New Method for Single-phase-grounded Fault Location in Small Current Grounding System

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Abstract. Based on the analysis of the single-phase-grounded fault characteristics in ungrounded systems, a single-end fault location method was proposed which is built on the zero-sequence voltage calculation at the fault point and impedance method. It calculates each phase voltages of the line fault point by introducing the connection between the line loss and the fault distance into the zero-sequence voltage trajectory calculation process. At the same time, combining the current characteristics of the ungrounded neutral point system, the functional relationship of the fault distance was deduced, with respect to the voltage difference between the voltage at the beginning of the fault and the fault point, and the fault location function was constructed according to the Kirchhoff voltage equation. The PSCAD/EMTDC platform is used to build the power cable model. The simulation verification of this method is carried out under the single-phase ground fault. The results show that the algorithm can complete the fault location without detecting the fault current data, and has a certain degree of robustness to the changes in load and fault resistance.

Introduction

With the development of feeder automation, more and more domestic and foreign scholars have devoted themselves to the research of automatic fault location in distribution networks. However, there are still many problems in the fault location of the neutral point ungrounded system, especially for the single-phase-grounded fault location that accounts for 80% of the total fault types [1].

Summarizing the research status at home and abroad, the algorithm for single-phase-grounded fault location in ungrounded systems is mainly divided into two categories. One is the injection detection method [2-4], which injects signals such as high-voltage pulses, S-waves, etc. into the line after the fault occurs, and then locates fault based on the signal characteristics of returned injection wave. This method can accurately locate faults and is less affected by load variations. However, this method requires the addition of professional traveling wave injection devices and detection devices, which have relatively high costs and are not conducive to generalize. Another is the passive detection method, which can be subdivided into two types: steady-state detection and transient monitoring. Reference [5-7] is about transient detection method, which finds the fault features of the traveling wave by extracting the traveling wave after fault and using the data analysis method, and locate fault finally. However, this method is now mostly in the theoretical stage and the economical efficiency of it still needs to be improved, due to the complexity of reflection of traveling wave and the dependence that algorithm has on the accurate identification of reflected wave front. Steady-state detection method, also known as impedance method, derives from locating the fault in long-distance transmission line. It locates in terms of the connection between the direct ratio of line impedance and the length of the line, which is characterized by simplicity and easy implementation. It has been highly favored, since the impedance ranging method is not affected by Double-end synchronism. Reference[8] presents a calculation of short-circuit current by using the differences between symmetrical component currents before and after fault to realize fault location. Reference [9,10], based on the principle of nodal impedance matrix, combines the bus-injected current after fault to complete the calculation of fault node voltages, and finally adds the magnitude...
of voltages into the ranging equation for positioning. Reference [11] constructs the ranging equation by assuming that the fault resistor consumes zero reactive power, and uses an iterative calculation method to obtain the short-circuit currents. However, it takes extended time to position and lacks of real-time performance. According to the above method, it can be found that most of the existing impedance methods need to detect the current data after the fault. However, the ground current of ungrounded system is often small and the fault characteristics are not obvious \(^{[12]}\), so there are still some difficulties in the single-ended detection of fault current.

For the existing problems, this paper proposes a single-end fault location method based on zero-sequence voltage calculation of fault point and impedance method. First, the faulty voltage phase is calculated by introducing the fault location into the equation of zero-sequence voltage trajectory. At the same time, combining with the fault current characteristics of the ungrounded neutral point system, the method for calculating the voltage rise between the fault point and initial point of the line is deduced on the basis of the impedance method. Finally, the fault can be located by combining the data of initial fault voltage and solving the equation based on the Kirchhoff Voltage. The PSCAD simulation verified that this method only requires the voltage data after the fault to complete the fault location.

### The Basic Principle of Fault Location

#### Zero-sequence Voltage Calculating Method

Traditional fault zero-sequence voltage calculation was originally used in judging the faulty line at the bus. The basic idea is presented as follows. First, the distribution networks can be equivalent to the circuit shown in Figure 1.

