frequencies, and it is equally passed through a series of low pass filters to
examine the low frequencies. Filtering a signal is synonymous with the mathematical operation of convolution of the signal with the impulse of the filter (Kim, 2001) as presented in eqn (1).

\[ x[n] \ast h[n] = \sum_{k=-\infty}^{\infty} x[k] \cdot h[n-k] \quad (1) \]

where \( x[n] \) is a discrete time function, \( n \) is an integer and \( h[n] \) is the low pass filter impulse.

Really the most important part of many signals is the low frequency content. It is what gives the signal its identity. The high frequency content, on the other hand, only impacts flavour. This is what brings into wavelet analysis, *approximations* and *details*.

*Approximations* are the high-scale, low frequency components of the signal, while *details* are the low-scale, high frequency components. Approximations (also known as the *scaling coefficients*) are computed by taking the inner products of the function \( f(t) \), the signal, with the scaling basis \( \phi_{j,k} \), achieved with eqn (2).

\[
A_{j,k} = \left< f(t), \phi_{j,k}(t) \right> = \int_{-\infty}^{\infty} f(t) \phi_{j,k}(t) \, dt 
\quad (2)
\]

\[
D_{j,k} = \left< f(t), \psi_{j,k}(t) \right> = \int_{-\infty}^{\infty} f(t) \psi_{j,k}(t) \, dt 
\quad (3)
\]

This is obtained by passing the original signal through a low pass filter while *details* (also known as the *wavelet coefficients*) are obtained by passing the signal through a high pass filter. This operation is computed mathematically by taking the inner products of the function \( f(t) \) with the wavelet basis as in eqn (3).

Where the scale function \( \phi_{j,k}(t) \) and the wavelet function \( \psi_{j,k}(t) \) are determined by the particular mother wavelet \( \psi_{a,b} \) selected (Lai, 2006). Unfortunately, performing the above operation on a real digital signal leads to twice the data one started with. Correcting this problem created by the filtering operations, the original signal must be down sampled. *Downsampling* a signal is synonymous with reducing the sampling rate, or removing some of the samples of the signal.

As mentioned earlier, the DWT analyses signals at different frequency bands with different resolutions by decomposing the signal into coarse approximation and detail information. DWT uses *scaling functions* and *wavelet functions* in achieving this. These two sets of functions are associated with low pass and high pass filters, respectively. The original signal \( x[n] \) is first passed through a half band high pass filter \( g[n] \) and a low pass filter \( h[n] \). As said previously, after the filtering exercise, half of the samples would be eliminated. The signal can therefore be sub sampled by two. This constitutes one level of decomposition and can be expressed, mathematically as follows:

\[
D_j[n] = \sum_k x[n] \cdot g[2n-k] 
\quad (4)
\]

\[
A_j[n] = \sum_k x[n] \cdot h[2n-k] 
\quad (5)
\]

where \( D_j \) is the output from the high-pass filter called Detail and \( A_j \) is the output from the low-pass filter called Approximation, at resolution \( j \), \( j=1, 2, \ldots, J \); \( k=1, 2, \ldots, K \), where \( K \) is the length of the filter vector, after downsampling by two (Vetterli, 1995). The signal decomposition process can be done iteratively with successive approximations being decomposed in turn, so that one signal is broken down into many lower-resolution components. Fig. 1 (Akorode, 2009) illustrates a multiple level decomposition procedure for a signal \( x[n] \).
3.1. System Model

The system studied in this paper is 30 MVA, 11 kV radial distribution network. It comprises four distribution feeders of different lengths and segment impedances. Each feeder carries loads behind its 11/0.415 kV star/star step-down transformer. The feeder under study is feeder F4 in Fig. 2, and it is 10 km in length. Because the selected feeder consists of small industrial, commercial and residential loads, the loads carried by each of these transformers are of different types. The industrial loads are composite loads with induction motors forming the bulk of these loads. Commercial and residential loads consist largely of lighting, heating and cooling, which unlike industrial loads, are independent of frequency and consume negligibly small reactive power.

