Study on T-Connection Transmission Line Fault Location Method Based on Transient Fault Traveling Wave Signal

Zhangzihao\textsuperscript{1,a} and Yaoxiaodong\textsuperscript{3,b}

Shanghai Dianji University

\textsuperscript{a}zhangzihao95@163.com; \textsuperscript{b}18321503128@139.com

Abstract. Aiming at the fault location of T-type transmission lines, which are susceptible to the influence of wave speed and transmission line length, this paper proposes a method of T-type transmission line fault location based on transient fault traveling wave information. Based on the fault reflection traveling wave generated at the fault point of the transmission line when a fault occurs, this paper detects the current and voltage traveling wave of the transmission line before and after the fault occurs through a current and voltage collector, and uses the non-stationary signal analysis to obtain the fault line. The initial time of the wave reflection to the transmission line port is obtained by simplifying the formula to obtain the modal maximum value of the initial time of the transient fault traveling wave. The modal maximum value of the initial reflected traveling wave time is brought into the calculation formula of the fault branch location criterion. Finally determine the fault distance. Experimental results based on PSCAD show that the method has better accuracy and efficiency than traditional fault analysis methods.

1. Introduction

With the complexity of the power system structure, the T-connection transmission line has been widely used in high-voltage transmission lines, and bears the important responsibility of transmitting electrical energy. When a double-ended transmission line fails, a fast and accurate fault location method can shorten the power recovery time, reduce power loss, and improve power supply reliability \cite{1-3}.

The current fault location methods mainly include traveling wave ranging method and fault analysis method \cite{4-6}. Impedance method is susceptible to fault transient resistance, fault type and uneven displacement of the line when measuring distance. There is little room for improvement in the accuracy and reliability of fault location. The traveling wave method has high ranging accuracy and simple calculation principle. Reference \cite{7} uses the time delay between the ground mode and line mode components in order to distinguish the primary reflected wave and the secondary reflected wave at the fault point, but this method is susceptible to changes in the speed of the ground mode. Reference \cite{8} uses the polarity to distinguish the reflected wave at the fault point from the refracted wave at the line port. However, when there is a transformer on the bus and there is no other output line except the fault line, the polarity of the bus reflected wave will change. This method cannot accurately identify waveform passed to the transmission port.

To address the effects of factors such as transition resistance, traveling wave speed, line parameters and other causes of fault location errors, the GPS timing system is used for three-terminal simultaneous sampling, and a traveling wave ranging method based on transient fault current information is proposed. First, perform phase simulation conversion on the collected fault voltage.
Then use Non-stationary signal analysis to multi-scale decompose the obtained line mode components, and obtain the time. When the initial wave head of the traveling wave head reaches each measurement point, the time information is extracted to determine the branch where the fault occurs. Finally, perform fault location.

2. Non-stationary signal detection using wavelet analysis
The essence of Non-stationary signal analysis is the inheritance and development of Fourier transform. It has good localization performance in the time domain [9-11]. It can accurately give the frequency information of the traveling wave signal at any time period. It has a good ability to detect signal mutations. The current traveling wave signal collected at the detection point is a Non-stationary signal with sudden changes. The sudden change point indicates that the current traveling wave signal reaches the detection point. The modulus maximum of the Non-stationary signal analysis corresponds to the current traveling wave signal one-to-one. The characteristics of Non-stationary signal analysis have obvious advantages when analyzing signals in non-stationary regions. Therefore, Non-stationary signal analysis has been widely used in signal fault location and local spectrum analysis [12 -13].

2.1. Multi-resolution analysis
Multi-resolution analysis can decompose mixed signals of different frequencies into sub-signals of different frequencies. An approximate signal A is obtained by an ideal low-pass filter, and a detailed value D is obtained by an ideal high-pass filter. Take the Non-stationary signal analysis that performs three-level decomposition as an example, and its wavelet decomposition tree is shown in Figure 1.

![Wavelet decomposition tree](image)

In Figure 1, S represents the original signal, cA1, cA2 and cA3 represent low-frequency signals, and cD1, cD2, and cD3 represent high-frequency signals. The decomposition relationship is $S = cA3 + cD1 + cD2 + cD3$. It can be known from Figure 1 that in the multi-resolution analysis process, the frequency resolution becomes higher and higher by multi-layer decomposition of the low-frequency part of the signal.

Based on the comprehensive analysis of the supporting length, symmetry, vanishing moment and regularity of the traveling wave signal in this paper, the db5 base wavelet and the detail coefficient D1 with high frequency components are used to identify the transient traveling wave signal generated by the fault.

