Fault Location Estimation based on Wavelet Analysis of Traveling Waves

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Abstract— **Improved fault location techniques are important particularly in EHV transmission lines and those subject to relatively high incidence of contingency faults over difficult terrain. Traveling wave based single end data techniques generally assume near total reflections at the fault point as well as line terminals. However, in practice effective impedances at the fault point and line terminals may not be significantly lesser than the line surge impedance. With this in view, a new traveling wave based algorithm, which does not assume near total reflections at discontinuities, and therefore more accurate over the wide range of variable parameters, is presented in this paper. Discrete wavelet transform was used to analyze the fault induced traveling waves. MATLAB/Simulink software was used to test and validate the proposed fault location approach. Various fault conditions were simulated by varying fault type, fault resistance, fault location and fault inception time, on a given power system model. The results showed that the proposed method for fault location was able to locate the faults on the transmission line rapidly and correctly.**

Keywords- Discrete wavelet transform; fault location; transmission line protection; traveling waves

I. Introduction

Most of the distance relaying algorithms developed for the protection of transmission lines use the estimate of the fault location to make the relaying decision. However, this estimate need to be accurate enough to determine whether the fault is in the appropriate zone of protection. More accurate estimate of the fault location is required for carrying out the repairs of the actual fault [1].

A variety of fault location algorithms have been developed and proposed over the years. These algorithms may be broadly classified as (i) those extracting fundamental frequency current and voltage phasors to compute fault location [2] (ii) those using differential equations of transmission line and estimating line parameters [3] (iii) those based on traveling wave (TW) theory [5-13]. Artificial intelligence techniques such as neural network also find applications in locating a fault on transmission line [4].

Hardware and software aspects of traveling wave distance relay were discussed and the relay was tested using simulation data as in [5]. Standard traveling wave techniques developed for EHV transmission systems were applied to distribution systems using cross-correlation technique to locate fault [6]. Fault location scheme using data from both the terminals and applying continuous wavelet transform was presented in [7]. Ref. [8] considered only high impedance LG fault for fault location method proposed. **The algorithm was proposed in [9] for traveling-wave distance protection for transmission lines, based on pattern recognition of the first wave front due to fault that arrives at the relay location using principal component analysis. Single ended TW method that used c**ross-correlation of the incident and reflected waves to estimate fault location was proposed in [11-12]. Fault position was obtained in [13] by analyzing distribution of wavelet modulus maxima of modal components of current traveling wave to identify incident and reflected waves.

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.

II. Wavelet Transform

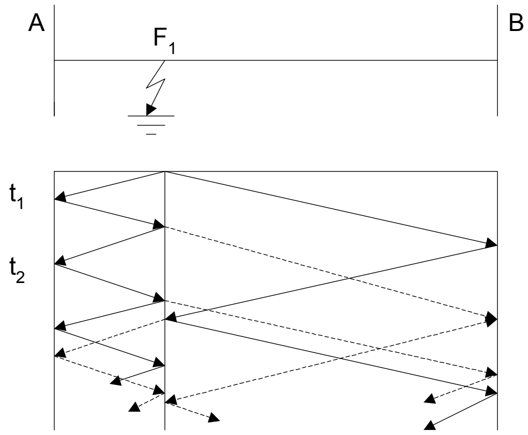
The wavelet transform (WT), a powerful mathematical tool is useful for the analysis of non-stationary signals such as those associated with faults or switching operations. It has been widely applied for the study of protective relaying of power systems, including high impedance fault detection, faulted phase identification, traveling wave fault location and transformer protection [14].

Wavelet Modulus Maxima (WMM) of wavelet transform are the local maxima of wavelet transform. Modulus maxima represent the singularity of traveling wave component of post fault current. 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 was used to obtain WMM. WaveLab which is available from Stanford University can be used as an alternative to the MATLAB wavelet toolbox.

