

Optimizing solution of fault location using single terminal quantities

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This paper firstly evaluated the impedance method and traveling waves method for fault location, and studied the robustness of fault location method based on impedance. Then it proposed an assembled fault location method for a transmission line based on single-terminal electrical quantities, in which the fault zone was firstly determined by impedance method with robustness then the accurate fault position was pinpointed by traveling waves method. EMTP (Electromagnetic Transient Program) simulations showed that the proposed method can overcome the drawbacks of impedance method and traveling waves method when either one is used alone, and improve both the accuracy and the reliability of fault location.

transmission line, accurate fault location, traveling waves method, impedance method, assembled method

1 Introduction

Fault location is of great importance for the safe and economical operation of power system. Pinpointing the fault point rapidly and accurately is helpful to restoring power supply, improving the reliability and safety of power system and relieving maintenance crew of workload. The subject of estimating the fault location has long since been of interest to electric power engineers.

Typically, fault location methods for transmission line can be divided into two categories according to the input-quantities^[1]: 1) double terminal method, which uses information from both two terminals of a transmission line, and 2) single terminal method, which only uses information from the local terminal. Moreover, according to the fault location principle, there are also two types of location methods^[1]: 1) the impedance method (in general), which uses lower frequency information to locate the fault mainly by calculating post-fault line impedance. And 2) the traveling wave method, which determines fault location with the time difference between initial traveling waves and/or its reflection at the point where fault locator is installed.

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With abundant fault information from both terminals of a transmission line, generally the double terminal methods are of more accuracy and reliability either with impedance^[2] or traveling wave principle^[3]. However, the communication channel is essential for the double terminal methods. In addition, the accurate synchronous sampling at both remote and local terminals may be necessary. This may introduce extra risks of unreliable as well as increases of the cost for the fault location system. In this aspect, the single terminal methods are preferable in practical use, which only use local quantities without any need for communication^[4,5]. In terms of reliability and cost-effectiveness, single-terminal methods enjoy obvious advantages. Single-terminal methods (including *impedance* and *traveling waves* methods) are the focus of this paper.

Because single-terminal algorithm based on impedance cannot eliminate the interference of the factors such as path resistance, it is not of high accuracy^[6]. In view of this, many measures have been taken to improve the accuracy of single-terminal algorithm based on impedance, and on some occasions, the improved algorithm may obtain exact fault location. However, in most cases, the result obtained is far from being satisfied. This fact has aroused suspicion of the validity of the theory and method of single-terminal fault location algorithm based on impedance.

Transient traveling waves generated by fault possess abundant information, which has been made use of successfully to develop directional elements^[7]. In fault location, the velocity of traveling wave is a constant for a given transmission line. So using this time information, location algorithm based on traveling wave can pinpoint the fault location in theory^[8]. But because of the existence of reflected wave from adjacent bus, from remote terminal bus and from middle transposition point, coupled with the influence of signal cable and transducer's transferring characteristics, it is difficult to identify the reflected waves from fault point.

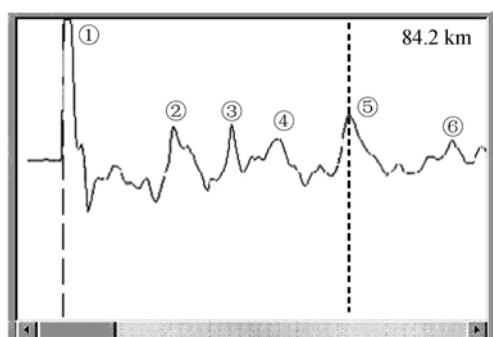


Figure 1 Waveform of current traveling wave recorded in field.

Figure 1 is transient current traveling wave of transmission line recorded in field^[9]. As Figure 1 shows, before the arrival of true reflected wave ⑤ from fault point, there are three traveling wave crests ②, ③ and ④ with the same polarity as the initial traveling wave crest ①. If it failed to identify +true reflected wave from fault point, the time difference between point ① and point ② would well be mistaken for the propagation time of the traveling wave. In this case, a false fault distance of 38.3 km was acquired. In

fact, the fault point is 84.2 km as shown by point ⑤ in Figure 1.

To solve the problem above, an assembled fault location algorithm is presented in this paper, which uses single terminal quantities with higher reliability and accuracy. Firstly, it uses a robust single-terminal fault location algorithm based on impedance to identify the fault zone of transmission line. Then, a fault location algorithm based on current traveling waves and wavelet transform is used to determine the exact fault location. This assembled algorithm possesses advantages of both two categories of fault location methods using single-terminal quantities, and solves the conflict between robustness and accuracy.

