Fault Location Technology Research on Single Phase-to-ground Fault in Distribution Networks with Phase-to-phase Power Supply Lines

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Abstract. Nowadays phase-to-phase power supply lines are adopted to part of MV distribution networks in order to improve the cost-effectiveness. However, the propagation of traveling wave is complicated if the single phase-to-ground fault occurs, which affects the accuracy of the fault location. This paper proposes a novel method. It considers the propagation mechanism of traveling wave produced by single phase-to-ground fault, including phase-mode transformation, the velocity of different mode, and the propagation characteristic at boundary. Whether the fault position is at the phase-to-phase power supply lines or the three-phase power supply lines can be identified and the fault distance calculated based on the time difference of the arrival surge between the aerial-mode and zero-mode components. EMTP/ATP simulation software verifies the reliability and accuracy of the method.

1. Introduction

China's distribution network is mostly a neutral point non-effective grounding system, and single phase-to-ground fault accounts for about 80% of all faults[1]. Accurate positioning of fault points is a hot topic that scholars have been studying for a long time. As an effective method, traveling wave method has been gradually applied in the distribution network[2].

The traveling wave method can be divided into a single-ended method and a double-ended method in principle[3-6]. Due to the large number of distribution network branches, the cost of using double-ended traveling wave fault location method is relatively high, and it is difficult to achieve full network coverage in engineering. Therefore, scholars have conducted in-depth analysis of single-ended traveling wave location method. The traditional single-ended method uses the time difference between the arrival time of the first wave head of the fault and the arrival time of the reflected wave of the opposite bus or the fault point. However, the distribution network has more phenomenon of reflection and refraction, and the recognition of reflected traveling waves is difficult. The voltage transformer's transmission characteristics are not high, resulting in low accuracy of single-ended traveling wave ranging. In [7], the distance measurement method based on the zero-aerial mode time difference is adopted, and the different distances of the different mode components are used to cause different arrival times, and the fault distance is obtained. The method realizes single-ended fault location, and does not need time synchronization and simple implementation, so it is widely used.

At present, many power supply companies use phase-to-phase power distribution in many parts of power distribution based on cost-saving considerations [8]. The specific implementation method is as follows: the 10kV medium voltage three-phase distribution line only takes out the two-phase line to the
end load at a certain position, pole or cable branch box, and connects the load through a 10kV/220V single-phase distribution transformer. The phase-to-phase power supply method can reduce the line cost and improve the reliability of the power supply and reduce the line loss to some extent. After the single phase-to-ground fault occurs in the distribution network with phase-to-phase power supply lines, the traveling wave transmission process is relatively complicated, which affects the fault location accuracy based on traveling wave. At present, there is little research on single phase-to-ground fault location technology with phase-to-phase power supply lines. Therefore, it is urgent to study the fault location method suitable for phase-to-phase power supply line to fill this gap.

In this paper, the fault location technology after single phase-to-ground fault in the radial distribution network with phase-to-phase power supply lines at the end of the circuits is studied in depth, including the analysis of the traveling wave transmission mechanism, the time difference between the aerial-mode and zero-mode components and the implementation of fault location. The reliability and accuracy of the proposed method are verified by EMTP/ATP simulation software.

2. Analysis of traveling wave transmission mechanism of distribution network with phase-to-phase power supply lines

2.1. Phase-mode transformation study

When a fault occurs, the transmission wave process of its transient voltage traveling wave can be expressed by a second-order partial differential equation:

$$\frac{\partial^2 U}{\partial x^2} = L \frac{\partial^2 U}{\partial t^2}$$  \hspace{1cm} (1)

Where \( U \) is the column vector of \( n \) conductor-to-ground voltages, \( x \) is the length of the transmission line, \( L \) and \( C \) are the matrix of inductance and capacitance parameters per unit length on the line, and \( t \) is time. Due to the coupling phenomenon in the line, both \( L \) and \( C \) are \( n \)-order full arrays, and the product is not a diagonal matrix. When analyzing the traveling wave transmission process, an appropriate matrix transformation is required to convert it into a diagonal matrix. Taking the voltage traveling wave as an example, the Karenbauer transformation matrix is used to perform the similar transformation [9]:

$$S^{-1} LCS = A_u$$  \hspace{1cm} (2)

Where \( A_u \) is the modulus diagonal matrix after matrix transformation, and \( S^{-1} \) is the Karenbauer inverse transformation matrix. For an \( n \)-phase transmission line.