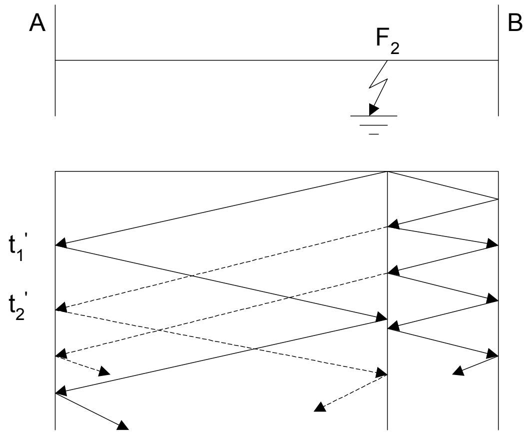
III. DISCRIMINANT TO ESTIMATE FAULTED LINE SECTION

When the fault occurs on the line, traveling waves travels away from fault point towards the line terminals. When the waves arrive at the discontinuity, part of the waves is reflected backward. The entire wave train launched by the fault, thus travels up and down the network, fragmented by the reflections, until it is dissipated through line losses and the new post fault steady state is reached. This phenomenon can be illustrated with the help of Bewley lattice diagram. Lattice diagram can be used to illustrate the necessity of discriminant for estimating fault section of the line, as shown in Fig. 1 (a) and Fig. 1 (b).

Fig. 1 (a) shows the transmission line with the fault F_1, which occurs on the first half of the line AB, and its Bewley-lattice diagram. A traveling wave based fault locator is placed at bus A. For a fault F_1on the first half of transmission line, it will record $t_2 - t_1$ as the time difference between the first two wavelet modulus maxima. Fig. 1 (b) shows the line with the fault F_2, which occurs on the second half of the line AB, and its Bewley-lattice diagram. As can be seen, an identical time difference is likely to be recorded as $t_2'-t_1'$ for fault F_2, which is on the second half section of the line.



(a)



(b)

Figure 1. Bewley-lattice diagram (a) for fault on the first half section, (b) for fault on the second half section of the line

Thus, fault locator gives wrong estimate of fault location for remote-end fault F_2. This is because reflections from the remote end arrive before fault reflections for the faults which are beyond centre of the line away from relay location. Therefore additional discriminant is required to differentiate between the faults occurring in first half section of line and the faults occurring in remote half section of line. This discriminant was obtained using wavelet analysis to get the correct results as proposed in the algorithm.

IV. POWER SYSTEM MODEL

The SimPowerSystem which is an extension to the Simulink of MATLAB software was used to simulate the double end fed power system [15]. The 200 km, 400 kV transmission line was modeled using distributed parameter model as shown in Fig.2. The value of bus bar capacitance C_s is assumed to be 0.1 μF.

The network and line data is given below.

Transmission line data:
Positive sequence impedance, $Z_1 = 5.5 + j\ 63.0\ \Omega$
Zero sequence impedance, $Z_0 = 55.0 + j\ 205.3\ \Omega$
Positive sequence susceptance, $B_1 = 4.084$ μS/ km
Zero sequence susceptance, $B_0 = 2.67$ μS/ km
Equivalent system at both terminals:
Positive sequence impedance = 1.31 + j 15.0 Ω
Negative sequence impedance = 2.33 + j 26.6 Ω

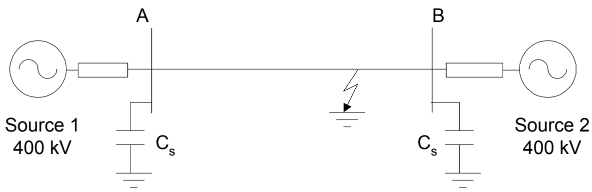


Figure 2. Power system model

V. ALGORITHM FOR FAULT LOCATION

The proposed algorithm to estimate the distance to the fault is presented below.

1. Obtain the superimposed current signals $\Delta i_p(t)$ from the transducer output.(p=a,b,c)
2. Transform the time domain signals into modal domain using Clark transformation matrix *T*, given by,

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

3. Analyze the appropriate mode signal component with wavelet transform. Let '$\omega mm1$' be a variable denoting the first modulus maximum of mode-1 traveling wave which corresponds to the first strike of mode-1 component wave at relay location. Similarly, let '$\omega mm2$' be a variable denoting the first modulus maximum of mode-2 traveling wave which corresponds to the first strike of mode-2 component wave at relay location. If $|\omega mm1| > |\omega mm2|$ then analyze mode-1 component else analyze mode-2 component.