2 Model for analysis and simulation of the algorithm

In Figures 2 and 3, the following model has been adopted to investigate the features of both the impedance method and the transient traveling wave method, and also used for analysis and test of the assembled method.

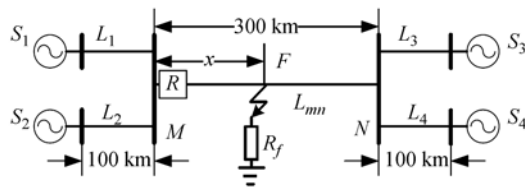


Figure 2 System model for analysis and simulation.

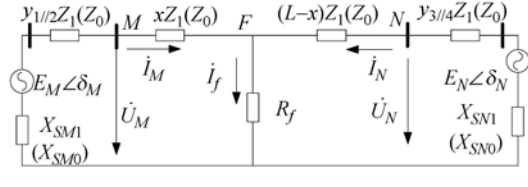


Figure 3 Equivalent circuit of the model.

L_{mn} is the faulted line, the locator R is installed on the bus M . The fault occurs at point F which is x km from the bus M , and L_{mn} is 300 km long. The lengths of $L_1 \sim L_4$ are all 100 km.

$Z_1(Z_0)$ is the positive (zero) sequence impedance of the line per km. $y_i Z_1(y_i Z_0)$ is an equivalent of the impedance of parallel lines L_1, L_2 or L_3, L_4 (So $y_i=50$ km in this model). $E_M \angle \delta_M$, $E_N \angle \delta_N$ and $X_{SM1}(X_{SM0})$, $X_{SN1}(X_{SN0})$ are equivalent sources and impedances of the systems of both sides. R_f denotes the fault path resistance.

For simulation the parameters of the transmission line are given as follows (per km):

Positive: $Z_1=0.0156+j0.3128 \Omega$, $C_1=0.0118 \mu\text{F}$;

Zero: $Z_0=0.0365+j0.9417 \Omega$, $C_0=0.007 \mu\text{F}$.

The system configurations are set to two different modes as Table 1.

Table 1 Equivalent source impedances of simulation system

(Ω)	X_{SM1}	X_{SM0}	X_{SN1}	X_{SN0}
Mode 1	0.606	0.722	60.6	72.2
Mode 2	60.6	72.2	0.606	0.722

The locator is installed on bus M . The impedance method focuses on the sinusoidal waveform of a longer time (several cycles after fault) with lower cutoff frequency at 500 Hz, and the traveling wave method focuses on sharp changes of the very front of current waveform with sampling rate at 1 MHz.

3 Robustness of impedance method

3.1 Robustness of fault location

On the basis of the time difference of the traveling wave propagation, many discrete points can be obtained, Most of them are surge impedance discontinuous points, and the fault point is definitely one of them. To ensure the reliability and accuracy of fault location, an algorithm based on impedance is necessary. A desirable impedance algorithm needs to be robust to output an approximate fault distance with reliable and acceptable fault zone in all kinds of fault cases. That means when system configuration changes or path resistance is high, this fault location algorithm can still get a stable approximate fault distance with acceptable fault zone, which should always cover the real accurate fault point.

There are many algorithms for impedance calculation^[10–13]. Frequency domain “measurement impedance method”^[10] gets post-fault impedance but with errors. “High resistance earth-fault method”^[11] is to solve the differential equation, there are still assumptions and errors in theory for this method. “Phase angle modification method”^[12] can get an accurate location result through iteration by solving a quadric equation. But false root may appear as interference and needs to be modified^[13]. Then tested most of these algorithms through simulation^[14,15] and the result shows that the “measurement impedance method”^[10] is the most robust algorithm, and that it remains valid even in some extreme situations such as serious current transformer saturation and high path resistance. The following discussion of robustness of the impedance method is based on this algorithm, and mainly focuses on system configuration and its consequential effect with the path resistance. Although the accuracy of this method is limited due to these effects, it has been proved to be suitable for assembled methods due to the reliable result with a robust error limit.

3.2 Analysis for robustness of impedance algorithm

One most important consideration of these impedance algorithms based on single-terminal quantities is the influence of fault path resistance R_f and its consequential effects: due to the existence of R_f , the fault current and voltage are determined by both ends of the transmission line, and the greatest difficulties come from the lack of information of the remote terminal.

