Identification and Classification of High Impedance Faults using Wavelet Multiresolution Analysis

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Abstract: This paper presents an application of Wavelet multiresolution analysis (MRA) for the identification and classification of high impedance faults. Daubechies eight (D-8) Wavelet transforms of three phase currents on transmission lines are used for the analysis. The peak absolute values, the mean of the peak absolute values and summation of the 3rd level output of MRA detail signals of current in each phase extracted from the original signals are used as the criterion for the analysis. Different types of transients are considered based on this criterion for identification purpose and a threshold level is determined for peak absolute value and mean of the peak absolute values to differentiate a high impedance fault from other types of transients. Similarly, different types of high impedance faults are considered for classification purpose and a simple characteristic relationship is found for each type of fault using the summation of values of 3rd level wavelet output. The effects of fault distance and fault inception angle are also examined. Extensive simulations are carried out on a 400kV, 300km long line and simulation results show that the method is simple, effective and robust for the analysis of high impedance faults.

Keywords: Wavelet transforms, Multiresolution analysis, EMTP, High impedance fault.

I. INTRODUCTION

The performance of a power system is frequently affected by faults, which give rise to disruption in power flow. Usually digital fault recorders placed at the two buses connecting the transmission line monitor the line voltages and currents and record disturbance incidents as digital fault records. These records are transferred to a central location for a detailed study and analysis.

High impedance faults on transmission lines draw a very low current and hence, it may not be cleared by the system, hence, it should be detected and classified as quickly as possible [1].

Many techniques are developed to improve the detection of high impedance faults [2]. They can be broadly classified as: time domain and frequency domain techniques. Conventional overcurrent protection systems. As the faults of this type are also capable of causing damage to

In time domain algorithms, ratio ground relay is used which depends on the ratio of zero sequence current to positive sequence current [3]. Energy variations in the phase current for a particular frequency or frequency band is used in these algorithms with time as a parameter to distinguish high impedance faults from the normal system events [4]. The arc phenomenon of intermitent arc re-ignition and extinction in high impedance faults are used in randomness algorithm [5]. In frequency domain, Fourier transform is used for high impedance fault identification and classification where odd harmonics or non-harmonics of phase current are compared [6]. Combining all these algorithms, comprehensive expert systems [7] were recommended, as these algorithms were not fully successful.

The problem of time localization of FFT can be solved to a large extent by using Short time Fourier Transform (STFT) which windows the input signal. But it does not provide multiple resolutions in time and frequency as the window size is fixed. The wavelet multiresolution analysis (MRA) is a new and powerful method of signal analysis well suited to fault generated signals [8]. The windowing of Wavelet transform is adjusted automatically for low and high frequencies i.e. it uses short time intervals for high frequency components and long intervals for low frequency components and thereby each frequency component gets treated in the same manner without any reinterpretation of the results. Wavelet analysis is based on the decomposition of a signal into 'Scales' using wavelet prototype function called ‘mother wavelet’. The temporal analysis is performed with a contracted, high frequency version of the ‘mother wavelet’, while the frequency analysis is performed with a dilated, low frequency version of the ‘mother wavelet’.

This work presents an application of Wavelet Multiresolution analysis for the identification, classification and location of high impedance faults. For the identification purpose, it depends on the Threshold value for comparison with lightning overvoltage or normal switching events similar to high impedance faults. For classification between various interphase short-circuits and ground faults involving high impedance faults, a simple characteristic relationship is obtained with the summation of 3rd level output of MRA signal of the three phase currents. For location of high impedance faults, an algorithm is established involving cubical interpolation technique i.e. a numerical technique is used along with the summation of 3rd level output of MRA signal of the three phase currents. The algorithm is independent of the effects of fault inception angle and fault distance. Simulation results indicate that the method is very effective and promising in identifying, classifying and locating high impedance faults.

II. Wavelet analysis and MRA

A. Wavelets:

Wavelets are functions that satisfy the requirements of both time and frequency localization. The necessary and sufficient condition for wavelets is that it must be oscillatory, must decay quickly to zero and must have an average value of zero. In addition, for the discrete Wavelet transform considered here, the Wavelets are orthogonal to each other.
Fourier basis functions are localized in frequency but not in time while Wavelets are localized in both time (through translation) and frequency (through dilation). Wavelets can provide multiple resolutions in both time and frequency unlike short time Fourier transform (STFT). As compared to the traditional Fourier analysis, the signal can be accurately reproduced with the Wavelet analysis using relatively small number of components [9]. Moreover, many classes of functions can be represented by Wavelets in a more compact way. The analyzing wavelets are called the "mother wavelets" and its dilated and translated versions are called the "daughter wavelets". The “mother wavelet" determines the shape of the components of the decomposed signals. A particular type of Wavelet is selected depending on the particular type of application. Similar to Fourier transform, it has a digitally implementable counterpart, the discrete Wavelet transform (DWT). The generated waveforms are analyzed with Wavelet multiresolution analysis (MRA) to extract sub-band information from the simulated transients. Daubechies Eight (D-8) wavelet is used in this work for the analysis as it is localized i.e. compactly supported in time and hence is good for short and fast transient analysis [10]. In this paper, Wavelet co-efficients of the signal are derived using matrix equations [11] based on decomposition and reconstruction of a discrete signal using Mallat’s algorithm [9].