The Karenbauer transformations of the phase-to-phase power supply lines and the three-phase power supply lines are:

$$\begin{bmatrix} u_{m(0)(2)} \\ u_{m(1)(2)} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \end{bmatrix}$$

$$\begin{bmatrix} u_{m(0)(3)} \\ u_{m(1)(3)} \\ u_{m(2)(3)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$  \hspace{1cm} (3)

where \( u_a \), \( u_b \) and \( u_c \) are phase voltage, \( u_{m(2)(2)} \), \( u_{m(1)(3)} \) and \( u_{m(2)(3)} \) are aerial mode components, \( u_{m(0)(2)} \) and \( u_{m(0)(3)} \) are zero mode components.

2.2. Modulus wave velocity study

Assume that the diagonal element of the line inductance parameter matrix is \( L_k \), the non-diagonal element is \( L_{ik} \), the diagonal element of the capacitance parameter matrix is \( C_k \), and the non-diagonal element is \( C_{ik} \). According to the literature[10], the modulus wave velocity of three-phase supply line can be obtained. The wave velocity of the aerial component and zero mode components are:
\[ v_{m(3)} = \frac{1}{\sqrt{(L_k + 2L_{ok})(C_k + 2C_{ok})}}, \quad v_{m(2)} = v_{m(3)} = \frac{1}{\sqrt{(L_k - L_{ok})(C_k - C_{ok})}} \]  

(4)

Where \( v_{m(3)} \) and \( v_{m(2)} \) represent the aerial-mode component wave velocity of the three-phase supply line and \( v_{m(0)} \) represents the zero-mode component wave velocity of the three-phase supply line.

Similarly, the wave velocity of the phase-to-phase power supply line’s aerial-mode component and the zero-mode component can be obtained as:

\[ v_{m(0)} = \frac{1}{\sqrt{(L_k + L_{ok})(C_k + C_{ok})}}, \quad v_{m(2)} = \frac{1}{\sqrt{(L_k - L_{ok})(C_k - C_{ok})}} \]  

(5)

Where \( v_{m(2)} \) and \( v_{m(0)} \) represent the wave speeds of the aerial-mode component and the zero-mode component of the phase-to-phase power supply line, respectively. Due to the short distribution line, the dispersion of the zero-mode component is not serious. The velocity of the zero-mode component is assumed to be determined only by the line parameters[10]. It can be seen from the analysis formulas (4) and (5) that the line mode component wave velocity of the phase-to-phase power supply line and the three-phase distribution branch are equal, but the difference between the zero-mode component wave velocity is large.

2.3. Analysis of traveling wave transmission process of single phase-to-ground fault

Figure 1 shows a schematic diagram of a phase-to-phase power supply line in distribution network, in which the A, B phase of the three-phase power supply line is connected to the phase-to-phase power supply line. Point P is the location of the detection device, point K is the boundary between the three-phase supply line supply line and the phase-to-phase power supply line, and the end of the phase-to-phase power supply line is the distribution transformer. The distance between the fault point and the detection device is \( l_f \), and \( l_1 \) is the distance from the boundary point to the detection device, \( l_2 \) is the distance from the junction point to the transformer at the end of the line.

