A Novel Transmission Line Fault Location Method Based on Time Frequency Correlation

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Abstract. The fault location method based on the transient traveling wave has been widely used in power grid. The location accuracy and reliability of traveling wave fault location may get affected by some factors including: length error of transmission line, timing error, secondary signal cable in substation. The paper proposes a novel fault location method based on the time-frequency correlation of the fault data collected from two ends of transmission line. It takes advantage of the symmetry and similarity of reflected waves at both ends while the resonance and the reflected waves of adjacent lines are not correlated with each other. Through time-frequency correlation analysis at both ends, the influence of interference and resonance is suppressed, reliability of reflected wave identification and fault location, as well as accuracy of fault location are improved. Effectiveness of the method is verified by simulation and field data.

Keywords: Traveling wave; Fault location; Time-frequency correlation.

1. Introduction

Since 1990s, the fault location device based on the transient traveling wave has been widely used in power grid. The operation experience of the device shows that it has adequate accuracy and reliability, compared with the impedance method used in the protection and fault-recorder[1,2]. The existing fault location device is basically based on two-ended method[3], which uses the initial traveling wave generated by faults. Two ended fault location method figures out fault point according to the time difference from two time points which are recorded when traveling wave arrive each end of transmission line[4]. But there are still some factors as follows that may affect method:

(1) Error of timing: 1 us timing error will lead to nearly 150 meters error in fault location, the timing error is mainly caused by loss of GPS signal on site.
(2) Error of line length: 1km length error of transmission line will lead to nearly 0.5km error in the fault location. In most cases, there will be error for measured length of the transmission line. In addition, the length of line is also affected by arc drooping changes seasonally.
(3) Error of secondary signal cable: a time delay will be generated in the process of secondary cable transmission, and the time-delay at both ends of the line is different.

Compared with the two ended traveling wave method mentioned above, the single ended traveling wave method uses the difference between the initial traveling wave and the reflected wave to complete the fault location, which is not affected by above mentioned factors. Therefore, single ended method combined with the two ended method is proposed to compensate parameter error and improve location accuracy in some literatures[5,6]. However in the practical fault analysis, the above methods need to deal with the problems of setting proper time-window[7,8] and suppressing signal resonance interference[9,10], meanwhile it is difficult to counteract the influence of timing error. To settle mentioned
problems, a novel method to identify and analyze reflected wave signal using time-frequency correlation analysis is presented in paper, which is based on correlation between signals of two end at transmission line and irrelevance between disturbance terms of two end. Error is corrected, as well as reliability and accuracy being improved when using the mentioned single ended / double ended method.

2. Algorithm Principle

![Figure 1. Symmetry of Signals at Both Ends.](image)

As shown in Figure 1, when the transmission line faults, reflected waves at both ends of the line (defined as M/N) are symmetrical. When the initial traveling waves from both ends are aligned, the reflected waves from the fault point and the reflected waves from the opposite bus are symmetrical on time axis. The interferences affecting the identification of reflected waves include: the reflected waves from the adjacent lines\[^{11,12}\], the back and forth reflected wave between the fault point and substation bus, and the resonance of the signal itself. They have the following characteristics:

1) The reflected wave of the adjacent lines and reflected wave between the fault point and the bus are mainly related to the line adjacent to the same bus and the location of fault point. Figure 2 shows the comparison of high-frequency components of signals at both ends of transmission lines under typical fault conditions. There is more high-frequency interference after signal fault on one side as shown in Figure 2 (a). At the same time, no similar signal is detected in Figure 2 (b). Such interference generally refers to line interference adjacent to the same bus or catadioptric interference between fault point and substation bus\[^{13}\].

2) According to the research in literature[14], the signal resonance after fault is mainly related to inductance and capacitance of line, and these parameters depend on the distance between the fault points and substation. Due to the difference of parameters at both ends, the resonance frequency of signal is generally irrelevant.

Considering that the reflected wave collected at two ends is symmetrical, and the main interferences are uncorrelated, so these interferences can be suppressed through cross-correlation analysis in theory. The principle is shown in Figure 3. By introducing reference signals, signals at both ends are used as
reference signals for cross-correlation operation, and common parts (fault point reflected wave and substation bus reflected wave) between signals are enhanced to reduce the interference of uncorrelated signals. Since transient traveling wave is considered as a broadband signal and wavelet analysis has better performance for multi-scale analysis, multi-scale wavelet transform is used in the research.