B. Dilation and Wavelet Equation [12]
The Wavelet transform involves two fundamental equations: (i) Dilation equation and (ii) Wavelet equation. The Dilation equation links a scaling function $\phi(x)$ and its translates $\phi(2x)$. This is given by:

$$\phi(x) = \sum_{k=0}^{L-1} c_k \phi(2x-k)$$

where L is an even number. Corresponding Wavelet equation is given by:

$$W(x) = \sum_{k=0}^{L-1} (-1)^k c_k \phi(2x+k-(L-1))$$

The numerical values of $c_k$ for D8 Wavelet considered in this work are taken from the available literature [12,13].

If the input signal be denoted by $g(x)$. Then the decomposed signal is given by

$$g(x) = a_0 \phi(x) + a_1 W(2x) + \sum_{i=2}^{N-1} a_i W[2x-(i-2)] + \sum_{j=4}^{N} a_j W[2x-(i-4)] + \ldots + \sum_{i=2^{N-1}}^{2^{N-1}} a_i W[2^{N-1}x-(i-2^{N-1})]$$

where $a_i$ represent Wavelet co-efficients.

C. Calculation of Wavelet Co-efficients
The coefficients $a_i$ are calculated using Mallat’s algorithm [9]. The calculation of $a_i$ requires the transformation matrices $L_i$ and $H_i$ for $i=1,2,\ldots,N$ which are of dimensions $(2^i \times 2)$, where $L$ and $H$ are formed from low-pass and high-pass D8 filter coefficients.

The wavelet coefficients are calculated using $L_i$ and $H_i$ as follows:

If we define $A_k = H_k \left( \prod_{i=k+1}^{N} L_i \right)$, where $k=0,1,2,\ldots,N-1$ and with $H_N=A_N$ and $H_0=1$, then

$$G = \begin{bmatrix} A_0 \\ A_1 \\ \vdots \\ A_N \end{bmatrix}$$

is a $(2N \times 2N)$ dimension matrix. If $(2^i)$ diagonal matrix D be defined as $D(1,1)=2^{-N}$, $D(2,2)=2^{-N}$, $D(i,j)=2^{-(N+i-1)}$ where $i=3,4,\ldots,N+1$ and $j=2^{i-2}+1,2^{i-2}+2,\ldots,2^{i-2}$ and if $a=\text{a vector of wavelet coefficients then}, a=DGy$

where $y$ is the $(2N \times 1)$ vector of the signal.

D. Signal Reconstruction and Individual Signal levels
If a signal of length $2^N$ is decomposed to $(N+1)$ levels and if the levels are denoted by $(y_1, y_2, y_3, \ldots, y_{N+1})$, then

$$y_1 = (A_0) a(1)$$

$$y_2 = (A_1) a(2)$$

$$y_3 = (A_2) \begin{bmatrix} a(3) \\ a(4) \end{bmatrix}$$

$$\vdots$$

$$y_{N+1} = (A_N) \begin{bmatrix} a(2N-1) + 1 \\ \vdots \\ a(2^N) \end{bmatrix}$$

The original signal is reconstructed as:

$$Y_r = \sum_{k=1}^{N+1} y_k$$

III. Simulation Details
The fault identification Algorithm is applied to a 200km, 230kV transmission line fed from both the ends. The model power system [14] is as shown in Fig.1.

The base values of the voltage and the power in the system are taken as 230kV and 100MVA.
The fault resistance recorded at the generator end, considered for the analysis, corresponds to a X/R ratio of 22.45. The current signals are sampled every 80 µs to 1800 at regular intervals of 180. Through an exhaustive experimentation, the parameter found to be most suitable for the identification is the peak absolute value of these three peak values of phase currents. Since, the value of 3rd level output for the three phase currents and the required to distinguish the faulted and the healthy phases. In case of a fault, the signatures of all the three phases are taken as Rf = 500Ω for the analysis using Wavelet transform. The fault resistance range of 00 to 1800 at regular intervals of 180. All the data used in the analysis are normalized to p.u. values so that the algorithm developed becomes general and can be applied to systems at different voltage levels without any modification.

