

Double Circuit Transmission Line Fault Distance Location Using Wavelet Transform and WMM Technique

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Abstract: Distance relays used for protection of transmission lines have problems of under-reach, over-reach and mal-operation due to high impedance faults. Further the problem is compounded when distance relays are used for protection of double circuit transmission lines due to effects of zero sequence mutual coupling. Different types of faults on protected transmission line should be located correctly. This paper presents wavelet analysis and Wavelet Modulus Maxima techniques for fault distance location for all the ten types of faults (3 LG, 3LLG, 3LL, 1LLL) in both circuits of a double circuit transmission line fed from sources at both the end. This technique uses only end of data and accurate fault distance location is achieved after one cycle from the inception of fault. The analysis for fast identification of fault is evaluated based on the representation of the travelling waves through wavelet modulus maxima. The present criterion can detect the instant of fault, location of fault and kind of fault. MATLAB/ Simulink software was used to test the proposed approach. Various fault conditions were simulated by varying fault type, fault resistance, fault location and fault inception angle, on a given power system model. The simulation results demonstrate the validity of the proposed approach of faulted phase selection.

Keywords: Wavelet Transform, Double Circuit fault Distance location; Mutual Coupling; Transmission line; WMM; traveling waves

1. Introduction

Fault location estimation is a desirable feature in any protective relaying scheme for transmission lines. By accurately locating a fault, the amount of time spent by line repair crews in searching for the fault can be kept minimum. Location the fault on the transmission line accelerates line restoration & maintains system stability different types of algorithms for finding fault location on EHV/UHV transmission lines have been developed and proposed over the years. These algorithms may be broadly classified as (i) those compute power frequency current and voltage phasors to find the impedance and hence fault location [1, 2], (ii) those using differential equations of line and calculating line parameters [3]. Most of the reactance-based schemes suffer from under reach due to high impedance fault and over reach due to DC offset current. These are required to minimize errors due to the remote end in feed and load flow variations.

Traveling wave algorithms are based on the fact that an abrupt change of voltage and current at the fault point results in transient waves which propagate along the transmission line in both directions away from the fault point close to the light velocity. These high frequency waves carry useful information associated to the relevant fault location. Information refers to the sequence of reflection transmission

Phenomena and can be useful for rapid identifying the fault location [4-7]. In traveling wave-based method, the fault location can be found by comparing the arrival time of the transient signals at a single end or multi-ends of the line terminals. Although the single-ended fault location method is less expensive than the multi-ended method, since only one unit is required per line and a communication link is not required, but the errors remain high. In this method the arrival times of the initial and reflected traveling waves at a single end of the line are used [8, 9].

However, the problem of distinguishing between traveling waves reflected from the fault and reflected from the remote End of the line was not addressed in most of the above mentioned papers. Moreover, the algorithms proposed were not supported by the results taking into account the effect of wide variation of uncontrolled fault parameters like fault inception angle and fault impedance. This paper addresses these issues. Accurate results can be obtained using algorithms that consider the fault data from two terminals of the line together. However, two-terminal data are not widely available. From the practical viewpoint, it is desirable for equipment to use only one terminal data. The paper essentially presents one terminal method for fault location.

2. Wavelet Transform

Wavelet transform (WT) is a mathematical technique used for many application of signal processing. Wavelet is much more powerful than conventional method in processing the stochastic signals because of analyzing the waveform time-scale region. In wavelet transform, the band of analysis can be adjusted so that low frequency and high frequency components can be windowing by different scale factor. Recently WT is widely used in signal processing applications, such as denoising, filtering, and image compression. Many pattern recognition algorithms have been developed based on the wavelet transforms. It also has been used widely by the power system researchers. According to scale factor, wavelet categorized different section. In this paper the wavelet which is named Discrete Wavelet Transform (DWT) by two scale factor was used. For any function (f). The function is the base Wavelet if it satisfies the equation

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

The function family $\psi_{s,b}(t)$ generated through dilation parameter 's' and translation parameter 'b' is defined as,

$$\Psi_{s,b}(t) = \frac{1}{\sqrt{s}} \Psi\left(\frac{t-b}{s}\right), s, b \in \mathbb{R}, s \neq 0$$

Where \mathbb{R} is a set of real numbers. The wavelet transform of any function $x(t)$ is defined as,

$$W_f(s,b) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t) \Psi^*\left(\frac{t-b}{s}\right) dt$$

$\Psi^*\left(\frac{t-b}{s}\right)$ is a conjugate of Wavelet transform $\Psi\left(\frac{t-b}{s}\right)$.

