Fault location method for neutral ungrounded system based on C-type travelling wave method

Haiyan Fan¹, Jincheng Qi²*, Zhilian Sun¹, Fayun Zhao¹, Ningming Guo³,⁴

¹Haibei power supply company, Haibei, QingHai, China
²Xian Jiaotong University, Xian, Shaanxi, China
³C-EPRI Electrical Power Engineering Co., Ltd, Beijing, China
⁴North China Electric Power University, Beijing, China

*Corresponding author e-mail: qbk1214@outlook.com

Abstract. In China, the 10 kV distribution network operates with neutral ungrounded. Due to the influence of high transition impedance and branches, the problem of fault location has not been effectively solved. The characteristics of C-type travelling wave method at neutral ungrounded system are analyzed in this paper. Multi-point fault location method based on C-type travelling wave method is proposed. By actively injecting high-voltage pulses into the circuit and using multiple measuring devices to detect the reflected wave of the fault point, the effect of high-impedance-grounded and branch points on the reflected wave of the fault point is effectively reduced, and the success rates of reflected wave detection of the fault point are improved. The validity of the method is verified by simulation.

1. Introduction

In the case of the neutral ungrounded system (NUS), among all faults, single-phase-to-ground fault is more than 70%, accurate fault location is of great significance for improving the power supply reliability and reducing the outage loss[1]. At present, the fault location methods based on travelling wave principle have been widely applied in transmission power system. From the operational experience, the accuracy of travelling wave method has satisfied the on-site requirement. However, when a single-phase-to-ground fault occurs in NUS, the transition resistance may have a high magnitude which causes the initial and reflected wave be relatively smooth during the transient period, therefore, the accuracy and reliability of fault location are significantly reduced. In addition, compared with transmission lines, there are many branches in distribution network which cause a series of interference to fault location. It is difficult to locate the fault point based on fault-travelling wave.

To solve the single-phase-to-ground fault location in neutral ungrounded system, based on the double-ended method, multi-terminal fault location method is presented in [2]. In the case of permanent fault, the value of transition resistor is relatively low [4]. Thus, in [5], the method based on C-type travelling wave scheme to solve the problem of fault distance determination is proposed, and to avoid the effect of branch point and transition resistance, the paper [7] proposes the method to acquire zero-mode waves by injecting symmetrical high-voltage pulse into three phase. Overall, existing research is based on multi-terminal fault location or C-type travelling-wave method, the former cannot avoid the effect from the large transition resistance during the transient period, and both of them need to face the problems of detection on weak signal.
Based on the existing research, in this paper, a multi-point fault location method based on C-type travelling wave method is proposed. To reduce the influence of branch lines, multiple measuring devices are distributed at the branch points and the ends of branches, so the identification success rate of reflected wave is improved. It ensures the reliability of Multi-point fault location.

2. Characteristics of C-type travelling wave method at neutral ungrounded system.

2.1. Principle of travelling wave

When a fault occurs, a fault-travelling wave propagating to both ends of the line will be generated at the fault point, and it will be reflected and refracted when encountering impedance discontinuities [8]. The energy and polarity of reflected and refracted waves will change to be a proportional relationship with the fault-travelling wave, this ratio is only affected by the wave-impedance of the line. Taking voltage travelling wave as an example, the specific calculation formulas are:

\[ \alpha = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]  
\[ \beta = \frac{2Z_2}{Z_1 + Z_2} \]  

Among them, \( \alpha \) is corresponding to the ratio of the reflected wave to the incident wave, \( \beta \) is corresponding to the ratio of the refracted wave to the incident wave. \( Z_1 \) is the impedance of the incident wave, \( Z_2 \) is the impedance of the refracting wave. The value of the reflection coefficient can be positive or negative. The value range is: \(-1 \leq \alpha \leq 1\); the value of the refractive index \( \beta \) is always positive and the value range is: \( 0 \leq \beta \leq 2 \). \( \alpha \) and \( \beta \) also satisfy the following relationship:

\[ \beta = 1 + \alpha \]  

It can be known from formula (1) that when the forward wave coefficient is larger than the backward wave impedance, the travelling wave returns to the same direction, otherwise, it returns to the negative direction [9]. In distribution network, impedance discontinuities include fault points, branch points and open circuit points. Assuming the initial travelling wave is positive, the reflected wave of fault and branch points will be negative while for open circuit points, it will be positive [5].