![Figure 1. Distribution network model including phase-to-phase power supply line](image)

2.3.1. The fault occurs in phase-to-phase supply line

In figure 1, F1 shows a A-phase-to-ground fault occurs in the phase-to-phase power supply line. According to the superposition theorem, the equivalent circuit after the fault can be equivalent to the normal network before the fault and the network of the additional power supply after the fault[11]. The fault transient traveling wave is a traveling wave generated by the additional power supply at the line fault point.

The aerial-mode component and the zero-mode component will continue to follow the time of the three-phase supply line, aerial-mode and zero-mode component reaching P are \( t_{p1} \) and \( t_{p0} \).
In summary, the process of traveling wave from phase-to-phase power supply line to three-phase is more complicated. The time difference of the initial wave head of the traveling wave aerial-mode component and the zero-mode component reaches P point is related to the process of the traveling wave in both three-phase power supply line and phase-to-phase power supply line.

2.3.2. The fault occurs in three-phase supply line

In figure 1, F2 and F3 shows the single phase-to-ground fault. The aerial-mode component and the zero-mode component will continue to follow the time of the three-phase supply line, aerial-mode and zero-mode component reaching P are \( t_{p1} \) and \( t_{p0} \):

\[
    t_{p1} = \frac{l_f}{v_{m3(2)}} + \frac{l_f - l_i}{v_{m3(3)}}; \quad t_{p0} = \frac{l_f}{v_{m0(3)}} + \frac{l_f - l_i}{v_{m0(2)}},
\]

In summary, the process of traveling wave from the three-phase power supply line to the phase-to-phase is complicated, but whenever the single phase-to-ground fault occurs in phase A, B or C of the three-phase distribution branch, the time when the initial wave head of the traveling wave aerial-mode component and the zero-mode component reaches the point P is only related to the transmission process of the traveling wave on the three-phase power supply line, and is not impacted by the traveling wave across the boundary point on the phase-to-phase power supply line.

3. Traveling wave fault location based on multi-mode wave velocity difference

Since the voltage transformer, FTU and other detection devices are rarely installed on the phase-to-phase power supply line, this paper studies the fault location using the detection device on the three-phase supply line, as shown in point P in Figure 1. At present, the sampling rate of the FTU is not enough to measure the traveling wave signal, and a special high-frequency sampling device can be used in parallel with the FTU to measure the voltage traveling wave signal. In the future, with the decline in the price of electronic products, FTU can be fully implemented with traveling wave detection.

3.1. Fault section decision

In order to achieve accurate positioning of the whole network and eliminate false fault points, it is necessary to first narrow down the fault range. This paper uses the more mature distribution network section positioning technology to determine the section where the fault point is located [12, 13]. When the fault zone is included in the phase-to-phase power supply line, it is necessary to determine whether the fault point is located in the three-phase power supply line or the phase-to-phase in the fault section.

Still taking the system shown in Figure 1 as an example, assuming that the fault occurs at the boundary K, the time difference between the arrival of the aerial-mode component and the zero-mode component obtained by the detecting device is \( \Delta t_{critical} \), and it can be calculated:

\[
    \Delta t_{critical} = \frac{l_i}{v_{m0(3)}} - \frac{l_i}{v_{m3(3)}}.
\]

Therefore, when the actual time difference \( \Delta t > \Delta t_{critical} \), the fault point is located on the phase-to-phase power supply line; when the actual time difference \( \Delta t < \Delta t_{critical} \), the fault point is located on the three-phase power supply line.