The 33/11 kV substation transformer is modelled as an ideal three-phase voltage source. The voltage magnitude on the feeder is equal to the transformer’s secondary side voltage; the substation transformer impedance is taken as the source impedance. The one-line diagram representing the chosen feeder is shown in Fig. 2. However, the shunt capacitance can be neglected entirely without much loss of accuracy since the
distribution feeder under study is less than 80 km in length and/or the line voltage is not greater than 69 kV (Saadat, 2002). Therefore, a line can be modelled with only series R-X losses with the propagation time neglected. The inductance per line segment is wholly a function of the conductor size and the spacing between the conductors (Uriarte, 2003). The spacing $d_{\text{mean}}$ is taken as the geometric-mean separation of the three phase conductors, and given by

$$d_{\text{mean}} = \sqrt[3]{d_{12}d_{23}d_{31}} \quad \text{m}$$

(6)

where $d_{ij}$ is the separation (in metres) between conductors $i$ and $j$.

Taking $d_{12} = d_{23} = 0.71\text{m}$ and $d_{13} = 1.42\text{m}$ (National, nd). Substituting these values in eqn (6) yields $d_{\text{mean}}$ to be 0.9m.

Having known the mean conductor separation $d_{\text{mean}}$, the inductance per phase per metre could be obtained with the expression in eqn (7).

$$L = \frac{\mu_0}{8\pi} \left\{1 + 4 \ln \left( \frac{d_{\text{mean}}}{r} \right) \right\} \quad H / m$$

(7)

Where $r$ is the radius of each phase conductor, found to be 9.4 mm (National, nd). Therefore, the per-kilometre inductance of the line of length 10 km of a conductor, taking $\mu_0 = 4\pi \times 10^{-7}$ and using eqn (7) gives:

$$L = 0.962 \quad H / km$$

The resistance per-phase is 0.133 $\Omega$ per kilometre as obtained (Saadat, 2002) for the modelled conductor size. Consequently, the reactance per-phase can be found in henry per kilometre using eqn (8).

$$X_L = 2\pi fL$$

$$X_L = 2\times\pi\times50\times0.962 = 0.3 H / km$$

It therefore, follows that the per kilometre impedance of the line as calculated is 0.133 + j 0.3 $\Omega$.

The linear transformer block model present in MATLAB consists of three coupled windings wound on the same core. The model takes into consideration the winding resistances ($R_1$, $R_2$, and $R_3$), the leakage inductance ($L_1$, $L_2$, and $L_3$) and the magnetizing characteristics of the core, modelled by a linear ($R_m$, $L_m$) branch. What the authors did was to set the entry of the third winding to zero in the MATLAB dialog box to obtain a transformer model with two windings and to feed in the values of the appropriate parameters.

Loads on a distribution feeder can be modelled as: constant real and reactive power (constant PQ) load, constant current load, constant impedance load and any combination of the three (Kersting, 2002). Because different types of loads present different characteristics during steady state operations, their response during a fault may be different from their steady state characteristics. However, the purpose of modelling in this study is to generate fault current waveforms. Further, all types of loads are modelled as constant impedance loads since only a constant impedance load model is available in Power System Blockset. The three types of loads considered in this study are all point loads.

The capacitor-switching model selected from (Sochulikova, 1999), is modified and implemented using MATLAB. The purpose of this model is to demonstrate the transient effect of
capacitor switching on a distribution feeder. In this study, three single-phase capacitors were connected to form a delta-connected capacitor bank. The network system is modelled as a generator bus and load bus connected by a short line. Since the short line is connected to a switch, a T model is used rather than a π model. Assuming a 3-phase balanced system, a single line diagram of the model is shown in Fig. 3, the parameters of which are presented in Table 1. The voltage across the customer’s load (bus 2) is monitored and shown in Fig. 6.

Table 1: The Circuit Elements Parameters

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line</td>
<td>( L_s = 0.1 \text{ mH} )</td>
<td>( \omega = 2\pi 50 \text{ Hz} )</td>
</tr>
<tr>
<td>Load</td>
<td>( R_d = 0.9 \Omega )</td>
<td>( V_s = 415 \text{ V} )</td>
</tr>
<tr>
<td>Load</td>
<td>( R = 400 \Omega )</td>
<td>( L_d = 45 \text{ mH} )</td>
</tr>
<tr>
<td>Capacitor ( a )</td>
<td>( C = 4.2 \mu\text{F} )</td>
<td>( L = 0.1 \text{ mH} )</td>
</tr>
<tr>
<td></td>
<td>( a = 0.6 )</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Capacitor Switching Equivalent Circuit.

where, in Fig. 3, \( 0 \leq a \leq 1 \); \( a \) is the capacitor position on the system.