According to Figure 3, for measurement impedance method^[10], the accurate impedance from the relay point to fault point Z_{MF} can be written as

$$Z_{MF} = \frac{\dot{U}_M}{\dot{I}_M} - \frac{\dot{I}_F}{\dot{I}_M} R_F = Z_M - \frac{R_F}{k} \left(\frac{\dot{I}_{FM}}{\dot{I}_M e^{j\gamma}} \right), \quad (1)$$

where $\dot{I}_F$ is the full fault current at the fault point, $\dot{I}_{FM}$ is the fault component current measured at M , $ke^{j\gamma}$ is distribution ratio between the fault component current from M bus and the full fault current flowing through path resistance and is determined by the ratio of Z_{F2N} (impedance from fault point to N include source equivalent) and Z_{total} (total line and source equivalent of both ends).

By solving the complex linear eq. (1) with the given line impedance angle φ_L , the result of accurate reactance from locator to fault point can be written as

$$X_{MF} = X_M - X_{mdf} = X_M - \frac{R_M \cdot \text{tg} \varphi_L - X_M}{\text{tg} \varphi_L \text{ctg}(\beta - \gamma) - 1}, \quad (2)$$

where X_{MF} is the accurate impedance from M to fault point F . R_M and X_M are directly derived from the ratio of measured $\dot{U}_M$ and $\dot{I}_M$ at M , X_M has been compensated by X_{mdf} . β is the angle difference between fault-component-current and fault-full-current at M point. In eq. (2), γ is unknown and in most cases it can be assumed to be zero, which inevitably brings error to this method.

Analysis of γ 's range: It is not feasible to calculate γ only using single-terminal quantities. However, the range of γ and its effect can be analyzed. From the fault component current and voltage, we can get the local system condition (system equivalent impedance X_{SM1} (X_{SM0})). Together with a given range of the remote terminal's equivalent, the range of γ 's value can be obtained more accurately. Normally, this information can be derived from remote terminal's capacity of short circuit. In this simulation system (see in Table 1) local M terminal equivalents are

$X_{SM1}=0.606$ and $X_{SM0}=0.722$, assuming those values of N side vary from 0 to 500 times of M side. γ 's value varies as: 1) Single phase to ground fault, γ is from -0.010° to 1.3° (mode 1) or -0.7° to 0.9° (mode 2), and 2) other fault: -0.014° to 1.4° (mode 1) and -0.9° to 0.9° (mode 2). Typically, γ 's value is quite small, mostly below 10° around 0° ^[10]. Therefore, assuming γ to be zero is acceptable.

Analysis of influence of γ : Also in eq. (1) the influence of assuming $\gamma=0$ can be illustrated in Figure 4: $x_{ZL}=Z_{MF}$ is the fully compensated impedance, and it indicates the real fault point. By assuming $\gamma=0$, the impedance is compensated to Z'_{MF} . So the error of reactance can be written as

$$Error \approx \frac{R_f}{k} \frac{I_{FA}}{I_A} \cdot (-\gamma) \cdot \cos \beta. \quad (3)$$

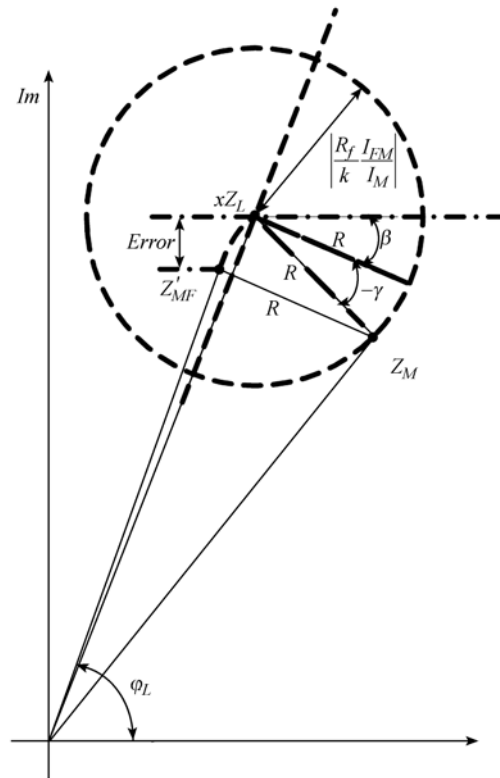


Figure 4 Error analysis for impedance method with assumption of $\gamma=0$.