Figure 3. Cross correlation operation flow.

When the data at both ends of the transmission line (defined as M-terminal and N-terminal in paper) are regarded as two independent signals, the calculation of wavelet cross-correlation sequence, under given wavelet transform scale $a$ and time delay $\Delta t$, is as follows

$$w(t) = x_M(t) \times x_N(t + \Delta t)$$  \hspace{1cm} (1)

In the formula 1, $X_M(t)$ and $X_N(t)$ are the wavelet transform coefficients of M-terminal and N-terminal respectively, $\Delta t$ is time-delay compensation. So, the cross-correlation sequence of signals at both ends can be obtained. Cross-correlation sequence of signals at both ends has following characteristics:

1) Since the reflected wave of fault point is positive and that of opposite substation bus is negative, the reflected wave of fault point and bus in cross correlation sequence are both negative.

2) Assuming that the initial wave has an amplitude as $A$, the reflected wave amplitude of fault point and bus is approximately equal to $A \times \alpha_0 \times \beta_1 \times \beta_2 \times \delta$; $\delta$ is refraction coefficient of fault resistance; $\alpha_0$ is refraction coefficient; $\beta_0$ is refraction of fault point, $\beta_1$ and $\beta_2$ are reflected coefficients of substation bus at M and N terminals respectively. The calculation can be described as follows:

$$\alpha_0 = \frac{2Z_{c1}}{Z_{c1} + R_g}$$  \hspace{1cm} \beta_0 = \frac{Z_{c1} - Z_{c1}}{Z_{c1} + R_g}$$

$$\beta_1 \approx (n_1 - 1)/(n_1 + 1)$$  \hspace{1cm} \beta_2 \approx (n_2 - 1)/(n_2 + 1)$$  \hspace{1cm} (2)

Where $n_1$ and $n_2$ are the number of adjacent lines to the same bus at M and N end respectively, $Z_{c1}$ is the characteristic impedance, and $R_g$ is the short-circuit transition resistance. In the actual fault analysis, both $\beta_1$ and $\beta_2$ are fixed values. The relationship between $\delta$ and transition resistance is shown in Figure 2, and $\delta$ generally does not exceed 0.25. In addition, a lower threshold value of 0.01 is set in actual fault analysis in order to avoid white noise interference. When the amplitude is less than $0.01 \times A$, interference is considered to be white noise. Hence, the reflected amplitude of fault point / bus should meet the following conditions: $0.01 \times A \leq A_f \leq 0.25 \times \beta_1 \times \beta_2 \times A$

Figure 4. Changing trend of $\delta$ and transition resistor.

3) Assuming that the arrival time of the initial traveling wave is $t_0$, and the arrival time of reflected wave from fault point is $t'_1$, and reflected wave from bus is $t'_2$, then $t'_2$ and $t'_1$ theoretically satisfy the following conditions: $(t'_1 - t_0) \times v + (t'_2 - t_0) \times v = L$, while considering the analysis scale and the line error is less than 3%, the screening conditions are given as follows:

Note: The unit of horizontal axis is sampling point, the unit of vertical axis is relative value.
\[ 0.97 \times L \leq (t_1 - t_0) \times v + (t_2 - t_0) \times v \leq 1.03 \times L \] (4)

Therefore, if two reflected waves can be selected from the all reflected waves and meet the formula 4, they can be considered as the reliable reflected wave, so the single ended fault location is completed. The flow chart of this method is shown in Figure 5.

![Flow Chart](image)

**Figure 5.** Operation flow of cross correlation.

### 3. EMTDC Simulation

Short circuit fault at different conditions is simulated in this research using PSCAD/EMTDC. Model of researched system is shown as Figure.6, with transmission line modeled as frequency-related model and simulating step of 1μs.