Wavelet transform $W_f(s,b)$ depends on scale factor and translation factor. Through variation of scale factor, the wavelet transform can be applied to high frequency components where short time intervals are necessary. Therefore, it is a suitable approach to analyze the traveling

waves. If $s = \frac{1}{2^j}$ ($j \in \mathbb{Z}$, \mathbb{Z} is a set of integers) and $b \in \mathbb{R}$ (\mathbb{R} is a set of real numbers), then it is a dyadic wavelet transform. It is translation invariant and hence used in signal edge detection. Wavelet Modulus Maxima (WMM) of wavelet transform are the local maxima of wavelet transform satisfying the following condition:

$$|W_m x(t)| \leq A s^\alpha$$

where, $W_m x(t)$ is the WMM of signal $x(t)$, A is constant, and α is the Lipschitz exponent.

Modulus maxima represent the singularity of step signal. The polarity of WMM is identical to polarity of sudden change of the signal and its magnitude depends on the amplitude and gradient of the sudden change of the signal. In this paper, WaveLab is used to obtain WMM. WaveLab which is available from Stanford University can be used as an alternative to the MATLAB wavelet toolbox.

3. Travelling Wave Theory

A fault on the transmission line sets up traveling waves which propagate from the fault point towards the line terminals at speeds close to that of light. Three-phase lines have significant electromagnetic coupling between conductors. As a result, during traveling wave conditions, the self and mutual surge impedances affect their behavior and 'single' surge impedance valid during different faults cannot be defined. In numerical relaying applications, this needs matrix manipulations which require more computational time to compute suitable relaying signals. Hence, it is necessary to transform a coupled three phase system to a decoupled systems having surge impedance terms independent of fault type. By means of modal decomposition, the coupled voltages and currents are decomposed into a new set of modal voltages and currents and each transformed signal can be treated independently in a manner similar to that of single-phase line. The relationship between three phase voltage and current signals and their respective modal components is given by

$$[e_p(t)] = [S][e^m(t)] \quad (1)$$

$$[i_p(t)] = [Q][i^m(t)]$$

where $[S]$ and $[Q]$ are the voltage and current modal transformation matrices and are equal to each other for

transposed lines. $[em(t)]$ and $[im(t)]$ are the modal voltage and current matrices. The elements of transposed matrix can be determined using matrix function theory and the properties of eigen values and eigen vectors. In protection applications, three of the widely used constant modal transformation matrices for perfectly transposed lines are the Clarke, Wedepohl, and Karrenbauer transformation. In the present work, Clarke transformation matrix is used.

Phase currents can be viewed as being made up of $i(0)$, $i(1)$ and $i(2)$ i.e. mode-0, mode-1 and mode-2 components. Each of these components represents a mode of the propagation equation. The mode-0 component has a characteristics impedance and velocity of propagation that are distinct from those of modes-1 and mode-2 components. Using Clarke transformation, we can write

$$T = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \quad (2)$$

From (2), we can express $i^{(0)}$, $i^{(1)}$, $i^{(2)}$ as

$$i^{(0)} = \frac{1}{3}(i_a + i_b + i_c) \quad (3)$$

$$i^{(1)} = \frac{1}{3}(2i_a - i_b - i_c) \quad (4)$$

$$i^{(2)} = \frac{1}{3}(\sqrt{3}i_b - \sqrt{3}i_c) \quad (5)$$

A. Fault Parameterization

The analysis for various types of faults can be obtained from the conditions which are unique to each fault. Now, consider a L-G fault from phase A to ground. The boundary conditions are defined by $i_b = i_c = 0$ and $v_a = 0$. This condition when substituted in the modal components leads to $i^{(0)} = \frac{1}{3}i_a$, $i^{(1)} = \frac{2}{3}i_a$ and $i^{(2)} = 0$.

B. Now, consider a L-L fault, that is, fault between B and C phases. The boundary conditions are $i_a = 0$, $i_b = -i_c$ and $v_b = v_c$. The condition on substitution in modal components reduce to $i^{(0)} = 0$; $i^{(1)} = 0$; $i^{(2)} = \frac{2\sqrt{3}}{3}i_b$

Similarly, the conditions in modal domain for other faults were obtained. Four fault parameters viz. $Wmm0$, $Wmm1$, $Wmm2$ are defined and obtained using wavelet analysis as follows. 'Wmm0' is the first modulus maximum of mode-0 traveling wave which corresponds to the first strike of mode-0 component wave at relay location. Similarly, 'Wmm1', 'Wmm2' are the first modulus maxima of mode-1, mode-2 waves launched by the fault, respectively.