![Figure 1. Zero-sequence voltage calculation model.](image)

where \( E_A, E_B, \) and \( E_C \) represents the symmetrical three-phase voltage at the beginning of the transmission-line and voltage satisfies \( E_A = \alpha E_B = \alpha E_C; \) \( C_A, C_B, \) and \( C_C \) represents relative capacitance of each phase; \( R_f \) represents the fault resistance. After that, assuming that the A-phase-grounded fault occurred in the system, the faulty line can be found by analyzing the phase voltage of each transmission-line at the bus after the fault occurred. This calculating method only needs the phase voltage data at the bus that could realize the calculation of fault zero-sequence voltage which is equal to the sum of three-phase fault voltage. The calculation method of zero-sequence voltage \( U_0 \) at the bus is shown in formula (1) according to the figure 1.

\[
U_o(R_f) = \frac{\dot{E}_A \left( \frac{1}{R_f} + j \omega C_A \right) + \dot{E}_B j \omega C_B + \dot{E}_C j \omega C_C}{\frac{1}{R_f} + j \omega C_A + j \omega C_B + j \omega C_C} \tag{1}
\]

If the relative capacitances are equal, that is, \( C_A = C_B = C_C = C_0, \) then the total capacitive reactance of the line to ground is \( 1/3j\omega C_0 = X_C. \) The formula above can be simplified as:

\[
U_o(R_f) = \dot{E}_A \frac{X_C}{R_f + X_C} \tag{2}
\]

At the same time, the angle between the zero-sequence voltage and the fault phase voltage \( E_A \) can be obtained by Equation (3).

\[
\theta = \arctan(-R_f/X_C) \tag{3}
\]
$X_C$ is a constant for transmission-lines with constant length. According to equation (2), the zero-sequence voltage of the system is a function of the fault resistance. Using equation (3) and combining the cosine theorem, the relationship between the voltage of each phase at the bus and the fault resistance can be further expressed as follows:

$$U_{AC}'(R_f) = \dot{E}_A + \dot{U}_a(R_f) = \frac{\dot{E}_A R_f}{R_f + X_C}$$  \hspace{1cm} (4)$$

$$U_{BC}'(R_f) = \dot{E}_B + \dot{U}_b(R_f) = \dot{E}_A \left[ \alpha - \frac{X_C}{R_f + X_C} \right]$$  \hspace{1cm} (5)$$

$$U_{CO}'(R_f) = \dot{E}_C + \dot{U}_c(R_f) = \dot{E}_A \left[ \alpha - \frac{X_C}{R_f + X_C} \right]$$  \hspace{1cm} (6)$$

However, considering that most of the actual distribution network lines are long, the line losses cannot be neglected, so that the initial voltage at the bus is not equal to the fault point voltage. Therefore, this paper proposed to incorporate the line loss into the zero-sequence voltage calculation process in order to improve the calculation accuracy of the zero-sequence voltage at the fault point.

Construct a $\pi$-type equivalent circuit to calculate the line loss as shown in Figure 2. Considering the capacitance to ground and the coupling between phases, the line loss can be calculated based on the injection current and the voltage at the beginning of the transmission-line. Assuming that the distance from the starting point of the fault point is $x$, then the voltage value of the fault point before the fault can be calculated according to formula (7) according to the reference[11].

$$\begin{bmatrix}
\dot{U}_{IA}(x) \\
\dot{U}_{IB}(x) \\
\dot{U}_{IC}(x)
\end{bmatrix} = \begin{bmatrix}
a_s & -b_s \\
-a_s & a_s \\
-b_s & b_s
\end{bmatrix} \begin{bmatrix}
\dot{E}_A & \dot{E}_B & \dot{E}_C \\
I_{IA} & I_{IB} & I_{IC}
\end{bmatrix}$$

$$a_s = U + 0.5x^2 \cdot Z_{ABC} \cdot Y_{ABC}$$

$$b_s = x \cdot Z_{ABC}$$

Simplified the Formula (7) can get (8):

$$\dot{U}_i(x) = \begin{bmatrix}
a_s & -b_s
\end{bmatrix} \begin{bmatrix}
\dot{E} \\
I
\end{bmatrix}$$  \hspace{1cm} (8)$$

In Equations (7) and (8): $E_A$, $E_B$, $E_C$ and $I_{IA}$, $I_{IB}$, $I_{IC}$ represent the three-phase voltage and current vector of the starting end respectively; Vector set $U_i(x)$ concluding the voltages $U_{IA}(x)$, $U_{IB}(x)$, $U_{IC}(x)$, which means the function about voltage of each phase at the fault point and fault distance; $Z_{ABC}$ represents the line transimpedance and self-impedance matrix; $Y_{ABC}$ represents the line charging susceptance matrix; $U$ represents the unit matrix.