2.2. Phase-analysis
In a three-phase transmission line, the three phases a, B, and C are not transmitted separately. There is a magnetic coupling phenomenon between the three phases, so during the transmission process, each phase will affect each other. Before traveling wave fault location, the line decoupling of traveling wave components must be decoupled. The result of decoupling can transform the three-phase interconnected phase components into independent modal components. Find out the fault. Among
them, Karen-Bell transform, Clark transform and symmetric component transform are three commonly used phase-mode transform methods.

The Clark component is used to convert the phase component of the voltage (or current) of the three-phase transmission line into a modal component. Taking the voltage component as an example, the transformation matrix is:

\[
\begin{bmatrix}
u_a \\ u_\beta \\ u_0
\end{bmatrix} = \frac{1}{3}
\begin{bmatrix}
2 & -1 & -1 \\
0 & \sqrt{3} & -\sqrt{3} \\
1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
u_a \\ u_\beta \\ u_0
\end{bmatrix}
\]

(1)

In the formula: \(u_0\), \(u_\alpha\), \(u_\beta\) are voltage 0 mode components, \(\alpha\) mode components, and \(\beta\) mode components; \(i_0\), \(i_\alpha\), and \(i_\beta\) are current 0 mode components, \(\alpha\) mode components, and \(\beta\) mode components, respectively; \(u_a\), \(u_b\), and \(u_c\) are line A, B, and C three-phase voltages; \(i_a\), \(i_b\), and \(i_c\) are the three-phase currents of lines A, B, and C, respectively.

In practical applications, due to the influence of geodetic parameters, the 0-mode component is vulnerable to severe attenuation, while the \(\alpha\) and \(\beta\)-mode components are relatively stable. Therefore, this paper mainly uses \(\alpha\)-modulus components for data processing.

3. Fault traveling wave location method for T connection transmission line

3.1. Fault distance location algorithm for T connection transmission line

The T-connection transmission line fault location algorithm is developed based on the traditional double-ended traveling wave location algorithm. Different from the double-ended transmission line, the T connection line has three end points, the three end points are designated as M, N, P, the fulcrum of T is set to T, and the three end points are respectively equipped with current and voltage traveling wave measuring devices. Traveling waves typically travel to the three end points of a line at a speed of propagation close to the speed of light. The absolute time of the three endpoints, namely \(t_M\), \(t_N\), \(t_P\). The distances from M, N, and P to the branch point T are \(L_{MT}\), \(L_{NT}\), and \(L_{PT}\), respectively. The length of the fault is determined by the absolute time \(t_M\), \(t_N\), and \(t_P\) of the line lengths \(L_{MT}\), \(L_{NT}\), \(L_{PT}\), and traveling waves to the three endpoint measurement points. The fault criterion elements \(d_{MN}\), \(d_{MP}\) and \(d_{NP}\) are introduced. In order to ensure synchronous sampling of signals, each port needs to be equipped with a wireless communication device with consistent time synchronization. The three-terminal T-shaped transmission line is shown in Figure 2 below

![Figure 2. T-connection transmission line fault model](image)

Determine the distances \(L_{MT}\), \(L_{NT}\), and \(L_{PT}\) from the branch point T to the three endpoints M, N, and P. When a fault occurs on the transmission line, the formula of the fault criterion component is:
In the formula, \( v \) is the traveling wave velocity.

The judgement basis of the fault branch is:
- If \( d_{MN} \leq L_{MT} \) and \( d_{MN} \leq L_{MT} \), the fault occurs in the MT branch;
- If \( d_{MN} > L_{MT} \) and \( d_{NP} < L_{NT} \), the fault occurs at the NT branch;
- If \( d_{MN} > L_{MT} \) and \( d_{NP} \geq L_{NT} \), the fault occurs at the PT branch;
- If \( d_{MN} = L_{MT} \) and \( d_{NP} = L_{NT} \), the fault occurs at branch point T;

After the fault branch is determined according to the fault branch criterion, it can be used

If the fault is on the MT branch, the distance from the fault point to the measurement point M is \( L_{FM} \), and the distance measurement formula is:

\[
L_{FM} = \frac{d_{MN} + d_{MP}}{2}
\]  

If the fault is on the NT branch, the distance from the fault point to the measurement point N is \( L_{FN} \), and the distance measurement formula is:

\[
L_{FN} = \frac{(L_{MT} + L_{NT} - d_{MN}) + d_{NP}}{2}
\]  

