Fault location method based on three-phase asymmetric phase current fault component and Euclidean distance

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Abstract. When a single-phase ground fault occurs in the distribution network, the three-phase current fault components of the fault path and the non-fault path in the system will be difference which can be used as a criterion for fault line selection. However the three-phase load current in the system is much larger than the fault component current, the three-phase phase fault component current is not obvious, which will cause the failure of the method. This paper proposes an improved fault location method based on the three-phase phase current: the fault component of the three-phase current of the system is obtained by subtracting the phase current before the fault occurs from the after. And then the zero-sequence current of this line is subtracted from the fault component to enhances the difference between the lines, and the fundamental amplitude of the result is obtained. The algorithm uses the three-phase fundamental amplitude as the coordinate axis to establish a coordinate system. The difference between the fault path and the non-fault path is enhanced by calculating the Euclidean distance of the three-phase current fundamental amplitude. And the location of the fault section can be judged locally by comparing the overall differences between the lines. In this paper, the specific fault section location process and criteria are proposed, and the feasibility of the method is verified by simulation experiments and actual field data.

1. Introduction
Most of the 10kV distribution networks in China use neutral point ungrounded or grounded through arc suppression coils. The trouble in distribution network fault location has not been perfectly solved, due to the extremely complex structure and huge coverage of distribution network, which greatly reduces the power supply reliability and the economy of the network [1].

At present, the positioning method can be roughly divided into two types according to the judgment signal used by the location method: the fault signal of the line itself [2] and the external injection signal [3]. In most cases, the fault location method based on the signal of the system itself is to depend on the zero sequence signal to locate the fault [4]-[8]. However the above methods still have some problems. Due to the requirement of the algorithm for judging the signal, additional signal injection devices or zero sequence voltage transformer are needed in the actual system, which will lead to poor economy and adaptability of the algorithm. At the same time, the fault location method based on the zero-sequence signal and the external injection signal usually needs to transmit the signal collected from the system to the master station for judgment, which relies heavily on communication. However, a technology that can achieve local positioning even if the communication fails is required in order to ensure the correct operation of the protection in the actual field.
In order to solve the above problems, experts have proposed fault location technology based on phase current. In reference [6], a fault location method is proposed based on the three-phase phase current mutation. This method uses the phase current mutation amount of the upstream and the downstream of the fault point and the non-fault line to identify the capacitance value of the line to the ground, and completes the fault location by judging whether the capacitance value of the ground is positive or negative. However, when the grounding resistance is large, the small amount of fault mutation increases the difficulty of detection. At the same time, because the load component of the distribution network has a certain harmonic component, it is difficult for the detection device to detect the amount of mutation. In reference [7], a method is proposed based on the steady-state quantity of three-phase phase current. It is pointed out in the article that single-phase ground fault will change the line phase current, and the three-phase current of the fault path and the non-fault path will change differently after the fault occurs, and the change is different from the current change caused by the load change, which can be used to locate the fault position. However, because the load current in the distribution network is much larger than the fault current, relying on the phase current as the judgment signal will cause the judgment signal to be weak, which may easily cause the problem of misjudgment.

In this paper, an improved fault location method is proposed based on the three-phase phase current of the line: the fault component of the three-phase current of the system is obtained by subtracting the phase current before the fault occurs from the after. And then the zero-sequence current of this line is subtracted from the fault component to enhance the difference between the lines, and the fundamental amplitude of the result is obtained. The algorithm uses the three-phase fundamental amplitude as the coordinate axis to establish a coordinate system. The difference between the fault path and the non-fault path is enhanced by calculating the Euclidean distance of the three-phase current fundamental amplitude. Finally, the location of the fault section can be judged locally by comparing the overall differences between the lines with the threshold. This method is not heavily dependent on communication. It can be uploaded to the master station for centralized fault location, or local fault indication can be performed locally to achieve local location. And only current is used as a judgment signal which improve the method’s applicability.