IV. High Impedance Fault Identification

In case of a fault, the signatures of all the three phases are required to distinguish the faulted and the healthy phases. Through an exhaustive experimentation, the parameter found to be most suitable for the identification is the peak absolute value of 3rd level output for the three phase currents and the mean of these three peak values of phase currents. Since, the simulation results show that inception angle has considerable effect on the current signal and therefore on the Wavelet transform output and as the waves are periodic in nature, hence the variation of the parameters for identification of faults with respect to fault inception angle are studied in the range of 0° to 180° at regular intervals of 18°.

Further, if r1 = |Aa/Ab|; r2 = |Aa/Ad|; r3 = |Aa/Ac|;
and Amean = (|Aa| + |Ab| + |Ac|)/3;
Also, S = (|Aa| + |Ab| + |Ac|)/3;

The frequency of the system is taken to be 50Hz. The transmission line parameters are: (A) Zero sequence parameters:
R0 = 0.4054 Ω/km, X0 = 2.8125 mH/km, C0 = 0.0044 μF/km;
(B) Positive sequence parameters:
R1 = 0.07375 Ω/km, X1 = 1.0794 mH/km, C1 = 0.0075 μF/km;
(C) Negative sequence parameters:
Rc = 0.07375 Ω/km, Xc = 1.0794 mH/km, Cc = 0.0075 μF/km;

Amplitude ratio between source voltages at P and Q = 1.0.
Load angle between sources = 20°, Voltage angle of ‘P’ is leading with respect to that of ‘Q’.

The total impedance of the generator and the transformer together on both sides are taken as (0.2+j4.49)Ω which corresponds to a X/R ratio of 22.45. The current signals recorded at the generator end, considered for the analysis are generated by simulating the system on EMTP. The generated time domain signals are sampled every 80µS and then used for the analysis using Wavelet transform. The fault resistance is taken as Rf = 500Ω.

Fig.1. 230kV transmission line system used for the simulation studies

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and Amean = (|Aa| + |Ab| + |Ac|)/3;
Also, S = (|Aa| + |Ab| + |Ac|)/3;

These parameters are used for identification of different types of disturbances.

Simulation results indicate that if any one value of (r1, r2 or r3) is equal to or less than a threshold value rth, then either a high impedance fault or switching event is said to have occurred. However, if any one value of (r1, r2 or r3) is more than rth, then it is a lightning transient. For finding out the threshold value of rth, simulations are carried out considering lightning transient, high impedance L-G, L-L-L, L-L-G, L-L faults and switching phenomena.

The variation of the ratio r1 with inception angle for lightning strike on phase ‘a’ at 195km from the sending end, high impedance L-G, L-L-L, L-L-G, L-L faults involving phase ‘a’ occurring at a distance of 5km from the sending end and switching phenomena is as shown in Fig 2. As can be seen from Fig 2, the ratio r1 for the lightning transient is very high as compared to high impedance faults or switching phenomena. Hence, a threshold level for the ratio r1 can be selected so that proper discrimination of lightning transient from high impedance faults and switching phenomena can be done.

Fig.2. Variation of r1 with Inception angle (αf) for high
impedance faults involving phase ‘a’ at 5 km (1) L-G fault, (2) L-L-L fault, (3) L-L-G fault, (4) L-L fault, and (5) Lightning strike at 195km, (6) Switching phenomena.

Considering the effect of fault distance also into account, a value of rth is selected as 200 for the system under consideration. This value is suitable as the maximum value of the ratio r1 involving the affected phase for high impedance faults at 5km and switching phenomena lie much below 200 (28.96 for high impedance L-G fault at 5 km and 4.62 for switching event) while the minimum value of the ratio r1 for lightning transient at 195km lies above 200 (600 for lightning strike at 195km). Once it is identified that the disturbance is either a high impedance fault or switching phenomena, the next step is to compare the value of Amean for different types of high.
impedance faults and switching phenomena as shown in Fig.3.

As can be seen from Fig.3, the value of $A_{\text{mean}}$ at a distance of 195km for high impedance L-L-L, L-L, L-L-G and L-G faults are less as compared to switching phenomena. Hence, a threshold level for $A_{\text{mean}}$ can be selected so that a discrimination of switching phenomena from different types of high impedance faults can be done.

The value of $A_{\text{th}}$ is selected as 1.0 for the system under consideration. In this case, $A_{\text{mean}}$ values at different inception angles for different types of high impedance faults at 195km i.e. at the remote end are always much less than 1.0. Hence, choosing a threshold value of $A_{\text{th}}=1.0$, all types of high impedance faults can be discriminated from the switching event.

V. High Impedance Fault Classification

Through an exhaustive experimentation, the parameter identified for the classification is the summation of 3rd level output for the three phase currents.

If $S_a=$Summation of 3rd level values for current in phase ‘a’,

$S_b=$Summation of 3rd level values for current in phase ‘b’ and

$S_c=$Summation of 3rd level values for current in phase ‘c’.

The flow chart for the fault classification algorithm is shown in Fig.4.