4. Power System Model

The Sim Power System which is an extension to the Simulink of MATLAB software was used to simulate the double end fed power system [15]. The 100 km, 400 kV double circuit transmission line was modeled using distributed parameter

model as shown in Fig.1. The value of bus bar capacitance C_s is assumed to be $0.1 \mu\text{F}$.

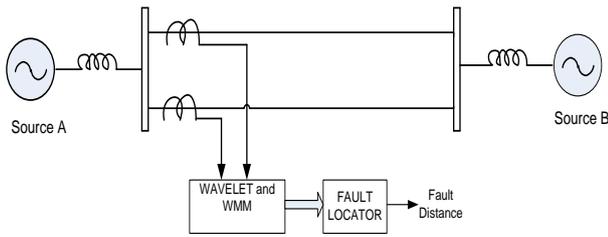


Figure1: Power System model

The transmission line parameters are as follows:

- Positive Sequence Resistance, $R_1 : 0.0275 \Omega / \text{km}$
- Zero Sequence Resistance, $R_0 : 0.275 \Omega / \text{km}$
- Zero Sequence Mutual Resistance, $R_{0m} : 0.21 \Omega / \text{km}$
- Positive Sequence Inductance, $L_1 : 0.00102 \text{ H/km}$
- Zero Sequence Inductance, $L_0 : 0.003268 \text{ H/km}$
- Zero Sequence Mutual Inductance, $L_{0m} : 0.0020 \text{ H/km}$
- Positive Sequence Capacitance, $C_1 : 13 e^{-0.009} \text{ F/km}$
- Zero Sequence Capacitance, $C_0 : 8.5 e^{-0.009} \text{ F/km}$
- Zero Sequence mutual Capacitance, $C_{0m} : -5e^{-0.009} \text{ F/km}$

5. Application of Wavelet transform

The proposed fault location algorithm using Wavelet Transform is show in the following steps :

1. Get the signals from transducer output.
2. Transform the signals into modal domain.
3. Apply Discrete Wavelet Transform and obtain the Wavelet Transform Coefficients (W_{mm}).
4. If the mode 0 (W_{mm0}) is zero, then the fault is identified as an ungrounded fault and the fault distance is given by the equation :

$$d = (v \times t_d) / 2 \quad (6)$$

where d is the fault location from source A, v is the wave velocity of mode 1 having magnitude slightly less than velocity of light, and t_d is the time gap between first two peaks of WTC of mode 1.

5. If the mode 0 (W_{mm0}) is nonzero, then the fault is identified as a grounded fault and the calculate the time gap t_{dm} between the first peaks of mode 0 and mode 1.

If $t_{dm} > t_{l/2}$, then

$$t_d^1 = (2l/v) - t_x \quad (7)$$

$$d = (v \times t_d^1) / 2 \quad (8)$$

where $t_{l/2}$ is the travel time delay between mode 0 and mode 1 if the fault is located at the center of the line, x is the distance to the fault, v is the wave velocity of mode 1, and t_x is the time delay between two consecutive peaks of the WTC mode 1. Else, the fault distance using (Fault is in second half section of line).

$$d = (v \times t_d) / 2 \quad (9)$$

6. Simulation Results

Mutual coupling between parallel lines mostly affect the ground mode (mode 0) signals, the effect on aerial modes (Mode 1 and Mode 2) are not significant. Since the ground

mode WTC's (WMM_0) are used only to discriminate between different types of faults (ungrounded, grounded near end, grounded far end) and not to obtain any time measurements ($t_d = t_2 - t_1$), so their strong mutual coupling to the parallel lines will not hinder the fault location calculations. Aerial mode WTC's (WMM_1 and WMM_2) are not significantly affected by the presence of mutually coupled lines (parallel lines or double circuit lines), therefore the distance calculation based on proposed algorithm of single circuit line remains valid for these cases.

a. Numerical Example

For Fig.2, as the mode 0 signal (WMM_0) is 0 therefore the fault is ungrounded fault and the distance to the fault point is given by

$$d = \frac{2.77 \times 10^8 \times (174 - 58) \times 10^{-6}}{2} = 16.066 \text{ km}$$