2. Analysis of fault characteristics
In this paper, the changing process of the phase current is analyzed by taking the neutral point through the arc suppression coil grounding system as an example. The system is shown in Figure 1:

![Figure 1 Model diagram of neutral point grounding system through arc suppression coil](image)

There are L lines in this system. $e_A$, $e_B$, $e_C$ is the power electromotive force; $C_i$ is the capacitance to ground on each line ($i = 1, 2, \ldots, L$); the fault occurred in phase A in the middle of the $L^{th}$ line. $C_L$ is the capacitance to the ground of the upstream line of fault; $C_L'$ is the capacitance to the ground of the downstream line of fault.

When a single-phase ground fault occurs in the low-current grounding system, the phase current on each line will change. According to the symmetrical component method, the grounding point of the circuit can be equivalent to the positive, negative, and zero sequence voltages.

After the fault occurs, the current in the system is generated by the generator power and the positive, negative and zero sequence voltage. At the same time, according to the analysis of the superposition theorem, the phase current on the line after the fault occurs is equivalent to the sum of load current
generated by the generator power supply and the fault component current generated by the positive, negative and zero sequence voltage, as shown in Equation 1. Considering that the generator power before and after the fault remains approximately unchanged, the load current on the line after the fault occurs is approximately equal to the load current before, and the load current before the fault occurs is the phase current in line.

According to this, the fault component current after the fault can be obtained by subtracting the phase current before the fault occurs from the after, and their time will be separated by a full cycle.

\[ I_f = I_d + I_f' \]  
\[ I_d = \dot{I}_d \]  
\[ I_f = I_f' - \dot{I}_d \]  

\( I_f \) is the phase current on the line after the fault occurs; \( I_d \) is the load current generated by the generator power supply; \( I_f' \) is the current generated by the positive, negative and zero sequence voltage; \( \dot{I}_d \) is the phase current before the fault occurs.

Since the positive and negative sequence currents in the fault component only form a loop in the power supply and the fault point, most of the positive and negative sequence currents are concentrated on the fault path. However, since the zero-sequence current forms a loop between the ground capacitance on each line and the fault point, the zero-sequence current will shunt at the fault point and flow to all lines of the system. The zero-sequence equivalent circuit is shown below:

![Zero sequence circuit equivalent diagram](image)

\( U_0 \) is the zero-sequence voltage; \( R_f \) is ground resistance; \( L_0 \) is the inductance of the arc suppression coil; \( C_i \) is the capacitance to ground on each line \( (i=1,2,\ldots, L) \); \( C_L \) is the capacitance to the ground at the upstream of the fault point; \( C'_L \) is the capacitance to the ground at the downstream of the fault.

It can be seen from the figure that the zero-sequence current shunts at the fault point. The zero-sequence current flows to the fault path and the non-fault path. The non-fault path can be divided into non-fault lines and downstream lines of the fault point. At the same time, the zero-sequence current on non-fault line flows to the fault point through the bus. \( \lambda_i \) is the shunt coefficient. According to the circuit theorem, \( \lambda_i \) of the zero-sequence current on the line \( i \) is as follows:

\[ \lambda_i = \frac{\dot{j} \omega L_0}{\alpha \cdot (\dot{j} \omega L_0 \sum_{m=1}^{L} C_m + 1)} \]  

\( C_m \) is the capacitance to ground on each line \( (m=1,2,\ldots, L) \); \( \alpha \) is the reactance value of the capacitance to ground or arc suppression coil on line \( i \).

Because the zero-sequence current on the fault path is the sum of the zero-sequence current except the downstream of the fault point, so its shunt coefficient is:
\[ \lambda_L = 1 - \frac{j\omega L_0}{j\omega C_L \cdot \left(j\omega L_0 \sum_{n=1}^{\infty} C_n + 1 \right)} \]  \hspace{1cm} (5) 

2.1. Fault component current analysis on fault path
Since the positive sequence and negative sequence currents in the fault component current form a loop between the fault point and the power supply through the bus and the zero sequence current in the fault component current form a loop between the grounding capacitance on each line through the bus and the fault point, the fault component current in the fault path includes three currents of positive sequence, negative sequence and partial zero sequence.