Thus the *Error* is almost linear with γ . In order to get a reliable fault zone, γ can be set to its greatest absolute value within its possible range, and the location error range can be written as

$$X_{Error} = K_{l1} \left(\left| \frac{R_M \cdot \tan \varphi_L - X_M}{\tan \varphi_L \tan \beta - 1} - \frac{R_M \cdot \tan \varphi_L - X_M}{\tan \varphi_L \tan (\beta - \gamma_{\max}) - 1} \right| + K_{l2} \right), \quad (4)$$

$$F_{Error} = X_{Error} / X_{LinePerKm} + 3\% \cdot x, \quad (5)$$

where K_{l1} and K_{l2} are introduced as relaxation factors to adjust the error range, $3\% \cdot x$ indicates the error regarding to distributed capacities, which increases with fault distance. F_{Error} is the range

of the error in length scale. With the greatest absolute value $\gamma_{\max}$ of γ , a fault zone as $x \pm |F_{\text{Error}}|$ will always cover the real fault point regardless of the remote terminal's information. Moreover, in eqs.(4) and (5), this error range is independent from path resistance R_f .

Figure 5 shows the result of the robust impedance method in case of a single phase to ground fault: The fault point is 175 km from locator of system mode 2. Path resistance is 50Ω , fault occurs at 0.04 s, the Output Fault Location is the average value of Impedance/Location Calculation Result from third cycle (0.08 s) after fault, and the Error Limit is the $F_{\text{Error}}=16$ km. Although the impedance method's output is $x=179.6$ km, the real fault point 175 km is still within the fault zone by $x \pm |F_{\text{Error}}|$.

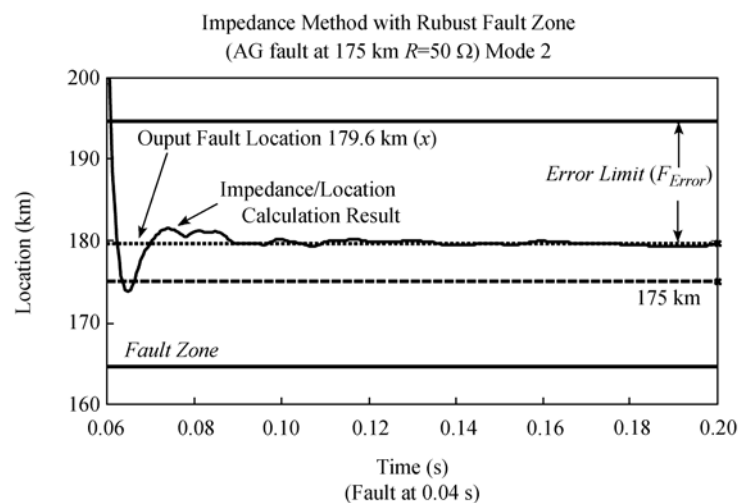


Figure 5 Result of robust impedance method.

In this simulation model, γ 's range is quite small, therefore, a better result of fault zone could be expected. The F_{Error} will increase in certain system configuration (if $\gamma_{\max}=5^\circ$ then F_{Error} reaches 40 km, 13% of total line length). However, the function of the impedance method is to give out a proper and robust fault zone for traveling wave method. According to field experiences of traveling wave method^[9,14,15], a fault zone with a range even up to $\pm 15\%$ of total line length is still acceptable for searching the reflection of traveling wave within the fault zone.

Hence, the calculation of impedance method with robust fault zone consists of four steps:

- Step 0. Preset γ 's range corresponding to possible system equivalent;
- Step 1. Calculate fault location according to eq.(2) with $\gamma=0$;
- Step 2. Estimate error range from eqs. (4) and (5) with the maximum absolute value of γ in step0;
- Step 3. Output the fault zone for further traveling wave algorithm.

3.3 Influence of other factors

Besides all these theoretical errors from certain assumption, there are other factors such as: 1) long line distribution parameter, 2) fault inception angle, 3) source angle difference, and 4) CT saturation. Theoretical analysis of these factors is beyond the scope of this paper. However, the reliability of the impedance method of this section in all these conditions has already been tested and proved through simulation by Chen^[14,15].

3.4 Summary of impedance method

The maximum error range simulated in these model cases (see in Figour 2) is about 10% of the length of the total length of L_{mn} (at remote end close-up fault). According to the above analysis, this impedance method with the reliable output of the fault location and fault zone will meet the requirement of the robustness for the assembled method.