4. Calculate the time difference Δt between two successive peaks of wavelet modulus maxima, which is traveling time between the first strike of wave originated from fault location at the bus and subsequent strike of wave reflected from the fault location or remote line terminal at the same bus.
5. Determine the fault location depending on the polarities of first and second wave fronts. When the fault occurs on the first half of the line, compute the distance to the fault 'x' using (3).

$$x = \frac{\Delta t \cdot v}{2} \qquad (3)$$

where, v is the wave velocity for the aerial mode, and Δt is the time difference between the first two wavelet modulus maxima of same polarity.
When the fault occurs on the second half of the line, calculate the distance to the fault 'x' using (4).

$$x = \frac{2l - \Delta t \cdot v}{2} \qquad (4)$$

where, v is the wave velocity for the aerial mode, and Δt is the time difference between the first two wavelet modulus maxima of opposite polarity.

A. Selection of Modal Signal

Wavelet coefficients of mode-0 signal are significant only during faults which involve ground. Therefore, this signal cannot be used for all types of fault. Mode-1 or mode-2 signal can be used for any type of fault. This is illustrated in Fig. 3, Fig. 4 and Fig. 5. For AG fault, magnitudes of modulus maxima of mode-0 signal and mode-1 signal are significant, but that of mode-2 signal are very small, as shown in Fig. 3. Since, |ω*mm1*|> |ω*mm2*| , mode-1 component was analyzed. Labels of the figures viz. WMM_0, WMM_1 and WMM_2 denote the wavelet modulus maxima of mode-0, mode-1 and mode-2 signals respectively, while 'index' refers to time in terms of sample numbers.

Consider AB fault, magnitudes of modulus maxima of mode-0 signal are negligible as expected since the fault does not involve ground. Modulus maxima of both mode-1 and mode-2 signals are significant, however |ω*mm1*|> |ω*mm2*| and mode-1 component was analyzed to obtain the fault location., as shown in Fig. 4.