2.2. Principle of C-type travelling wave fault locations

As is shown in the Figure, by injecting high-voltage pulses into the line, the location is completed by recording the time difference between the injecting time and arrival time of the reflected wave on the fault point. Therefore, C-type travelling wave fault location also be called active travelling wave fault location. While the distance between the fault point and the measuring point is:
\[ d = \frac{(t_f - t_i) \times v}{2} \]  

In formula (4), \( t_i \) is the time of injecting, \( t_f \) is the arrival time of wave reflected by the fault point, and \( v \) is the propagation speed of the travelling wave. However, the amplitude of travelling waves will decay to \( 2/3 \) when passing through a branch point[7], so as the reflected wave. Notice that the branch point C is closer than the fault point to the injection point, so the reflected wave of fault point is much weaker than the one of branch point.

2.3. Fault point at the branches
The fault location of the neutral point ungrounded system is generally divided into three steps. The first step is fault line selection, the second step is fault selection, and the third step is accurate location. It is impossible to determine which branch the fault occurred by only recording the distance from the injection point to fault point, especially when a high-impedance-grounded fault occurs there.

![Waveform of no fault and high-impedance-grounded on branch line](image)

(a) Non-fault on branch line  
(b) High-impedance-grounded on branch line

Figure 2. Waveform of no fault and high-impedance-grounded on branch line

It can be seen from Figure 2, when a high-impedance-grounded fault occurs on branch lines, the detected waveform at the branch point is basically same as the waveform when there is no fault. However, even if there is a metallic-grounded, when the distance of fault point is shorter than the short branch, it is difficult to determine which branch the fault occurred on.

2.4. Dead area
Due to the characteristic of C-type travelling wave method and distribution network, it is difficult to accurately locate the fault point using the C-type travelling wave method when a fault occurs near the endpoint or branch point. And when the fault point is too close to the injection terminal, the reflected wave of fault point will be submerged by injecting signal. This dead area can be shortened by minimizing the width of injecting signal, but it is difficult to eliminate it completely. In additional, the reflect wave of branch point may superimpose with the reflected wave of fault point.

From the principle above, it can be concluded that the characteristics of C-type travelling wave fault location in the neutral point ungrounded system as follows:

1. The travelling wave injection method can be repeatedly used after the transient period, thus it can avoid the influence of large transition resistance.
2. The travelling wave injection method can determine whether the line has a permanent failure when offline, combined with auto-reclosing can determine whether the line fault has been eliminated and decide whether to reclose again.
(3) Since both the branch point and the fault point can reflect travelling waves, in extreme cases, when a fault occurs near the branch point, it is difficult to distinguish between them.

(4) The travelling wave will be attenuated each time when it passes through a branch point, as is the reflected wave of the fault point. Therefore, the signal of the reflected wave may be too small to be detected after passing through too many branch points.

(5) There may be a “false fault point” when the fault occurs on a branch line, double ended method can distinguish whether the fault occurs on circuit or branches if the length of circuit has been known. But when there are more than one branches in a branch point, it can hardly locate the fault point accurately.

3. Multi-measuring-point method based on C-type travelling wave principle

3.1. Basic Principles

From the analysis of section 2, it can be concluded the key to whether the C-type travelling wave method can be used to locate fault in a neutral ungrounded system is to accurately detect the reflected wave of the fault point. In order to reduce the effect of high-impedance-grounded and branch points on the reflected wave of the fault point, a multi-point locating method is proposed, which uses multiple measuring devices to separately record reflected wave of the fault point. At the same time, single-ended method is used to accurately locate the fault point.