If the fault is on the PT branch, the distance from the fault point to the measurement point P is \( L_{FP} \), and the distance measurement formula is:

\[
L_{FP} = \frac{(L_{MT} + L_{PT} - d_{MP}) + (L_{NT} + L_{PT} - d_{NP})}{2}
\]  

### 3.2. Steps of fault location algorithm for transmission lines based on transient traveling waves

The Non-stationary signal analysis T line transmission line fault location steps are as follows:

1. Collect the fault voltage traveling wave signal of the three-phase transmission line.
2. Perform Clark line decoupling on the fault traveling wave information to obtain the line mode component of the transient voltage traveling wave.
3. Take the voltage line mode component and perform Non-stationary signal analysis to obtain the time when the fault initial traveling wave reaches the three-terminal detection point.
4. Locate the faulty branch according to the measurement time.
5. After determining the faulty branch, perform the corresponding fault location according to formulas (3), (4), and (5).

### 4. Simulation analysis

#### 4.1. Analysis of single-phase fault simulation results

Based on the T-terminal three-terminal fault diagram in Figure 3, a structural diagram is established on PSCAD-EMTDC. Due to transmission line failure 80% are single-phase ground faults, so the experiments mainly take the A-phase ground fault and F-fault as an example.
Figure 3. Fault simulation diagram of T-connected three-terminal transmission line

See Table 1 for transmission line parameters

| Table 1. Structural parameters of the line. |
|------------------------------------------|
| Transmission line model | resistance (Ωkm⁻¹) | inductance (H km⁻¹) | Capacitance (μF km⁻¹) |
|------------------------------------------|
| Positive sequence                      | 0.0321              | 0.00135            | 0.0075               |
| Negative sequence                      | 0.0321              | 0.00366            | 0.0075               |

Among them, the model parameters are: three-phase power supply voltage level is 220kV, transmission line voltage level is 500kV, frequency is 50Hz, sampling frequency is 1MHz, simulation time is 0.2s, MT, NT, and PT lengths on the transmission line are 185, 120, 140km, the transition resistance is 100; when the fault distance is 100km from the M terminal, the fault current traveling wave signals at the M, N, and P terminals are shown in Figure 4, Figure 5, and Figure 6.

Figure 4. M terminal fault current signal when phase A short circuit.

Figure 5. N terminal fault current signal when phase A short circuit.

Figure 6. P terminal fault current signal when phase A short circuit.

Because the observation range of the time domain and frequency of the Non-stationary signal analysis cannot be reduced or enlarged at the same time, after analyzing and comparing the results of each Because the observation range of time domain and frequency of Non-stationary signal analysis cannot be reduced or expanded at the same time, based on the analysis and comparison of the decomposition results of various scales, this paper chooses the optimal 5-scale decomposition to determine the time when the traveling wave head reaches each measurement point. The Non-stationary signal analysis results of the α-mode current traveling wave component measured at each measurement point are shown in Figure 7-9.
Figure 7. Non-stationary signal analysis result of fault current traveling wave reaching M terminal

Figure 8. Non-stationary signal analysis result of fault current traveling wave reaching N terminal

Figure 9. Non-stationary signal analysis result of fault current traveling wave reaching P terminal

From Figure 7 to Figure 9, at the beginning of the fault, the time when the traveling wave reaches each measuring point is $t_M = 0.070337\text{Ss}$, $t_N = 0.070705\text{Ss}$, $t_P = 0.070768\text{Ss}$. Substituting into the calculation of formula (3), we can know from the fault branch criterion the fault branch is MT, which is consistent with the actual fault branch. The distance $d = 99.81245\text{km}$ from the fault to the M measurement point is calculated, and the ranging error is 0.18755%.

4.2. Detection results at different fault distances

In order to verify the accuracy of the fault location method of the T-connection transmission line, fault location was performed on resistances such as 0, 10, 20, 50, 200, and fault points at the distance M, fault location experiments were performed at 10, 20, 50, 80, and 120 km, respectively. Finally, the average errors of six kinds of fault distance calculation results are given. The average error formula takes formula (6) as an example:

$$\Delta x = \left| \frac{d_j - L_{IT}}{L} \right| \times 100\%$$

(6)

Where $d_j$ is the calculated fault distance, $L_{IT}$ is the actual fault distance, and $L$ is the total line length.