Since the line loss is taken into account in the calculation of the zero-sequence voltage, the equivalent circuit model of Figure 1 will be replaced by the form of Figure 3 adaptively.
Figure 3. Fault point zero-sequence voltage calculation model.

For the equivalent circuit of figure 3, the A-phase grounded fault is still taken as an example. Substituted the line loss (8) into the formula (4), (5) and (6). The expression of the zero-sequence voltage phasor $U_{f0}(x,R_f)$ considering the line lose can be shown as follow.

$$U_{f0}(x,R_f) = -U_{fa}(x) \frac{X_c}{R_f + X_c}$$

(9)

According to equation (9), the calculation formulas of the voltages at the fault points after considering the line losses can be obtained can be expressed as equations (10), (11) and (12) and its zero-sequence voltage phasor trajectory is shown in Figure 4.

Figure 4. Zero-sequence voltage phasor trajectory.

Where $G$ represents the neutral point; $E_A$, $E_B$, $E_C$ represent the source voltage phasor; $U_{fa}(x)$, $U_{fb}(x)$, $U_{fc}(x)$ represent the voltage phasor at the fault point after considering the line loss; $\omega$ represents the overall impedance angle; $\gamma$ represents the angle between the zero-sequence voltage and the fault phase voltage at the fault point.

Among them, the integrated impedance angle represents the superposition of the cable line impedance angle and the load impedance angle. For the calculation method, refer to formula (13).

$$U_{AG}(x,R_f) = \hat{U}_{ja}(x)R_f / R_f + X_c$$

(10)

$$U_{BG}(x,R_f) = \hat{U}_{ja}(x)\left[\alpha^2 - \left(\frac{X_c}{R_f} + X_c\right)\right]$$

(11)

$$U_{CG}(x,R_f) = \hat{U}_{ja}(x)\left[\alpha - \left(\frac{X_c}{R_f} + X_c\right)\right]$$

(12)

$$\omega = \arctan\left[\left(\frac{X_{line} + X_{load}}{\left(R_{line} + R_{load}\right)\right}\right]$$

(13)

$$\gamma = -\frac{R_f}{X_c}$$

(14)

It can be seen from the above analysis that zero-sequence calculating method does not require fault current data that could express the formula of each phase voltage. In this way, single-ended tracking of the zero-sequence voltage at the fault point is achieved.

Method for Calculating Voltage Rise from Fault Point to Monitoring Point

Because the actual transmission-line has impedance and usually with long distance form the bus,
the voltage of each phase at the fault point is not equal to the actual measured voltage at the beginning of the transmission-line. Therefore, by calculating the zero-sequence voltage at the fault point to fault location is not enough. The further analysis about how to calculate the voltage difference between the actual measured voltage and the fault point voltage at fault point is still required. The equivalent circuit is shown as Figure. 5.

![Figure 5. Current calculating equivalent circuit.](image)

According to the analysis in section 1.1 of this chapter, the zero-sequence voltage at the fault point can be obtained. Due to the short-circuit current generated by the capacitive effect against the ground, the total grounding short-circuit current can be calculated according to equation (15).

\[
I_{0a}(x,R_f) = 3 \times j \omega C_0 \times \frac{x}{L} \cdot U_{f0}(x,R_f)
\]  

(15)

Since the location of the fault is random, in the π-type equivalent circuit, the values of the left and right ground-to-ground capacitances will be adaptively allocated as the ratio of the fault distance \(x\) to the total length of the transmission-line. Therefore, as shown in Figure. 5, the short-circuit currents at the left and right ends of the faulty line can be calculated by substituted the values of the capacitances to the ground of the left and right into the equation (15).

\[
I_{0a1}(x,R_f) = 3 \times j \omega C_0 \times \frac{x}{L} \cdot U_{f0}(x,R_f)
\]  

(16)

\[
I_{0a2}(x,R_f) = 3 \times j \omega C_0 \times \frac{L-x}{L} \cdot U_{f0}(x,R_f)
\]  

(17)