![EMTDC Simulation System Model](image)

**Figure 6.** EMTDC Simulation System Model.

Different fault points are set in simulation: start point, end point and half point of transmission line. Typical conditions of fault include transition resistor of 1Ω and initial phase of 45°. Detail coefficients after wavelet transform of original signals at two ends are shown as Figure.7(a), and Figure.7(b) shows the result of calculation for correlation coefficients. The cross-correlation sequence is shown in the figure 7, as mentioned in the previous analysis, the resonance and noise are suppressed and the reflected wave signal is enhanced after the application of correlation analysis. And the reflected waves of fault point and bus are negative reflection, which effectively reduces the difficulty of identifying the reflected waves.
Analysis for simulation result under different fault conditions is shown in Table 1. Single ended traveling wave method achieve a higher accuracy with fault point and transmission-to-end reflected wave being accurately determined. In the simulation process, a high level of measurement accuracy is still acquired when analog transition resistance is set to $150\, \Omega$, which has a distance error less than 300m basically.

**Table 2. Result of Simulation.**

| Fault Distance | Transition Resistor (1\, \Omega) | Transition Resistor (150\, \Omega) |
|----------------|---------------------------------|----------------------------------|
|                | Measurement Distance(km) | Error(km) | Measurement Distance(km) | Error(km) |
| 10km           | 10.098 | 0.098 | 10.19 | 0.19 |
| 100km          | 100.22 | 0.22 | 100.33 | 0.33 |
| 80km           | 80.36 | 0.36 | 80.47 | 0.47 |

4. Analysis of Field Data
In the following, the method is verified through the field data analysis. The fault condition is: the voltage level is 220kV and total length is 55.48km. The fault point is 16.919km away from one end of the line (noted as M-terminal) and 38.5km away from the opposite end (noted as N-terminal). The waveforms at two ends of the fault time are as follows. When the fault occurs, the device fails to complete fault calculation due to loss of GPS satellite signal, sampling frequency of data is $625kHz$.

**Figure 8. Original Wave Form from Two Ends of Transmission line.**

After the main analysis scale is selected and wavelet transform is carried out for the linear modulus
component obtained by modulus transformation, the transformation coefficient is shown in Fig. 9 (b). The modulus maximum method is used to identify the initial fault time at both ends of the line. However, after the initial fault time, there are many clutter interferences in the transient signal, making it difficult to identify the reflected wave by amplitude and polarity.

After the translation compensation for the data at both ends, the cross-correlation sequence extracted by wavelet transform is shown in Figure.10. Compared with the wavelet transform detail coefficient shown in Figure.9 (b), the clutter interference is effectively suppressed after cross-correlation analysis, and the red circle part is the reflected wave of actual fault point and line-to-end bus, which is consistent from above, recognizing as negative reflection.

According to the polarity and amplitude conditions mentioned above, two types of reflected wave can be identified. The time difference between the two reflected waves and the initial traveling wave is given by: \((t_1' - t_0) = 72, (t_2' - t_0) = 163\). Considering that the wave velocity of 220kV double-circuit transmission line is about 295m/us, the constraint condition of line length wave velocity \((t_1' - t_0) \times V + (t_2' - t_0) \times V = L\) is satisfied, and \((t_1' - t_0)\) and \((t_2' - t_0)\) are substituted into formula 5,
The calculated fault point is 16.998 km, the error of fault location is just 79 m. In the whole calculation process, the absolute time scale provided by GPS is not necessary, and fault location can be completed in case that abnormal double terminal time scale is chosen. Moreover, fault location is acquired based on the single terminal method, which is not affected by length of the line cable in station, meanwhile the influence of line length and structure is relatively reduced.

5. Conclusion

The length error of transmission line, timing error and cable in substation will affect the accuracy and reliability. Researchers propose to use single terminal / double terminal method to reduce the interference of the mentioned factors. However, the existing single ended method is mainly based on polarity and amplitude to identify the reflected wave, which is difficult to solve the influence of signal resonance, reflected wave and other factors of adjacent lines on the same bus, and the reliability of reflected wave identification is not satisfactory. In view of the above problems, this paper proposes to suppress the influence of the above factors through the time-frequency correlation of the signals at both ends of the transmission line.

The proposed method makes use of the axial symmetry and waveform similarity of reflected waves at both ends, while the signal resonance and reflected waves of adjacent lines on the same bus are uncorrelated. Based on wavelet correlation analysis, cross-correlation of two pole signals is analyzed to achieve clutter interference suppression, which solves the most important problem of reflected wave identification in single ended traveling wave method, so as to improve the reliability and accuracy of fault location system.

Acknowledgement

This analyzed data in paper is from the State Grid Heilongjiang Corporation Qiqihar Company. The paper was funded by State Grid Heilongjiang Corporation, the number of project is 5224131900A2.

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