4 Precise fault location using current traveling waves

Transient traveling waves are generated by the fault. At the surge impedance discontinuous point (mostly the fault point, or bus-bar), there are reflection and refraction of the traveling waves. The initial wave comes directly from the fault. Due to the reflection on the bus-bar and then on the fault point, there will be reflected wave after the initial wave. By identifying the waves and measuring the time difference of the initial wave and reflected wave, the fault location can be accurately pinpointed^[16,17].

The current and voltage traveling waves are two basic types of traveling waves. However, generally capacity-coupling voltage transformers (CVT) for EHV system are not capable to transform transient traveling waves due to their high frequency characteristics. While traditional CT is capable of transferring these high-frequency signals^[16]. This leads to the development of fault location only using current traveling waves. In most cases, the initial current traveling wave and the reflected one are of the same polarity^[16,17]. For traditional traveling wave method based on single-terminal information, the first wave after initial wave with the same polarity is detected as the reflected wave from the fault point.

The wavelets representation of traveling wave provides a clear mathematical description. Modulus maxima (MM) of dyadic wavelet transform (WT) are more useful in this case. These MM denote WT component's local extremum and indicate the exact time points of the sharp changes of waveform^[7,17] as in Figure 6. Fault location can be simply calculated with the following formula^[17]:

$$x_l = \frac{1}{2}(T_{m1} - T_{m2}) \cdot v, \quad (6)$$

where x_l is the calculated fault distance; T_{m1} is the modulus maximum point corresponding to the initial wave; T_{m2} is the modulus maximum point corresponding to the reflected wave; v is the velocity of propagation of traveling wave along the line. In this case, the component of scale $s = 2^2$

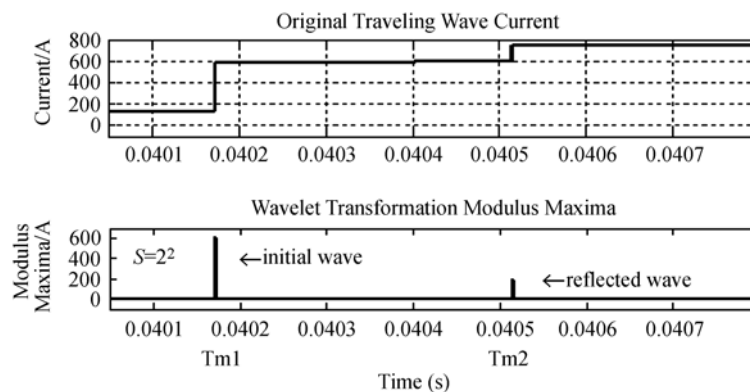


Figure 6 Current Traveling Wave and MM of Dyadic WT.

of the dyadic wavelet transform is adopted.

With the accurate fault location based on the initial and reflected waves of current traveling waves, the fault point can be accurately pinpointed. Although there may be other interference results, this method guarantees the accuracy of the assembled method for the exact fault point.

5 Assembled fault location method

The field-recorded traveling wave is shown in Figure 7: The points ①, ②, ③, ④, ⑤ and ⑥ are all modulus maxima corresponding to the crests of traveling waves in a given scale in Figure 7. Δt_i ($i=1,2,3,4,5$) are the time differences between points ① and (i) ($i=2,3,4,5,6$). According to eq. (6) the possible fault locations x_1, x_2, x_3, x_4 and x_5 are obtained as shown in Figure 7(a).

According to the impedance method's output of fault zone in Figure 7(b). Fault location can be pinpointed at $x_4 = 84.2$ km.

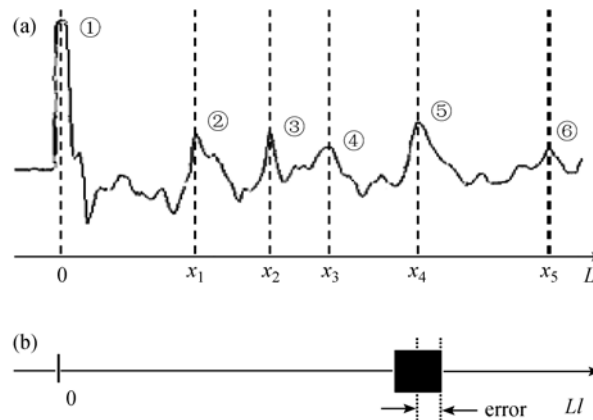


Figure 7 Illustration of the assembled fault location method. (a) Results of dyadic wavelet transform; (b) fault location results of algorithm based on impedance.