It is assumed that the positive, negative and zero sequence currents at the fault point obtained by the system through the symmetrical component method is equal to \( K \). \( \lambda_L \) is the shunt coefficient of the zero-sequence current on the fault path, and the direction factor is \( a = e^{j120^\circ} \). Therefore, the fault component of each phase on the fault line is \( I_{fa} \), \( I_{fb} \), \( I_{fc} \).

\[
\begin{bmatrix}
I_{fa} \\
I_{fb} \\
I_{fc}
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & \lambda_L \\
a & a^2 & \lambda_L \\
a^2 & a & \lambda_L
\end{bmatrix}
\begin{bmatrix}
\hat{K} \\
\hat{K} \\
\hat{K}
\end{bmatrix}
= 
\begin{bmatrix}
(\lambda_L + 2) \cdot \hat{K} \\
(\lambda_L - 1) \cdot \hat{K} \\
(\lambda_L - 1) \cdot \hat{K}
\end{bmatrix} 
\hspace{1cm} (6) 
\]

2.2. Fault component current analysis on non-fault path
Non-faulty paths are divided into normal lines and downstream lines of the fault point. Since the positive and negative sequence currents in the fault current only form a loop between the fault point and the power supply through the bus without passing through the non-fault path, the positive and negative sequence currents in the non-fault path are 0; the zero sequence current in the fault current forms a loop through the ground capacitance on each line, the bus and the fault point, and the shunt coefficient of the different lines in the above can be used to specifically obtain the magnitude of the zero-sequence current of the corresponding line. The zero sequence current on the line is \( I_0 = \lambda L \hat{K} \). Therefore, the fault component current in the non-fault path is mainly composed of the zero-sequence current on its own line. Then the fault components of the three-phase current on the non-fault path are \( \tilde{I}_{fa} \), \( \tilde{I}_{fb} \), \( \tilde{I}_{fc} \).

\[
\begin{bmatrix}
\tilde{I}_{fa} \\
\tilde{I}_{fb} \\
\tilde{I}_{fc}
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & \lambda_L \\
a & a^2 & \lambda_L \\
a^2 & a & \lambda_L
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
\hat{K}
\end{bmatrix}
= 
\begin{bmatrix}
\lambda L \hat{K} \\
\lambda L \hat{K} \\
\lambda L \hat{K}
\end{bmatrix} 
\hspace{1cm} (7) 
\]

3. Fault location algorithm and process based on asymmetric phase current

3.1. Fault location algorithm based on asymmetric phase current
It can be obtained from the above analysis: the fault component of the fault phase on the fault path is twice that of the non-fault phase, and the fault components of the non-fault phase are equal; the fault components of the three-phase current on the non-fault path are all equal. However, there is interference of the shunt coefficient in the result, which makes the fault characteristics very vague. When the fault component is small, it is easy to cause malfunction. Therefore, it is impossible to accurately locate the fault only by relying on the equal value.

In order to reduce the effect of \( \lambda \) on the fault characteristics, the algorithm uses the three-phase current to calculate the zero-sequence current and subtracts the zero-sequence current from the fault component to eliminate the effect of \( \lambda \) on the result.

After subtracting the zero sequence current from fault component current of the fault path:
After subtracting the zero-sequence current from the fault current component of the non-fault path:

\[
\begin{bmatrix}
I_A - I_{A0} \\
I_B - I_{B0} \\
I_C - I_{C0}
\end{bmatrix} = \begin{bmatrix}
2K \\
-K \\
-K
\end{bmatrix}
\]

(8)

After subtracting the zero-sequence current from the fault current component of the non-fault path:

\[
\begin{bmatrix}
I_A - I_{A0} \\
I_B - I_{B0} \\
I_C - I_{C0}
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]

(9)

It can be seen from the results that after subtracting the zero-sequence current from the result, the fault phase in the fault path is opposite to the normal direction and the amplitude is doubled. The three-phase result of the non-fault path is 0.

Due to harmonic interference in the system or limited by the sensitivity of the detection device, the quantitative relationship and phase relationship of the fault component current cannot be completely consistent with the theoretical analysis. The algorithm will mis-operate or refuse to operate. Therefore, it is necessary to locate the fault path through the whole circumstance.