The simulation results are shown in Figs.5 –12.

Fig.5 shows the plot for a high impedance L-L-L fault at 5km, Fig.6 shows the plot for a high impedance L-L-L fault at 195km. In this case the magnitude of all the summation values $S_a$, $S_b$ and $S_c$ are comparable to each other and $S_a+S_b+S_c \approx 0$.

The simulation results shown in Fig. 7 and Fig.8 for a high impedance L-L fault, suggest that $S_a + S_b = 0$ with $|S_c| << |S_a|$ or $|S_b|$ so that $S_a+S_b+S_c \approx 0$. Hence, as per the algorithm described above, it indicates a high impedance L-L fault involving phases ‘a’, ‘b’, which is same as assumed in the study for the system.

Fig.7 shows the plot for a high impedance L-L fault at 5km and Fig.8 shows the same for a high impedance L-L fault at 195km.
If $S_a + S_b = 0$, then it is a fault involving a and b phase.
If $S_a + S_c = 0$, then it is a fault involving a and c phase.
If $S_b + S_c = 0$, then it is a fault involving b and c phase.

If $S_a + S_b + S_c \neq 0$, then it is either a high impedance L-G or L-L-G fault.

The simulation results shown in Fig.9 and Fig.10 for a high impedance L-G fault, suggest that $|S_b| = |S_c|$ with $|S_a| >> |S_b|$ or $|S_c|$ so that $S_a + S_b + S_c \neq 0$. Hence, it indicates a high impedance L-G fault involving phases ‘a’ and ground, which is same as assumed in the study for the system.

While Fig.9 shows the plot for a high impedance L-G fault at 5km, Fig.10 shows the same for a high impedance L-G fault at 195km.

If $S_{\min} = \min (|S_a|, |S_b|, |S_c|)$, then

If $S_{\min} = |S_b| \& << |S_a|$ or $|S_c|$, then it is a high impedance L-L-G fault involving phases a and b.
If $S_{\min} = |S_b| \& << |S_a|$ or $|S_c|$, then it is a high impedance L-L-G fault involving phases a and c.
If $S_{\min} = |S_a| \& << |S_b|$ or $|S_c|$, then it is a high impedance L-L-G fault involving phases b and c.

The simulation results shown in Fig.11 and Fig.12 for a high impedance L-L-G fault, suggest that $|S_a| \neq |S_b| \neq |S_c|$ with $|S_c| << |S_b|$ or $|S_b|$ so that $S_a + S_b + S_c \neq 0$. Hence, it indicates a high impedance L-L-G fault involving phases ‘a’, ‘b’ and ground, which is same as assumed in the study for the system.

While Fig.11 shows the plot for a high impedance L-L-G fault at 5km, Fig.12 shows the same for a high impedance L-L-G fault at 195km.
The proposed method is a better and superior method when compared with some of the existing methods as outlined below in Table -I:

<table>
<thead>
<tr>
<th>Ref. No.</th>
<th>Objective</th>
<th>Procedure and shortcomings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Identification</td>
<td>Dependent on counting of burst pulses of intermittent arc phenomena which is very irregular in nature and confined only to identification of faults.</td>
</tr>
<tr>
<td>10</td>
<td>Identification and Classification</td>
<td>Valid for cable faults. Simulations carried out only for inception angles of 0°, 45° and 90° for a system fed from one end only. Duration of the analysis is 51.2 ms with 2048 sample points.</td>
</tr>
<tr>
<td>15</td>
<td>Identification and Classification</td>
<td>Sharp variation values of three phase detail signals are used for identification of faults while relative ratios of sum of the first three sharp variation values of three phase detail signals are used for the classification of faults. It also requires the calculation of zero-sequence component of current for classification purpose. Total time period of the analysis is 0.25s.</td>
</tr>
<tr>
<td>16</td>
<td>Classification</td>
<td>Total time period of the analysis is 0.25s and valid for fault impedance as high as 100Ω.</td>
</tr>
<tr>
<td>Present</td>
<td>Identification</td>
<td>Total duration of the analysis is 0.04s with only 512 sample points. It is valid for fault impedance as high as 500Ω and for any method and inception angles ranging from 0° to 180°. Only summation of 3rd level wavelet transform output is required for the analysis and does not depend on any burst pulses.</td>
</tr>
</tbody>
</table>

VII. CONCLUSIONS

In this paper an application of Wavelet MRA theory has been proposed for the identification and classification of high impedance faults on a power transmission line. The property of multiresolution in time and frequency using Wavelets is found very effective for the scheme. The proposed scheme is generalized in nature and is independent of fault location, fault inception angle and fault impedance and is also suitable for transmission lines at any voltage levels.

VIII. REFERENCES


Fig.12. Effect of inception angle (αF) for high impedance L-L-G fault involving phases ‘a’, ‘b’ and ground at 195km.