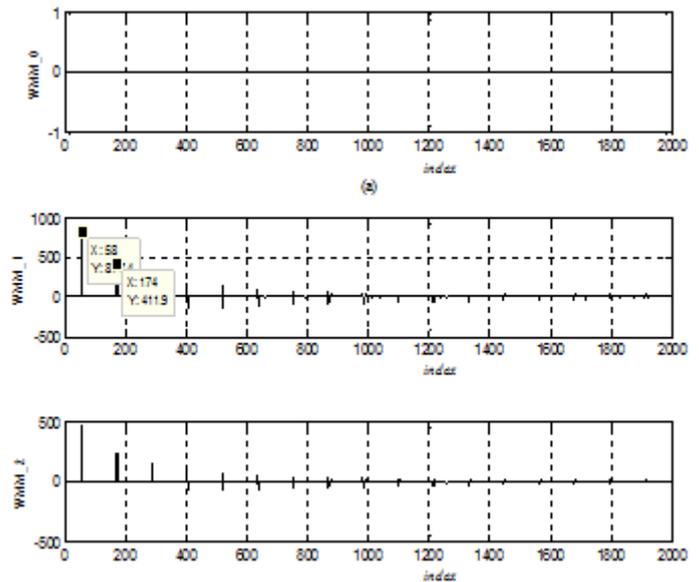


Figure 2: WMM spikes during C1A1 fault at 16km

For Fig.3 Travel time delay between first peak of mode 0 (WMM_0) and mode 1 (WMM_1) of signals is given by

$$t_{l/2} = (207 - 181) \times 10^{-6} \text{ s} = 26 \times 10^{-6} \text{ s}$$

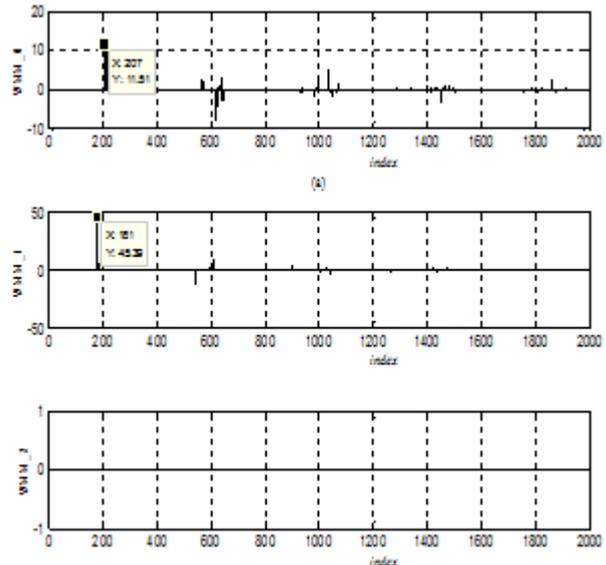


Figure 3: WMM spikes during A2G fault at 50km

For Fig.4, the travel time delay between the first peak of mode 0 (WMM_0) and mode 1 (WMM_1) of signals is given by

$$t_{dm} = (100 - 87) * 10^{-6} = 13 * 10^{-6} s$$

$t_{dm} < t_{1/2}$ Therefore the fault is in first half section of line and the distance to the fault is given by

$$d = \frac{2.77 * 10^8 * (260 - 87) * 10^{-6}}{2} = 23.960 km$$

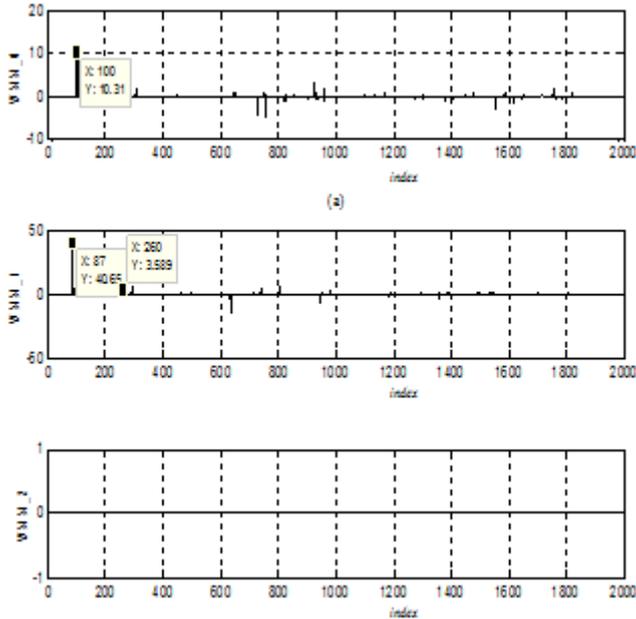


Figure 4: WMM spikes during A2G fault at 24km

For Fig.5, the travel time delay between the first peak of mode 0 (WMM_0) and mode 1 (WMM_1) of signals is given by

$$t_{dm} = (315 - 275) * 10^{-6} s = 40 * 10^{-6} s$$

As $t_{dm} > t_{1/2}$ the fault located in second half section of line and then the travel time delay between the first 2 consecutive peaks of mode 1 (WMM_1) signal is given by

$$t_{d'} = \frac{2 * 100 * 10^3}{2.77 * 10^8} - 173 * 10^{-6} s = 549 * 10^{-6} s$$