Euclidean distance as a way to judge the geometric distance between two points can be used in this algorithm to judge the overall situation of the three-phase fundamental amplitude on different lines. It can be obtain from the above analysis that the amplitude of the three-phase fundamental wave on the fault path is \(2K\), \(K\) and \(K\) and the amplitude of the three-phase fundamental wave on the non-fault path is 0,0 and 0. So A three-dimensional coordinate system can be established according to the magnitude of three-phase fault components. The Euclidean distance in the coordinate axis from the corresponding point of each line to the origin can be calculated after the fault occurs.

The Euclidean distance of the fault line is \( Ed_f \).

\[
Ed_f = \sqrt{(2K - 0)^2 + (K - 0)^2 + (K - 0)^2} = \sqrt{6K}
\]

(10)

The Euclidean distance of the fault line is \( Ed_f \).

\[
Ed_f = \sqrt{(0 - 0)^2 + (0 - 0)^2 + (0 - 0)^2} = 0
\]

(11)

\( K \) is the amplitude of the positive and negative zero-sequence component fundamental wave at the fault point.

Because the Euclidean distance between fault path and non-fault path is quite different, the algorithm can set threshold to compare the relationship between threshold and Euclidean distance value of different lines to achieve fault location. If the Euclidean distance of the line is greater than the threshold, it will be the fault path, otherwise the non-fault path. \( Ed_0 \) is threshold.

Due to the calculated Euclidean distance of each line is related to the amplitude of the zero-sequence fault component at the fault point, the adaptive threshold is set according to the zero-sequence current.
of the line itself. Threshold is \( Ed_0 = \sqrt{\delta_{rel} I_0} \). Since \( I_0 \) is smaller than \( K \), it will not affect the judgment result. \( \delta_{rel} \) is the reliability factor, which can be taken as 0.95.

Thus, the fault location can be completed according to the relationship between the Euclidean distance of the three-phase current fault component amplitude of the line itself and the threshold.

### 3.2. Process of fault location method

Firstly, record the time as \( t_0 \) when the fault occurs. Secondly, the zero sequence current on the line can be calculated according to its three-phase current after the fault occurs
\[
\dot{I}_0 = (\dot{I}_A + \dot{I}_B + \dot{I}_C)/3
\]
And then, the calculated data is obtained by subtracting the three-phase current values before the fault occurs and the zero sequence current from the three-phase current values after the fault occurs. And then use fast Fourier transform to obtain the fundamental amplitude of the zero-sequence current and the calculated data, and calculate the Euclidean distance of each line. Finally, locate the fault according to the \( Ed_0 \): the line whose the Euclidean distance is greater than the threshold is the fault path, whose the Euclidean distance is less than or equal to the threshold is the non-fault path. At the same time, the phase corresponding to the maximum value on the fault path can be judged as the fault phase.

### 4. Simulation

This article uses the ATP to carry out simulation experiments. In the experiment, two grounding modes, arc-grounded and ungrounded, are selected. The fault time is set at 0.0624s. The time 0 is used as the starting point for recording. The number of sampling points per cycle is 100. The experiment is conducted for 25 cycles.

In order to facilitate the construction of the model, the line number is set as 2, which are divided into faulty lines and non-faulty lines. The faulty line is divided into the fault point upstream line and the fault point downstream line.

#### 4.1. Grounding system of neutral point via arc suppression coil

The grounding system model of the neutral point through the arc suppression coil is shown in the figure below. After setting the corresponding parameter values in the simulation software, the algorithm is used for testing.

![ATP model diagram of neutral point grounding system through arc suppression coil](image)

**Figure. 4 ATP model diagram of neutral point grounding system through arc suppression coil**

After the data are processed by the algorithm, the current amplitude of each phase and the calculation results are listed in the following table:

|                  | Amplitude of phase A (A) | Amplitude of phase B (A) | Amplitude of phase C (A) | Euclidean distance results |
|------------------|--------------------------|--------------------------|--------------------------|----------------------------|
| Normal line      | 0.4615                   | 0.2308                   | 0.2308                   | 0.5653                     |
| Fault point down  | 0.3415                   | 0.1708                   | 0.1708                   | 0.4183                     |
| Fault path       | 11.2684                  | 5.6342                   | 5.6342                   | 12.8201                    |
4.2. **Neutral point ungrounded system**

The neutral point ungrounded system model is shown in the figure below. After setting the corresponding parameter values in the simulation software, the algorithm is used for testing.