3.2. HIF Model

The HIF modelled in this study, depicted in Fig. 4, is that of a fallen energized conductor on to a high impedance ground. The model presented here is based on arcing in sandy soil. The two resistances of which stand for the fault resistance at the fault point. The asymmetric characteristic of HIF fault current could be obtained when \( R_1 \) and \( R_2 \) are set at different values. In the event that the phase voltage is higher than \( S_1 \), the current flows to the ground, and vice versa if less than \( S_2 \).
3.3. Simulation Results

Case I – Fault Case
Using the Power System Blockset of MATLAB, a high impedance fault caused by a broken, downed conductor on the Blue phase of feeder F4 is simulated at point A; 6 km away from the sub station, as shown in Fig. 2. The fault was initiated at the 200th ms and allowed to last for 256 ms i.e. to make two complete cycles after fault inception before being cleared by isolating the faulted phase. The waveform of the fault current recorded at the relaying point is as presented in Fig. 5. The base value for the current is taken as 520 A. Looking at Fig. 6, it is obvious that most drastic fluctuation can be noticed at 200th milli- seconds, i.e. where HIF occurs.
Case II – Non-Fault Case (Normal Operation)
In order to demonstrate a non-fault transient whose effects in power systems, looks like that of HIFs, the circuit in Fig. 3; the capacitor of which was energised at the 150th ms, is simulated using MATLAB and its resulting voltage waveform shown in Fig. 6, in which the base voltage is taken as 1000 V. Further analysis and discussion on this are carried out in the next section.

4. Detection Procedure
4.1. Implementation of Discrete Wavelet Transform
The waveforms of voltage and current generated in the simulations carried out in Section 3 are transferred to discrete wavelet transform toolbox of MATLAB to analyse the frequency characteristics of the signals. Performing one-stage decomposition on these signals, using db4 wavelet, yields level 1 detail and approximation coefficients plotted. The resulting D1 coefficients are thereafter plotted against time as shown in Figs. 7 (a) and (b) respectively.
4.2. Pattern Recognition

Taking the sampling frequency to be 6 kHz, to reduce computational time; and summat ing the D1 coefficients – the output of DWT – presented in Fig. 7, over a one-cycle window gives the graphs obtained in Fig. 8. The whole process is based on a moving window approach whereby the one-cycle window is moved continuously by one sample (Huang, 1999).

\[ \text{Sum}_D1 = \text{absolute sum value of the detailed output (D1 components) for one cycle period.} \]

The criterion for the protection relay to initiate a trip signal is that \( \text{Sum}_D1 \) must stay above a threshold level \( q \) continuously for \( D \) samples after fault inception as presented in the flow chart of Fig. 9; where \( i \)

\[ \text{is a counter, which indicates the sample number that contains the information about the presence of HIF. Extensive studies have revealed that, to maintain the relay stability for normal operations, the optimal setting for } q \text{ and } D \text{ are respectively 0.1 and 240 (Huang, 1999).} \]
The parameter 240 corresponds to a two-cycle period at power frequency (50 Hz). Based upon this criterion, the HIF detection algorithm flow chart presented in Fig. 9 is developed for accurate and effective detection of HIFs. The criterion for a high impedance fault is that Sum_D must be greater than or equal to q for at least, two cycles consecutively.

5. Conclusion
This paper has presented a wavelet transform based technique for detecting high impedance faults (HIFs) in electric distribution feeders. The attribute of wavelet transform has greatly facilitated detection of signal features and has been very useful in characterising the source of disturbance in power systems, as applied to this study. The study involved computer simulations of HIF models using the Power System Blockset and Simulink of MATLAB; discrete wavelet transforms of the resulted signals from the simulations, and pattern classification of these signals. The difference in frequency characteristics and the duration of the transient event between HIFs and normal non-fault events, such as capacitor and line switchings, etc., can be recognised by the developed classifier. The algorithm, when tested with the data generated from various computer simulations carried out in this study, provided satisfactory results in both detection and discrimination of HIFs; this is very crucial to prevent false trips. The additional feature of the developed algorithm in the study is its capability of producing the magnitude of the fault current.

Figure: 9 HIF Detection Flow Chart
References