So for the assembled method, power frequency current/voltage and high frequency traveling wave currents are obtained real-time from data gathering units with different filters, sampling rate limits, and storage memories. The results, i.e., the continuous fault zone of impedance method and the discrete reflection points of traveling wave method, are assembled to pinpoint the accurate fault location within a less than 1 km error limit.

6 Simulation of the assembled method

In this section, fault cases of different system conditions and path resistances are tested. The following Figure 8 show the results of assembled method, each figure consisting of two diagrams. The upper diagram is the result of the traveling wave method's modulus maxima (MM) of the scale $s=2^2$ dyadic wavelet decomposition, which indicates the accurate fault point by time difference of the initial wave and reflected wave. The lower diagram is the result of the impedance method with the fault occurring at 0.04 s. The impedance method continuously outputs the calculated fault results from the second cycle after the fault (0.06 s), and the fault zone is calculated through eqs. (4) and (5). The output fault location is the average location result of the four cycles

since 0.08 s.

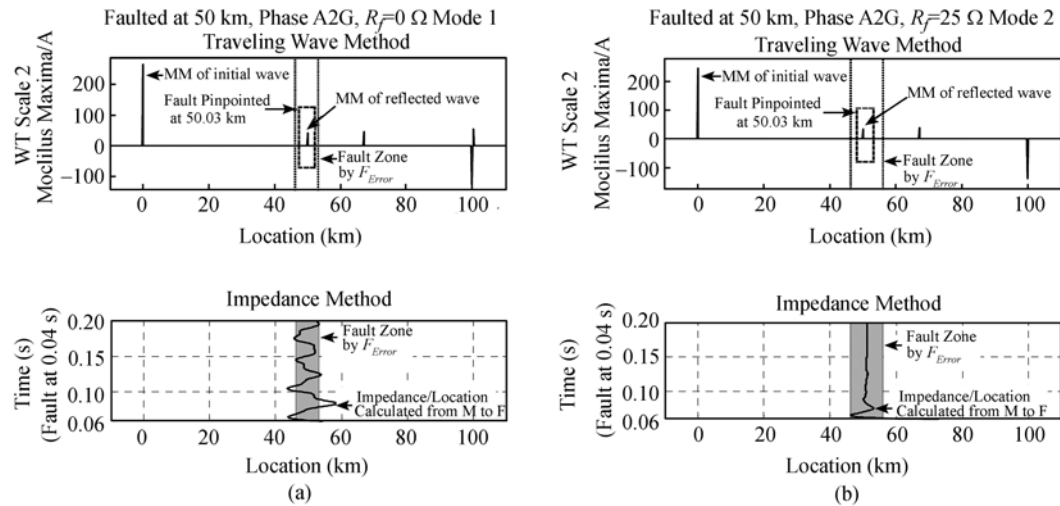


Figure 8 Testing results of assembled algorithm with typical fault under different system modes with lower path resistances. (a) Result: 50.03 km with Mode 1, $R=0\ \Omega$ (Fault Zone 49.7 ± 3.5 km); (b) Result: 50.03 km with Mode 2, $R=25\ \Omega$ (Fault Zone 51.2 ± 5.0 km).

6.1 Typical fault cases

In case of typical faults with lower path resistance, the impedance method will output a relatively accurate location result with a relatively small fault zone. Therefore, this will be the most favorable situation for impedance method. Fault point can be uniquely identified.

Figure 8(a) is the fault case of the single phase to ground fault simulated at 50 km with zero path resistance under system mode 1 (system mode refers to X_{SM} and X_{SN} in Figure 3 and Table 1). Figure 8(b) is the fault case of the single phase to ground fault simulated at 50 km with path resistance $R_f=25\Omega$ under system mode 2.

6.2 Fault cases with high path resistance

In these fault cases, with high path resistance, the output fault zone will become larger. However, in most cases, the assembled method is still capable of precisely pinpointing the fault point. Figure 9(a) shows the result of fault case simulated at 125 km with high path resistance $100\ \Omega$ under system mode 1; Figure 9(b) shows the result of the same fault case under system mode 2.

In Figure 9(a), before the MM point of the real reflected wave from fault point, there is another MM point at 100 km with the same polarity as the initial one. However, only the MM point within the fault zone is detected as the fault point.

6.3 Remote end close-up fault with high path resistance

Since close-up fault near the bus-bar generates intensive reflections and refractions of traveling waves, it is difficult to uniquely identify the reflected wave from the fault point. This problem is more remarkable when fault occurs at remote end with high path resistance, where the fault zone will be relatively larger. The following cases are mainly about these extreme situations.