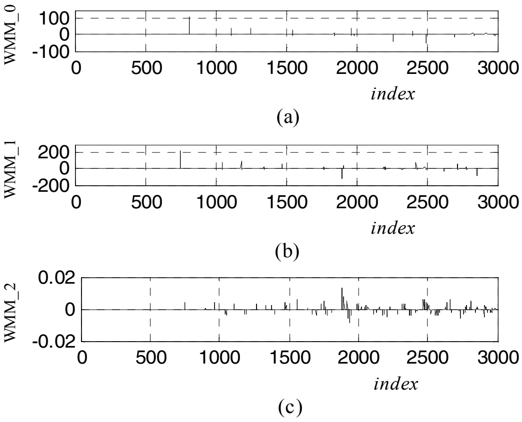


Figure 3. Wavelet modulus maxima signals for AG Fault

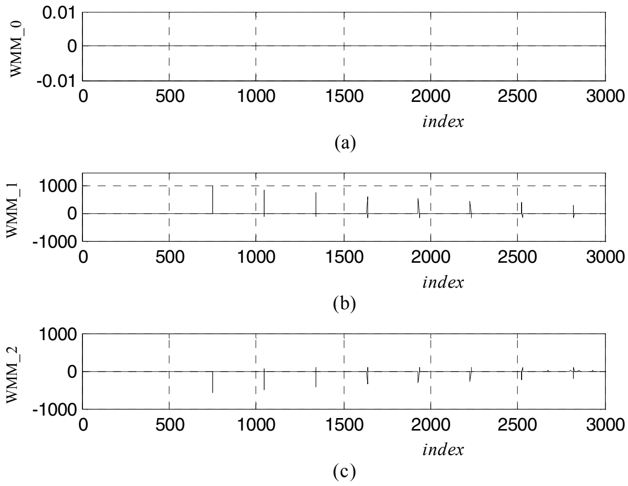


Figure 4. Wavelet modulus maxima signals for AB Fault

B. Fault Section Discrimination

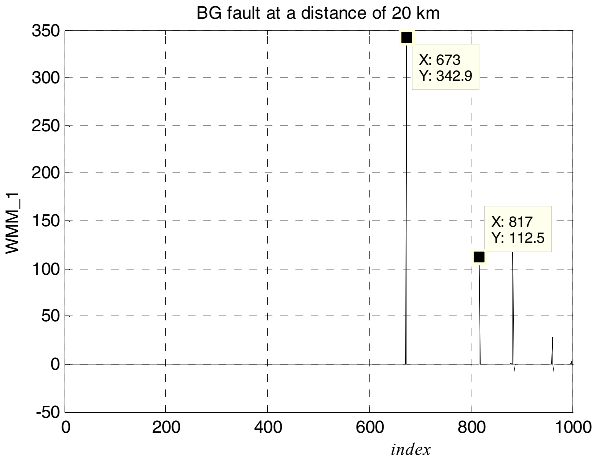
The position where modulus maxima appear is the exact position where sharp variations in the signal occur. When the traveling wave arrives at the relay, the modulus maxima of wavelet transform of current signal appear accordingly. The amplitude and polarity of modulus maxima in a given scale represents the variation in amplitude and polarity of post fault current. Fig. 6 (a) and Fig. 6 (b) show WMM for the BG fault occurring at a distance of 20 km and 180 km respectively. It can be seen that Δt which is the time difference between the first two wavelet modulus maxima is same in both the cases, but they are of same polarity for the fault occurring in the first half section of the line and are of opposite polarity for fault on the second half section of the transmission line. Referring to Fig. 6 (a), the distance to fault at the location of 20 km from relay location can be calculated using (2):

$$x = \frac{278000 \times (817 - 673) \times 1 \times 10^{-6}}{2} = 20.016km$$

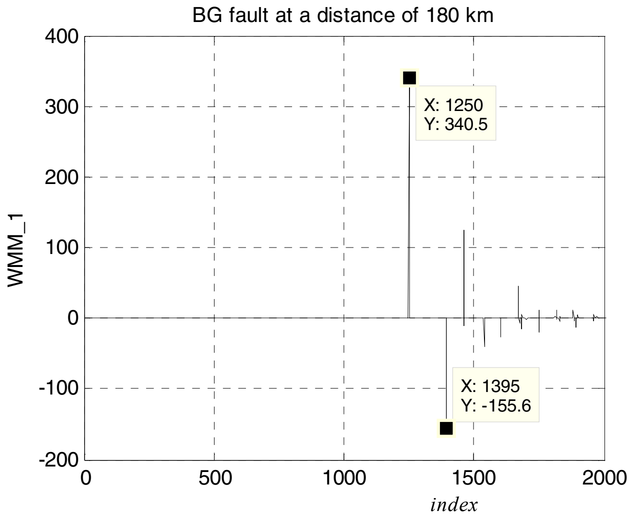
Similarly, referring to Fig. 6 (b), distance to fault at the location 180 km from relay location can be calculated using (3):

$$x = \frac{2 \times 200 - 278000 \times (1395 - 1250) \times 1 \times 10^{-6}}{2} = 179.845km$$

The condition for fault section determination was further tested with large number of fault cases and was found to be consistent. Thus the discriminant was obtained using wavelet analysis to get the correct results.



(a)



(b)

Figure 6. BG fault at a distance of (a) 20 Km (b) 180 Km

VI. Results and Discussion

Since the transient based techniques are based on the extraction of the characteristics of transient components generated by fault, a high sampling rate is always set to capture the wavefronts of transients. The sampling period was chosen to be 1 µs. Simulation studies were carried out on the typical model of 400 kV transmission line system shown in Fig. 2. A variety of fault scenarios, including different fault inception angles, fault resistances, fault locations and fault types, were simulated to evaluate the validity of this approach.

A. Effect of Fault Resistance

The effect of fault resistance on the estimation of distance to the fault was considered, by keeping fault location and inception angle constant and varying the fault resistance (R_f) from 10 Ω to 200 Ω for a particular type of fault. The sample case of AG fault occurring at a distance of 35 km from bus 'A' is discussed. It was observed that, time instances at which first two modulus maxima occur and hence Δt, the time difference between the first two wavelet modulus maxima remained constant. Thus, estimated fault location was found to be independent of large variation of R_f. However, with the increase in the value of fault resistance, the magnitude of WMMs decreases.

This variation of modulus maxima with Rf is illustrated with the graph shown in Fig. 7. The term '*first_ωmm*' refers to the first wavelet modulus maxima, which corresponds to the first strike of modal traveling wave at the relay location. Similarly, the term 'second_*ωmm*' refers to the second wavelet modulus maxima, which corresponds to the second strike of modal traveling wave at the relay location.