3.1.1. Arrangement of measuring devices. Compared with the transmission line, the length of the distribution line is shorter, and the amplitude of the travelling wave is mainly affected by the branch point. To reduce this influence, a measuring device is set in front of each branch point of the main circuit. However, it is still difficult to accurately locate a fault point occurring on a branch. Therefore, a measuring device is set at each branches’ terminal to select the faulty branch line as shown in Figure 3.

3.1.2. Identification of the fault section. After collecting the data of the measuring devices on the main circuit, the effective data is intercepted according to the line length and the arrival time of injecting signal and reflected wave can be figured out by modular maximum method based on wavelet transform [10]. Compared with the waveform of non-fault, the reflected wave of fault point can be determined and the distance from fault point and the measuring point is calculated according the formula (4). Thus, the fault section including branches has been identified.

![Figure 3. Diagram of measuring points](image)

Note: squares represent measuring points

3.1.2. Identification of the fault section. After collecting the data of the measuring devices on the main circuit, the effective data is intercepted according to the line length and the arrival time of injecting signal and reflected wave can be figured out by modular maximum method based on wavelet transform [10]. Compared with the waveform of non-fault, the reflected wave of fault point can be determined and the distance from fault point and the measuring point is calculated according the formula (4). Thus, the fault section including branches has been identified.
3.1.3. Selection of fault branch line. When a fault occurs on branch line, it need a secondary location according to the data collected from measuring device on the ends of branch lines like 3.1.2.

3.2. Algorithmic Flow
The core of multi-point travelling wave fault location is to calculate the distance between fault point and measuring point based on the data recorded at the measuring points and the structure of the line. The algorithm flows are as follow:

(1) Collecting the data recorded at all measuring devices and intercepting the effective interval according to the line length. Then recording the data with a hierarchical tree list according to the topology.

(2) According to the data collected on the main circuit, figure out the arrival time of injecting signal and reflected wave by the modulus maximum method based on wavelet transform, eliminate the reflected waves at the branch points, and find whether there are abnormal points. If so, find the nearest measuring point, calculate the distance according to formula (4), and select the branches and circuit that the fault may occur on.

(3) Determining whether the fault occurs on the branch line according to the method described in 3.1.3. if so, give the location of the fault point on the branch line. Otherwise, give the fault point calculated based on the fault distance calculated in the second step and locating the fault on the circuit.

4. Simulation and results analysis

4.1. Simulation Verification
Based on the section 3.1.1 model, the proposed method is verified through EMTDC simulation. In the simulation, the frequency dependent parameters module is used with the distribution line structure shown in Figure 4. The amplitude of the injected signal is 1kV and the pulse width is 3 μs while sampling rate is set to 10MHz. Assuming the fault point is on the B12 to B122 branch line, and 0.9km from the B122 measuring point.

![Figure 4. The power distribution line in simulation](image-url)

(a) non-fault (b) fault
Figure 5. The waveform of the measuring point on circuit.

The simulation results are processed through MATLAB program. As shown in Figure 5, however, the reflected wave of fault point still cannot be distinguished after removing the reflected waves of the branch points according to the line structure. Therefore, to locate the fault point, the data collected from measuring devices in the terminal of branches need to be analyzed.

Figure 6. The waveform of the measuring point B121 and B122.

As shown in Figure 6, from the data of measuring point B121 and measuring point B122 the reflect wave of fault point is detected. As is shown in Figure 6(b) the time difference from injecting signal to the reflected wave is 6.8μs. Assuming that the velocity of travelling wave is 296.2m/μs, the distance between the fault point and measuring point B122 is 1.007km, the error is about 100 meters.

It has been noticed that the fault occurs on branches may cannot be detected by measuring devices which on the circuit. In the example above, the reflected wave of fault point is submerged by the reflected wave of point A and B11.