Figure 10 shows single phase to ground close-up fault cases at remote end of 275 km with high resistance $R=100\ \Omega$. Figure 10(a) indicates the fault case with system mode 1, while Figure 10(b) is with system mode 2.

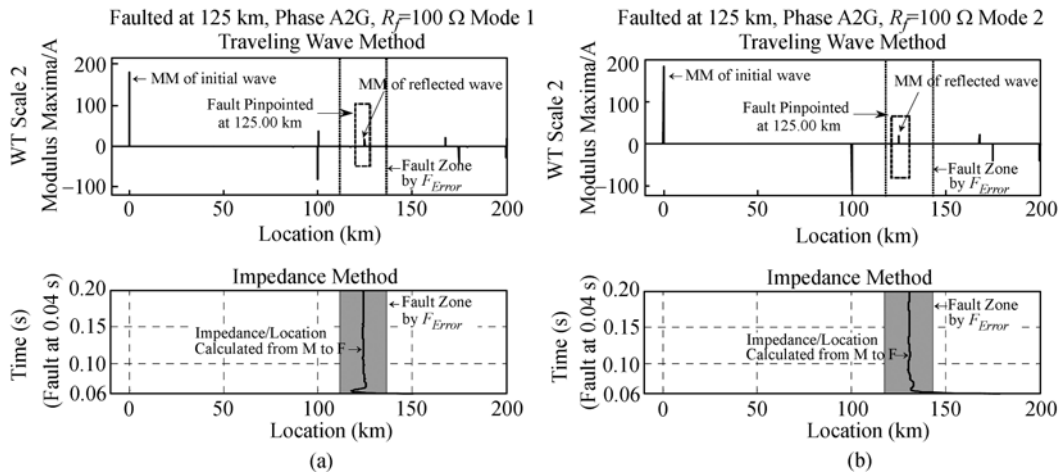


Figure 9 Testing results of assembled algorithm with fault of high path resistance under different system modes. Result: 125.00 km with Mode 1, $R=100\ \Omega$ (Fault Zone: 124.2 ± 12.4 km); (b) Result: 125.00 km with Mode 2, $R=100\ \Omega$ (Fault Zone: 130.7 ± 12.7 km).

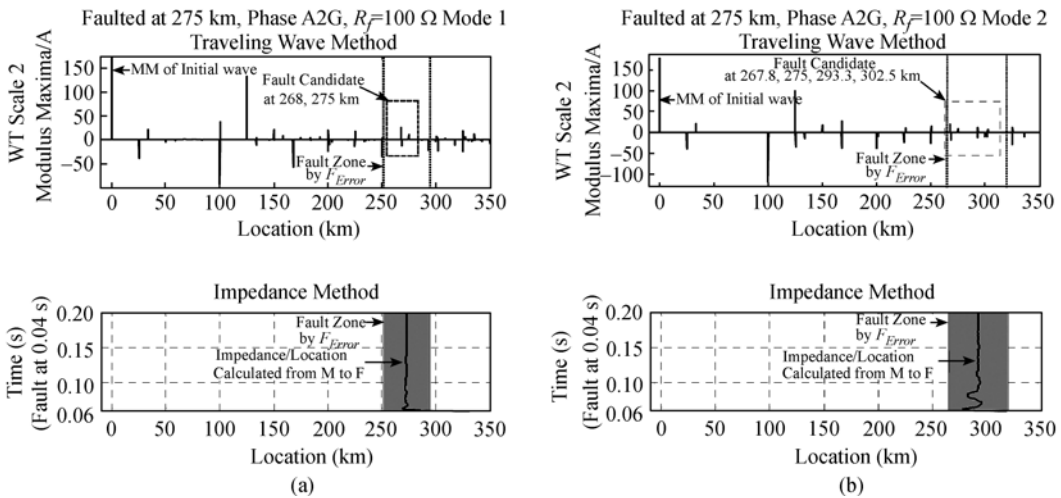


Figure 10 Testing results of assembled algorithm at remote end fault with large resistance. (a) Result: 268 km, Candidate: 275 km with Mode 1 (Fault Zone: 272.8 ± 21.5 km); (b) Result: 267.8 km, Candidate: 275, 293.3, 302.5 km with Mode 2 (Fault Zone: 292.3 ± 27.7 km).