The current characteristics of ungrounded systems in the event of a single-phase ground fault, that is, the load current remains constant due to line voltage symmetry [13]. Therefore, the current flowing in the line can be regarded as the superposition of the upstream capacitive current \(I_{0a1}\) and the load current \(I_La\). The current \(I_A\) at the beginning of the transmission-line can be expressed as the sum of equation (16) and the load current, as shown in formula (18).

\[
I_A(x,R_f) = I_{La} + I_{0a1}(x,R_f)
\]  

(18)

Finally, based on the Kirchhoff equation, the current flowing through the faulty line is multiplied by the line impedance to obtain the voltage difference \(U_{re}(x,R_f)\) and fault difference between the fault point and the measurement point after faulted. The function of fault location can be expressed as the following form:

\[
U_{re}(x,R_f) = I_A(x,R_f) \cdot \left[ x \cdot R_{line} + x \cdot jX_{line} \right]
\]  

(19)

Where \(R_{line} + jX_{line}\) represents the unit impedance value of the transmission-line.

**Solution to the Fault Location**

The fault location algorithm proposed in this paper is to bring the measurement voltage at the beginning of the bus into the fault location function to achieve fault location. Therefore, according to Kirchhoff’s voltage law, as shown in Figure 6. The measured voltage phasor \(U_{ma}\) at the beginning of the transmission-line is equal to the fault phase voltage at the fault point plus the voltage rise between it and the measurement terminal.
Therefore, the voltage rise obtained by the previous analysis is superimposed with the function of the fault phase voltage, and the expression of the measured voltage value at the measurement point when the A-phase grounded fault occurs can be obtained, as shown in formula (20).

\[ U_{ma} = U_{ma}(x, R_f) + U_{AG}(x, R_f) \]  

(20)

As can be seen from the formula above, the formula has only one equation, but there are two unknowns. To solve this problem, the two sides of the equation are decomposed into a superposition of real and imaginary parts. The real part and the imaginary part of the left and right sides of the formula correspond to each other, and then a system of equations containing two unknowns is obtained. As shown in formulas (21) and (22), fault location is finally achieved.

\[ \text{re}[U_{ma}] = \text{re}\{U_{ma}(x, R_f) + U_{AG}(x, R_f)\} \]  

(21)

\[ \text{im}[U_{ma}] = \text{im}\{U_{ma}(x, R_f) + U_{AG}(x, R_f)\} \]  

(22)

PSCAD Simulation Analysis

In order to verify the validity of the proposed method, the fault location simulation model, shown in Figure 7, was built based on the PSCAD/EMTDC platform as an example. In the figure, the system uses 10.5kV three-phase symmetrical power source with the neutral point ungrounded. The frequency is 50Hz. The initial phase of the system is zero. The load uses a constant impedance model. There are lumped parameter model and distributed parameter model in the transmission-line can be used in this simulation process. But for shorter transmission lines (usually less than 300km), the difference between lumped parameters and distribution parameters is not obvious. Therefore, in order to simplify the process of analysis, the lumped parameters model are selected to simulate the transmission-line. The parameters of the transmission-line are shown in Table 1.
Table 1. Impedance parameters.

<table>
<thead>
<tr>
<th></th>
<th>R/Ω·km⁻¹</th>
<th>X₀/Ω·km⁻¹</th>
<th>X₀/MΩ •m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posi-sequence</td>
<td>0.01273</td>
<td>0.2931</td>
<td>249.977</td>
</tr>
<tr>
<td>zero-sequence</td>
<td>0.3864</td>
<td>1.2956</td>
<td>410.877</td>
</tr>
</tbody>
</table>

Assuming that system has A-phase grounded fault, the fault point is located 5.5km away from the monitoring point and the fault resistance is set to 1000 Ω. The system running time is 2s, and the fault occurs in 1.6s and last 0.4s. The voltage and current waveforms at the monitoring point after the fault occur are shown in Figure 8. From the fault current waveform, it can be seen that when a single-phase grounded fault occurs, especially after a high-resistance ground fault, the change of current amplitude is relatively small, so that the fault current is not easily extracted. Considering the problems above, applying the method proposed in this paper, the fault location can be completed without fault current information, and it is applicable to the transmission-line running in ungrounded mode. The basic process is as follows.

Figure 8. Voltage and current waveforms during fault.