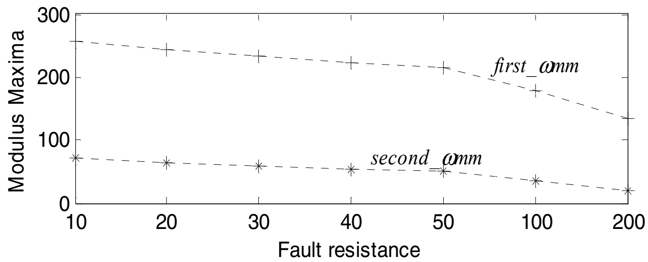


Figure 7. Effect of fault resistance

B. Effect of Fault Inception Angle

The effect of fault inception angle on the estimation of distance to the fault was considered by varying inception angle from 5^0 to 90^0. The sample case of AG fault occurring at a distance of 66 km from bus 'A' is discussed. The time instances were measured in terms of sample numbers. It can be seen that, time instances at which first two modulus maxima occur are different for each inception time, but Δt, the time difference between the first two wavelet modulus maxima remained constant. Thus fault location estimation is found to be independent of inception time. However, the values of WMMs tend to increase with increase in the inception angle as illustrated in Fig. 8.

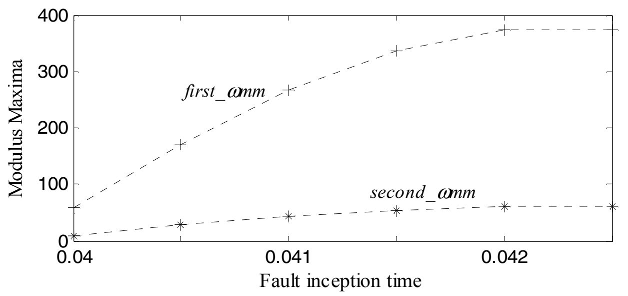


Figure 8. Effect of fault inception angle

For the cases of fault inception at zero crossing, theoretically, no traveling wave is generated from the fault location. Therefore, traveling based fault locator cannot operate under this situation. But as long as fault does not occur at absolute zero, the locator algorithm based on traveling wave can work properly. The test case with low inception angle had been tested. In practice, the insulation destruction is always caused by a significant voltage.

Various types of faults involving single phase, two phases and three phases with different system conditions were evaluated and the results are presented in Table I. These examples demonstrate the validity of fault location algorithm. The error in the fault location estimation was calculated using the following definition.

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

As can be seen, parameters such as fault resistance and fault inception time have no impact on the estimation of fault location. Error in all the cases was found to be less than 0.5%. The algorithm had also been tested on many other faults, and the results were found to be satisfactory as those presented here.

TABLE I. TEST RESULTS

Fault type	Fault inception time (ms)	Fault resistance (Ω)	Actual Fault location (km)	Estimated fault location (km)	Percentage error
AC	0.0404	15	37	37.52	0.26 %
BG	0.041	95	152	151.42	0.29 %
ABG	0.0417	171	75	75.88	0.44 %
AG	0.0425	68	85	85.96	0.48 %
BCG	0.0409	120	46	46.48	0.24 %
AB	0.0438	1	5	5.04	0.02 %
ABC	0.0412	8	12	12.04	0.02 %
ACG	0.042	176	134	133.22	0.39 %
BC	0.0418	10	22	22.12	0.06 %

VII. CONCLUSION

Many recent developments have a direct bearing on traveling wave based computer relaying. The renewed interest in the field of traveling wave based relaying is due to the advances in the fields of transducer technology, data acquisition & processing. For example, optical instrument transformers have high bandwidth and are capable of reproducing a fairly accurate replica of the high frequency wave fronts. This, together with the developments in data converters and digital signal processors made it possible for the traveling wave relays to handle the high frequency inputs and meet the high computational speed requirements.

Faults on transmission line cause short to long term power outages and may lead to significant losses especially to the utility and thus the problem has attracted widespread attention among researchers in power-system technology in recent years.

A new algorithm was presented in this paper for estimating fault location using traveling wave theory assisted by wavelet transform. The mathematical tool of wavelet analysis was used to analyze the fault generated traveling waves. The method was found to be insensitive to the uncontrolled parameters like fault location, fault inception angle, fault resistance, and remote end infeed.

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