| Malfunction distance | 0Ω | 10Ω | 20Ω | 50Ω | 100Ω | 200Ω |
|----------------------|----|----|----|----|------|------|
| 10km                 | 0.23 | 0.22 | 0.23 | 0.23 | 0.23 | 0.23 |
| 20km                 | 0.18 | 0.18 | 0.16 | 0.23 | 0.17 | 0.18 |
| 50km                 | 0.23 | 0.19 | 0.19 | 0.18 | 0.23 | 0.19 |
| 80km                 | 0.17 | 0.22 | 0.19 | 0.25 | 0.35 | 0.23 |
| 120km                | 0.12 | 0.13 | 0.15 | 0.33 | 0.23 | 0.12 |

Table 2. Test results of different fault distances and transition resistances

It can be seen from Table 2 that the method has certain fluctuations under the influence of different over-resistances, but the overall impact is small and the larger error is about 0.35%. For most tens of kilometers or even hundreds of kilometers of high-voltage transmission lines, this error is acceptable. Although these simulation results have errors, the differences between the two are not large, and most of them remain around 0.21%. Therefore, the method proposed in this paper is effective for different transition resistances.
5. Conclusion
This paper combines the fault location method of T-connected transmission lines based on the double-ended traveling wave ranging method with non-stationary signal analysis to accurately obtain the fault location of the transmission line problem. Aiming at the problems encountered in current transmission lines, through a large number of simulation experiments on fault distances of different transmission lines, it is proved that the method has high ranging accuracy. At the same time, it proves that for different transition resistance factors, the method also proves that the method is suitable for fault location of actual transmission lines.

References
[1] Gao Yanfeng, Zhu Yongli, Yan Hongyan, Fan Guochen. Traveling Wave Fault Location for Transmission Lines Based on Improved Double-Terminal Method [J]. Electrical Measurement and Instrument, 2015, 52(01): 41-46+52.
[2] Yan Feng, Yang Qixun, Qi Zheng, Yang Yihan, Hu Lifeng. Study on fault location method of distribution network based on traveling wave theory [J]. Journal of China Electrical Engineering, 2004(09): 41-47.
[3] Xin Zhengxiang, Zhao Xiaoxue, Jing Li, Chen Ping. A fault location method for T-type hybrid transmission line based on time axis setting [J]. Hydroelectric Energy Science, 2019, 37(07): 150-153+145.
[4] Qin Jian, Peng Liping, Wang Hechun. Single-ended Traveling Wave Fault Location for Transmission Lines Based on Wavelet Transform [J]. Power System Automation, 2005(19): 62-65+86.
[5] Qin Jian, Ge Weichun, Qiu Jinhui, Zheng Xinguang. Comparison of single-ended traveling wave ranging method and double-ended traveling wave ranging method for transmission lines [J]. Automation of Electric Power Systems, 2006 (06): 92-95.
[6] Qin Jian, Ge Weichun, Qiu Jinhui, Zheng Xinguang. Analysis of Main Factors Affecting Traveling Wave Fault Location Precision of Transmission Lines [J]. Power System Technology, 2007 (02): 28-35.
[7] A Abur, F.H Magnago. Use of time delays between modal components in wavelet based fault location [J]. International Journal of Electrical Power and Energy Systems, 2000, 22(6).
[8] Zhengzhou, Lu Yanping, Wang Jie, Wu Fan. A new method of double-ended traveling wave ranging based on wavelet transform [J]. Power System Technology, 2010, 34 (01): 203-207.
[9] Gao Hongyu, Chen Qing, Xu Bingxuan, Wang Lei, Song Weiping. A New Algorithm for Single-Ended Traveling Wave Fault Location of Transmission Lines [J]. Automation of Electric Power Systems, 2017, 41 (05): 121-127.
[10] Wang Mei, Zhu Liang, Zhang Guoqiang, Wang Liang, Liu Chi. New algorithm for fault location of T-line based on wavelet energy spectrum [J]. Vibration. Test and Diagnosis, 2018, 38 (03): 479-485.
[11] Lu Yu, Zhu Sicheng, Wang Nannan, Wang Jiacheng, Zhao Chengyong, Xu Jianzhong, Tang Hao. Location method of bipolar short-circuit fault in DC grid area based on current variation[J]. proceedings of the Chinese Academy of electrical engineering, 2019, 39 (16): 4686-4694+4971.
[12] Engineering - Power Delivery; New Power Delivery Findings Reported from National Taipei University of Technology (Multi-terminal Nonhomogeneous Transmission Line Fault Location Utilizing Synchronized Data)[J]. Energy Weekly News, 2019.
[13] Xin Zhengxiang, Zhao Xiaoxue, Jing Li, Chen Ping. A fault location method for T-type hybrid transmission line based on time axis setting [J]. Hydroelectric Energy Science, 2019, 37(07): 150-153+145.