4.2. Results analysis

In order to verify the feasibility of this method, different fault points are set as Figure 7.
Metallic and high-impedance-grounded faults are simulated respectively. The results of simulation are shown in the table 1. The data of point γ is collected by measuring device B, for there is a dead area in the data of measuring device O. The identifying of the reflected wave is precise; even under complex condition, its errors are basically within 200m. Considering that most of permanent faults are metal-grounding that the value of transition resistance is low, so the accuracy of this method satisfy the requirement of fault location in neutral ungrounded system.

| Fault point | Fault transition resistance = 0Ω | Fault transition resistance = 100Ω | Fault transition resistance = 1kΩ |
|-------------|----------------------------------|-----------------------------------|-----------------------------------|
| α           | 1007.1                           | 1021.9                            | 1051.5                            |
| β           | 1199.6                           | 1184.8                            | 1170.0                            |
| γ           | 651.64                           | 622.02                            | 562.78                            |

5. Conclusion
In NUS, the problem of fault location has not been effectively solved. Influenced by branch lines, the existing fault location method based on travelling wave method in transmission lines cannot be used directly. The success rate of reflected wave identification is relatively low. To solve the above problems, the following research work has been carried out:

(1) In NUS, the interference caused by branches and fault transition resistance are the main influence factors for fault location based on travelling wave method. Both of them can cause the reflected wave be too weak to be detected. However, the reflected wave of fault point can be accurately detected by multi-measuring-devices. Thus, it is feasible to suppress interference by multi-measuring-points method.

(2) A novel fault location method for NUS based on C-type travelling wave is proposed in paper. Using multi measuring devices to detect reflected wave, it can suppress the influence by reducing the number of branch points passed by reflected wave before arriving the measuring device. The validity of the method is verified by simulation data analysis in paper.
References

[1] Yadong Liu, Gehao Sheng, Yue Sun, et al. A distributed fault algorithm for single-phase ground fault by comprehensive analysis on fault current information. J. Power System Technology, 2012 Vol 36(8) pp87-94.

[2] Feng D, Xinran L, Xiangjun Z, et al, A novel multi-terminal fault location method based on travelling wave time difference for radial distribution system with distributed generators, J. Proceedings of the CSEE, 2018 Vol 36(15) pp. 4399-4409.

[3] Huibin Jia, Hai Feng Zhao, Qianghua Fang, et al, A single-phase earth fault location method for distribution network based on multi-terminal travelling wave. Automation of Electric Power Systems. 2012, Vol 36(2), pp. 96-100.

[4] Jiale Suonan, Ling Dui, Guobing Song, et al. Permanent fault identification method of transmission lines using transition resistance parameter. J. High Voltage Engineering. 2011, Vol 37(8) pp. 1944-1951

[5] Shengnan YU, Yi-han YANG, Hai BAO, Study on fault location in distribution network based on C-type travelling-wave scheme, J. Relay, 2007 Vol 35(10) pp. 1-pp. 4, 12

[6] Feng Yan, Shuangshuang Li, Composite fault location method based on C-travelling wave and SVM for distribution lines. J. Proceedings of the CSU-EPSA, 2016 Vol 28(1), pp. 86-90

[7] Qin Ren, Qin Shu, Yong Liu, A fault location algorithm for distribution network based on extracting features from the reflected wave of symmetrical injection method, J. Power System Protection and Control, 2015, Vol 43(24), pp. 19-25.

[8] Yaozhong Ge, Theory and techniques for new types of protective relaying and fault location, second ed. M. Xi’an: Xi’an Jiaotong University Press, 2007

[9] Huiqiong Liu, Research on travelling waves fault location for multiple branch distribution networks. D. Changsha, Changsha University of Science& Technology, 2014.

[10] Jian Qin, Chun Wei, Jinhui Qiu, et al. Study on single terminal method and double terminal method of travelling wave fault location in transmission line. J. Automation of Electric Power Systems, 2006, Vol 30(6), pp. 92-95.