In our algorithm, the first MM point with the same polarity as the initial wave regarding to reflection of wave within the fault zone is reported as the fault point. Other MM points within the zone will be reported as referential fault locations. Although in some cases, the fault point may not be uniquely pinpointed, this method still output a reliable range that covers the real fault point, and one of these candidate MM points within the fault zone will surely be the real accurate fault point. As an example, the result in the above cases is 268 km in Figure 10(a) and 267.8 km in Figure 10(b). However, real fault points (275 km) are among those candidate referential points.

The following lists are algorithm results of single phase to ground fault in Mode 1 (see in Table 1).

Table 2 is the output results of the assembled algorithm by reporting the first modulus maxima which indicates the first reflected wave within the fault zone. Although the first reflected wave

may not correctly indicate the fault point, with the robust fault zone of impedance method, the actual fault point will be always included within the output (Table 2) and referential fault points (Table 3). These non-unique results often occur in the situation of the remote end fault with a larger fault zone by impedance method, or causes by the intensive reflection when fault occurs near the bus-bar.

Generally, according to the results, although not all faults are uniquely pinpointed, the assembled algorithm is capable of outputting a set of results that always include the exact fault point with great reliability as well as satisfying accuracy.

Table 2 Output results of assembled algorithm (the first same polarity MM point within the fault zone)

Location Result (km)		Simulated Fault Point (km)						
		5	25	75	125	175	225	275
Path Resitance	0 (Ω)	4.96	25.09	74.98	125.00	175.00	224.90	275.00
	25 (Ω)	4.96	25.09	74.98	125.00	168.00	224.90	268.00
	50 (Ω)	4.96	25.09	74.98	125.00	167.90	224.90	268.00
	100 (Ω)	4.96	25.09	74.98	125.00	167.90	224.90	268.00
	150 (Ω)	4.96	25.09	74.98	125.00	167.90	224.90	268.00

Table 3 Referential locating results corresponding to other possible reflections within the fault zone

Location Result (km)		Simulated Fault Point (km)						
		5	25	75	125	175	225	275
Path Resisance	0 (Ω)	N/A*	N/A	N/A	N/A	N/A	N/A	N/A
	25 (Ω)	6.71	N/A	N/A	N/A	175.00	N/A	275.00
	50 (Ω)	6.71	N/A	N/A	N/A	175.00	N/A	275.00
	100 (Ω)	6.71	N/A	N/A	N/A	175.00	N/A	275.00
	150 (Ω)	6.71	33.05	N/A	N/A	175.00	N/A	275.00

* N/A: not applicable, fault point uniquely located within fault zone, no referential results.

7 Evaluation of Assembled Method

In summary, there are several aspects about the algorithm performances.

1) Robust impedance algorithm of the assembled method does not intend to seek any accurate result but to output a robust fault zone. Especially in case of some remote end fault or with a certain system conditions of a larger $\gamma_{\max}$ setting, the output fault zone may not be of accuracy but will always cover the real fault point.

2) There is no need of either iteration or equation solving, thus this method avoids the problem of false root or non-convergence.

2) Only reporting the first MM point of same polarity as initial wave within the fault zone may not exactly pinpoint the fault when there are more than one MM points within the fault zone. Still, other corresponding MM points within the fault zone are candidates for the real fault point.

3) Failure to obtain traveling wave information may fail to locate the accurate location. However, robust impedance method still can output a relatively reliable result.

4) The evaluation standard of impedance method comes from field experience of traveling wave method: error limit up to $\pm 15\%$ of the total line length of this impedance method is acceptable for traveling wave method to pinpoint the real fault point.

5) The assembled method in this paper has already been tested and is being implemented on HPR7000 high precision fault recorder by relay group of Tsinghua University, and site trial will

be carried out in one of Langfang's 220 kV stations, Hebei, China.

8 Conclusion

Traditional methods of fault location are impedance method solely based on power frequency quantity, or traveling wave method only using transient information. Although many impedance methods are reliable, almost all of the impedance methods are not accurate. Traveling wave method is accurate but of lower reliability.

In order to take the advantages of both methods, the robustness of fault location algorithms based on impedance has been defined and studied first; and then the assembled method of fault location based on single-terminal electrical quantities has been proposed.

The proposed assembled method uses fault location algorithm based on impedance to calculate a fault zone of transmission line. Then it uses wavelet transform as feature extraction method for fault location based on current traveling wave to pinpoint the fault position.

The assembled method can get an accurate location result within the error limit less than 1km. It can also give a robust result in special cases such as high impedance and weak system. EMTP simulation results show the new method is effective to solve the problem of fault location which has long since been a great challenge for protection engineers.

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