![Figure 5 ATP model of ungrounded neutral system](image)

After the data are processed by the algorithm, the current amplitude of each phase and the calculation results are listed in the following table:

|                  | Amplitude of phase A (A) | Amplitude of phase B (A) | Amplitude of phase C (A) | Euclidean distance results |
|------------------|--------------------------|--------------------------|--------------------------|----------------------------|
| Normal line      | 0.3106                   | 0.1553                   | 0.1553                   | 0.3804                     |
| Fault point      | 0.3015                   | 0.1508                   | 0.1508                   | 0.3693                     |
| Fault path       | 8.6254                   | 4.3127                   | 4.3127                   | 10.5639                    |

From the above table, the calculated amplitude of phase A in the fault path is greater than that of phases B and C, and the numerical relationship is two times. The amplitude in the non-fault path is extremely small and is approximately 0. The experimental results are consistent with the analysis results in the above article. At the same time, the Euclidean distance value of the fault path is much larger than that of the non-fault path. The fault path can be obviously selected by setting the threshold. The algorithm can complete the fault location in the neutral point ungrounded system and the neutral point through the arc suppression coil grounding system.

5. **Field test data analysis**

The actual data of a substation is used for algorithm testing. There are three outgoing lines in the measured data of this substation. Two of them are non-fault lines and one is a fault line. A single-phase ground fault occurred in the fault line, and the fault phase was A. There are two groups of measurement data in the fault line, one is upstream data of fault point, the other is downstream data of fault point. After the data are processed by the algorithm, the results are as follows:

![Figure 6 Normal line waveform](image)

![Figure 7 Normal line waveform](image)
The test results are shown in Table 3:

|                  | Amplitude of phase A (A) | Amplitude of phase B (A) | Amplitude of phase C (A) | Euclidean distance results |
|------------------|--------------------------|--------------------------|--------------------------|---------------------------|
| Normal line      | 1.0926                   | 1.2641                   | 1.4251                   | 2.1960                    |
| Normal line      | 0.5124                   | 0.4645                   | 0.5352                   | 0.8745                    |
| Fault point      | 0.9780                   | 0.8562                   | 0.9214                   | 1.5932                    |
| Fault path       | 5.6241                   | 2.6152                   | 2.6261                   | 6.7354                    |

It can be seen from the figure 6-9 and table 3 that the current waveform presents an irregular shape and the quantitative relationship between the phases of the line is no longer obvious under actual operating conditions, due to the interference of a large number of harmonic components in the line. If the algorithm judges only based on the quantity relationship, the protection device cannot operate accurately. However after calculating the Euclidean distance according to the algorithm, the difference between the fault path and the non-fault path is very obvious, and the local fault location is effectively and accurately completed according to the threshold.

6. Conclusion
Through the establishment of models for experimental simulation and actual data testing, the conclusions are as follows:

1. The experimental results of the ATP simulation experiment are the same as the analysis results, which verifies the correctness of the theoretical analysis. The algorithm can effectively complete the local fault location of the system through the arc suppression coil grounding and neutral point ungrounded system, and accurately determine the fault path and fault phase.

2. The actual data test results show that a large number of harmonic components in the actual data will interfere with the quantitative relationship and cause the current waveform to exhibit irregular changes. However the algorithm can still effectively complete the local fault location, which shows that the method has certain engineering application value.

3. The principle of this method is simple and reliable, which is convenient for programming. And the algorithm can only use three-phase current on the line to complete the fault location, which has strong applicability. At the same time, this method can not only upload data to the master station for centralized fault location, but also local fault judgment to achieve local fault location, which is not highly dependent on communication and has certain economic and applicability.

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