First, a Fast Fourier transform (FFT) is applied to the voltage and current waveforms collected before and after the single-ended fault to obtain the voltage phase and amplitude of the fault phase at the monitoring point. Similarly, the three-phase current and voltage before the fault can be obtained. Effective value. After that, the above result is brought into formula (20) and calculated according to the methods of formulas (21) and (22), and finally fault location can be performed. Simulation results show that the fault location method has a higher positioning accuracy.

Because of the actual fault type and the uncertainty of the load current, in order to reflect the adaptability of the proposed method, this paper further analyzes under different conditions of fault resistance, fault distance and load variation. And use the following calculation method to measure the accuracy of fault location, as shown in formula (23).

\[ W\% = \frac{(X_{\text{act}} - X_{\text{cal}})}{L} \times 100\% \]  

Where: \( W\% \) represents the calculation error of the fault location; \( X_{\text{act}} \) represents the actual fault distance; \( X_{\text{cal}} \) represents the calculation of the fault distance; \( L \) is the total length of the cable line.

Influence of Fault Resistance on Ranging Accuracy

In order to analyze the influence of the fault resistance on the accuracy of the algorithm, four typical fault resistances were chosen as 100 Ω, 250 Ω, 500 Ω, and 1000 Ω, respectively, and single-phase ground faults were set up at different positions in the line for simulation. As shown in table 2.
Table 2. Fault location results under different positions.

<table>
<thead>
<tr>
<th>Fault location/km</th>
<th>Fault Resistance/Ω 100</th>
<th>250</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.723</td>
<td>0.025% 0.021% 0.018% 0.010%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.580</td>
<td>0.045% 0.040% 0.029% 0.021%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.560</td>
<td>0.036% 0.029% 0.020% 0.017%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.040</td>
<td>0.046% 0.042% 0.038% 0.022%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.630</td>
<td>0.062% 0.053% 0.041% 0.033%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.540</td>
<td>0.089% 0.081% 0.062% 0.043%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from the figure:

1) The algorithm has high positioning accuracy for the entire power cable line, and the overall positioning error does not exceed 0.1%. With the growth of cables, the positioning accuracy has declined, but it is still within an acceptable range.

2) As shown in Figure 9, the fault location accuracy increases with the increase of the fault resistance. The main reason is that the high impedance causes the line impedance to weaken the influence of the zero-sequence voltage tracking, thus improving the zero-sequence voltage accuracy.

Figure 9. Effect of fault resistance on fault location.

Effect of Load Variation on Ranging Accuracy

Considering that in the actual power system, the load varies with the user's needs, it is very important to analyze the ranging algorithm's robustness to load variation.

Table 3 shows the effect of a 25% change in load on the fault ranging result when the fault resistance is 1000 Ω. As shown in Figure 10, with a 25% increase in load, the fault location accuracy is slightly less than the positioning accuracy at rated load. However, when the load is reduced by 25%, the fault location accuracy is improved, and the overall error does not exceed 0.1%. The results show that the proposed method is robust to load variation. The fault location can be effectively performed under the condition that the load current changes.

Table 3. Fault location results under load variation.

<table>
<thead>
<tr>
<th>Fault location/km</th>
<th>Error (+25%)/%</th>
<th>Error (-25%)/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.723</td>
<td>0.010%</td>
<td>0.008%</td>
</tr>
<tr>
<td>3.580</td>
<td>0.026%</td>
<td>0.019%</td>
</tr>
<tr>
<td>7.560</td>
<td>0.023%</td>
<td>0.017%</td>
</tr>
<tr>
<td>11.040</td>
<td>0.032%</td>
<td>0.021%</td>
</tr>
<tr>
<td>13.630</td>
<td>0.045%</td>
<td>0.030%</td>
</tr>
<tr>
<td>16.540</td>
<td>0.054%</td>
<td>0.038%</td>
</tr>
</tbody>
</table>

Summary

In this paper, a simple and effective single-phase ground fault location method in ungrounded systems was proposed. This method only needs the current and voltage information before the fault occurred to complete the calculation of the zero-sequence voltage at the fault point, and realized the
fault location when the current data after the fault occurred is unknown. The method described in
this paper is verified by PSCAD simulation. The results shown that the algorithm has high accuracy
of fault location, and it has strong robustness against fault resistance and load variation.

![Figure 10. Effects of Load Variation on Fault location.]

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References