3.2. Fault distance calculation

If the fault point is on the phase-to-phase power supply line, according to the analysis results in section 1.3.1, the location algorithm must fully consider the transmission process of the fault traveling wave on the phase-to-phase power supply line and the three-phase. If the detecting device at point P detects that
the time difference between the arrival of the aerial-mode component and the zero-mode component is \( \Delta t = t_{p0} - t_{p1} \), then the fault distance can be calculated according to formulas (6)

\[
I_f = I_1 + \frac{v_{m1}(2)v_{m0}(2)(\Delta t + \frac{I_1}{v_{m1}(3)} - \frac{I_1}{v_{m0}(3)})}{v_{m1}(2) - v_{m0}(2)}
\]  

(8)

If the fault point is on the three-phase power supply line, according to the analysis result in section 1.3.2, the detecting device at point P detects that the time difference between the arrival of the aerial-mode component and the zero-mode component is \( \Delta t = t_{p0} - t_{p1} \), then the fault distance can be calculated according to equations (7):

\[
I_f = \frac{v_{m1}(3)v_{m0}(3)}{v_{m1}(3) - v_{m0}(3)} \Delta t
\]  

(9)

3.3. Algorithm flow

In summary, the process of fault location is as follows:

1. The detection device located on the three-phase power supply line measures data such as voltage and current in real time. When a single phase-to-ground fault occurs, the segmentation technology is used to judge that the fault point is located downstream of a detection device [12, 13].

2. The detecting device intercepts the three-phase voltage signal for a period of time before and after the fault, and uses the Karenbauer transform to obtain the line mode and zero mode component of the voltage traveling wave.

3. Using Hilbert Transform [14, 15] as the method of wave head extraction, obtain the arrival time of the wave head of aerial-mode component and the zero-mode component of the voltage traveling wave, and then find the arrival time difference \( \Delta t \) between the aerial-mode component and the zero-mode component.

4. Determine the three-phase power supply line or the phase-to-phase where the fault point is located. Using the network structure to calculate \( \Delta t_{critical} \), when the actual time difference \( \Delta t > \Delta t_{critical} \), the fault point is located on the phase-to-phase power supply line, otherwise the fault point is located on the three-phase power supply line.

5. If the fault point is on the phase-to-phase power supply line, calculate the fault distance using equation (8); if the fault point is on the three-phase power supply line, calculate the fault distance using equation (9).

4. Simulation analysis

![ATP model of 10kV distribution network](image-url)
In this paper, the model matched with the actual distribution network is built by EMTP/ATP simulation software, as shown in Figure 2. The positioning technology described in this paper relies on the scientific and technological project of Liaoning Province to realize the on-site application. The sampling frequency of the detection device is 2MHz. The P-K-Q segment of the line is the faulty line, and the three-phase power supply line is extended to the phase-to-phase power supply line through the A and B phases. It is assumed that the detection device is located at point P, and the length of the three-phase distribution branch downstream of point P is 5 km.

The model number of the conductor is LGJ-120, and the inductance and capacitance parameters of the three-phase power supply line and phase-to-phase power supply line are shown in Table 1.

|                  | \( L_1 \) (10^{-3}mH/km) | \( L_2 \) (10^{-3}mH/km) | \( C_1 \) (10^{-6}uF/km) | \( C_2 \) (10^{-6}uF/km) |
|------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Single-phase     | 1.058                    | 3.698                    | 10.678                   | 5.733                    |
| Three-phase      | 1.058                    | 5.018                    | 10.6778                  | 2.871                    |

According to Table 1 and the parameters of Figure 2, using (4) (5), wave velocity can be calculated as follows:

\[
\begin{align*}
    v_{m1(1)} &= 2.9752 \times 10^5 \text{km/s}, \\
    v_{m1(2)} &= 2.6348 \times 10^5 \text{km/s}, \\
    v_{m2(3)} &= 2.1718 \times 10^5 \text{km/s}.
\end{align*}
\]

And the \( \Delta t_{\text{critical}} = 2.17\mu s \).

4.1. Grounded via low transition resistance

The single phase-to-ground fault occurs on the phase-to-phase power supply line, the transition resistance is 10Ω, the fault point is 2.54km away from the boundary K, and the fault type is phase A ground fault. Measuring the three-phase voltage traveling wave at the point of the detecting device P, the aerial-mode component of the A-C phase and the zero-mode component of the three-phase voltage are calculated, and the result is shown in Figure 3. It can be clearly seen that there is a time difference between the arrival time of the voltage traveling wave aerial-mode and the zero-mode component. The Hilbert-transform is performed on the A-C phase aerial-mode component and the three-phase zero-mode component, and the transformed waveform is obtained as shown in Figure 4.