The distance to the fault is given by

$$d = \frac{2.77 * 10^8 * 549 * 10^{-6}}{2} = 76.036 km$$

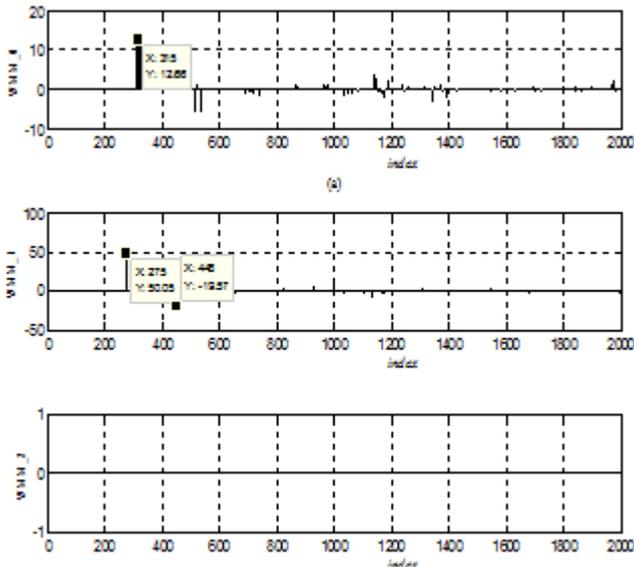


Figure 5: WMM spikes during A2G fault at 76km

C. Effect of Fault Resistance

The effect of fault resistance on the fault location calculation is tested, by maintaining fault location and inception angle constant and varying the fault resistance (R_F) from 10 ohms to 100 ohms for a particular type of fault. The sample results for A1G fault occurring at a distance of 56km from bus 'A' are tabulated in

Table 1: Effect of fault resistance

Fault Resistance	Actual Fault Location	Error (%)
10	55.957	0.043%
20	55.957	0.043%
30	55.957	0.043%
40	55.957	0.043%
50	55.957	0.043%
60	55.957	0.043%
70	55.957	0.043%
80	55.957	0.043%
90	55.957	0.043%
100	55.957	0.043%

D. Effect of Fault Inception Angle

The effect of fault inception angle on calculation of fault location is tested by maintaining fault location and fault resistance constant and inception angle from 0^0 to 90^0 . The sample results for A2G fault occurring at a distance of 24km from bus 'A' are shown in Table 2.

Table 2: Effect of fault inception angle

Fault Inception Angle	Actual Fault Location	Error (%)
4^0	24.099	0.099%
18^0	24.099	0.099%
36^0	24.099	0.099%
54^0	24.099	0.099%
72^0	24.099	0.099%
90^0	24.099	0.099%

Table 3 Test results for TW based fault locator for double circuit line

Fault type	FIA	RF (Ω)	Actual fault location (km)	Estimated fault location (km)	Absolute % error
A1C1G	36^0	45	33	32.963	0.037%
B1C1G	18^0	66	54	53.879	0.121%
A2B2G	54^0	33	76	75.901	0.099%
C2G	4^0	56	35	35.040	0.040%
A1G	54^0	22	12	11.911	0.089%
B1G	18^0	45	20	19.944	0.056%
A2B2	4^0	10	68	68.003	0.003%
A1C 1	36^0	12	83	82.961	0.961%
A1B1C 1'	54^0	7	93	93.072	0.072%

The fault location error is calculated as

$$Error(\%) = \frac{|Calculated\ Fault\ Location - Actual\ Fault\ Location|}{Total\ Line\ Length} * 100 \quad (10)$$

7. Conclusion

An accurate traveling wave based algorithm for fault distance location on double circuit transmission line fed from sources at both ends is presented covering all types of faults in both the circuits. The algorithm effectively eliminates the effect of varying fault type, fault location, fault resistance, fault inception angle, mutual coupling and remote source infeed. The complexity of all ten types of faults, fault locations (0-100km), fault inception angles (0-90⁰), fault resistance (0-100 Ω) are considered. The simulation results show that all ten types of faults are correctly located with fault location error less than 0.1%.

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