![Figure 3. Aerial and zero mode component waveform](image1)

![Figure 4. Hilbert transformation result of both aerial-mode and zero-mode component](image2)

From Figure 5, the time difference between the voltage aerial-mode component and the zero-mode component is calculated as \( \Delta t = 5.5\mu s \), and it can be found that the fault is located on the phase-to-phase power supply line. From formula (8), the distance between the fault point and point P can be calculated as:
\[ l_f = l_i + \frac{v_{m(2)} v_{m(0)} (\Delta t + \frac{l_i}{v_{m(3)}} - \frac{l_i}{v_{m(0)}})}{v_{m(2)} - v_{m(0)}} = 7677.28 \text{m} \]

Compared with the actual fault distance of 7.54km, the error is 0.137km and the relative error is 1.8%. Fault location in metallic ground faults, multimode ranging methods can achieve higher accuracy.

In order to verify the accuracy of the multi-mode wave velocity difference location algorithm proposed in this paper, Table 2. shows the simulation results of different fault resistances of phase A-phase-to-ground fault.

**Table 2. The simulation results of different fault resistances of phase C-to-ground fault**

| Fault resistances (Ω) | Fault distance (m) | Calculation result (m) | Relative error |
|-----------------------|--------------------|------------------------|---------------|
| 10                    | 7540               | 7677.28                | 1.8%          |
| 100                   | 7540               | 7677.28                | 1.8%          |
| 1000                  | 7540               | 7743.58                | 2.7%          |
| 2000                  | 7540               | 7743.58                | 2.7%          |
| 3000                  | 7540               | 7796.36                | 3.4%          |

From Table 2, it can be seen that with the increases of the fault resistance, the relevant error is slightly increased. However, the maximum error is within an acceptable limit.

### 4.2. The influence of the distance between the fault point and the detecting device

The accuracy of traveling wave fault location is affected by the distance between the fault point and the position of the detecting device. Table 3 is the simulation result of the different distances from the fault point to the detection device (the grounding resistance is 100Ω). It can be seen that it is difficult to accurately locate the fault at the exit of the detecting device, and there is a dead zone. This is because the sampling rate limit cannot effectively determine the arrival time of the voltage traveling wave mode and the zero mode wave head.

**Table 3. Simulation of different fault location**

| Fault distance /km | Fault location result /km | Absolute error | Relevant error |
|--------------------|---------------------------|---------------|---------------|
| 1                  | 1.11                      | 0.11          | 11 %          |
| 0.8                | 0.63                      | 0.17          | 21.3%         |
| 0.4                | 0.58                      | 0.18          | 45%           |
| 0.1                | 0.21                      | 0.11          | 110%          |

### 5. Conclusion

This paper analyzes the traveling wave transmission characteristics of a single phase-to-ground fault after the single phase-to-ground fault in the radial distribution network with phase-to-phase power supply line at the end of the line, and reveals the difference between phase-to-mode transformation of the three-phase power supply line and the phase-to-phase power supply line. In this paper, the fault branch judgment and fault location method based on multi-mode wave velocity difference are proposed. The positioning method based on zero-aerial-mode component wave velocity difference is complemented and improved. The ATP simulation shows that the proposed method can effectively solve the single phase-to-ground fault location problem of the radial distribution network with phase-to-phase power supply line at the end of the circuits, which is less affected by the transition resistance.

This paper is based on the analysis of conventional radial distribution network. As the ring network structure increases and the distributed power supply (DG) is more connected [16,17], the traveling wave based fault location technology proposed in this paper is a challenge and it will be further analyzed in depth in the research work in the future.

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