A Method of Single Phase-to-ground Fault Section Location for Closed-loop Distribution Networks

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Abstract. In the field of fault location technology for neutral point non-effectively grounded distribution network, the original radial mode of operation is no longer applicable due to the gradual expansion of the scope of application of loop operation mode. By analyzing the zero-sequence equivalent circuit of closed-loop network, this paper finds out the characteristics of zero-sequence current when single phase-to-ground fault occurs in different sections, and puts forward the location method according to the characteristics. ATP simulation shows that this method is accurate and effective.

1. Introduction

With the rapid development of distribution network construction, the structure of distribution network has gradually evolved from radial to closed-loop [1-3]. In the closed-loop network, the distribution of zero-sequence current is different from the radiation network when the single phase-to-ground fault occurs in the neutral non-effectively grounded system. Thus it is difficult to locate the fault section correctly and the scope of the accident will expand eventually [4]. Therefore, it is necessary to study the section location of single phase-to-ground fault in the closed-loop network.

At present, domestic and foreign researches mostly focuses on single phase-to-ground fault location of radiation network [5-8] and the processing of loop closing operation [9]. There are few studies focusing on fault location in closed-loop network. Reference [10] proposes a new non-communication protection method for 20 kV distribution network, but it limits to symmetrical faults location. Reference [11] proposes a closed-loop analysis based on closed-loop transient process, but this method requires high-precision communication devices support to upload instantaneous data accurately and quickly. The above research is not applicable to single phase-to-ground fault in neutral point non-effectively grounded system.

Based on the circuit analysis of closed-loop network in the non-effectively grounded system, this paper calculates the phase difference between zero-sequence current and zero-sequence voltage and sums up a single phase-to-ground fault location method for it. Typical closed-loop network model is built by ATP simulation software. Faults are set up in different sections to verify the correctness of the location method. The simulation results show that the section location method in this paper has certain reliability and validity.

2. Principle of fault section location

This paper chooses a typical single-side closed-loop network model for analysis. The line in figure 1 is divided into two parts. One is radiation cable line named line 4 and transformer line. The sum zero-
sequence impedance and zero-sequence capacitance of them is equivalent to \( Z_4 \) and \( C_4 \). The other is one-sided closed-loop network named as a virtual line, which links the ends of two lines with a contact line, whose switch remains closed. The fault grounding point is set on line 1, and the positive current direction is shown in the figure 1. The arrow in the positive direction of current points to the downstream section and vice versa, the upstream section. The upstream zero sequence impedance and capacitance of the fault point are set to \( Z_1 \) and \( C_1 \), and downstream are set to \( Z_2 \) and \( C_2 \).

![Figure 1. Equivalent zero-sequence circuit diagram of single phase-to-ground fault in non-effectively distribution network.](image)

Equation (1) is derived from Kirchhoff's theorem and node voltage method.

\[
\begin{align*}
-Z_3 \cdot \hat{U}_a + G_2 \cdot \hat{U}_a - Z_4 \cdot \hat{U}_a &= 0 \\
-Z_1 \cdot \hat{U}_a - Z_2 \cdot \hat{U}_a + G_3 \cdot \hat{U}_a &= 0 \\
\hat{U}_a &= U_f
\end{align*}
\]

(1)

Where \( G_1, G_2, \) and \( G_3 \) denote self-admittance of nodes, \( \hat{U}_a, \hat{U}_a, \hat{U}_a \) denote voltage of nodes. \( U_f \) is a known quantity, representing the voltage at the grounding point.

As the grounding point moving downstream gradually, the expressions of zero-sequence current \( I_1, I_2, \) and \( I_3 \) varying with length of line are shown in equation (2). Using MATLAB and ORIGIN, the phase change diagram of zero-sequence current and its comparison with zero-sequence voltage are drawn respectively, as shown in figure 2 and figure 3.

\[
\begin{align*}
I_1 &= \frac{Nl - M}{Ml} \\
I_2 &= \frac{M \left[ \frac{1}{l} + jwc(2l - l_1) \right] - N}{M \left[ \frac{1}{l} + jwc(2l_1 - 3l + l_1^2) \right]} \\
I_3 &= \frac{N - 2z_1 - jz^2 l_1}{M}
\end{align*}
\]

(2)

Where \( M \) and \( N \) denote respectively in equation (3), and \( l \) denotes the length of line 1 or line 3, \( l_1 \) denotes the upstream length of line 1. \( Z \) and \( C \) represent the unit length impedance and capacitance of overhead lines, respectively.

\[
\begin{align*}
M &= 2z^2 l^2 - z^3 w e c k \left( 2l^4 l_1 - 3l^3 l_1^2 + l^2 l_1^3 \right) + j z^3 k \left( \frac{2l^2 l_1 - l_1^2}{l^4 l_1 - l_1^2} \right) + z^3 w e c \left( 2l^3 l_1 - 2l^3 l_1^2 + l_1^4 \right) \\
N &= 2z l + jz^2 w e \left( 2l^3 l_1 + l_1^4 \right)
\end{align*}
\]

(3)

Because the length of line 4 does not change in practice, the calculation of line 4’s self-admittance
is simplified as follows: ignoring real part of it, replacing with \( jk = j\omega c_j (1 + j\omega c_z) \). 

Figure 2. Zero sequence current phase change current with grounding point.

It can be seen that \( I_2 \) always leads the zero-sequence voltage by 90 degrees and \( I_1 \) often lags by 90 degrees. The current \( I_3 \) leads in the first place and lags later. The turning point can be calculated by equation (2).

3. Method of fault section location

3.1 Optimized settings of Feeder Terminal Unit (FTU)

Line impedance and line-to-ground capacitance will change with the change of line length. According to equation (1), various current flows will occur and make it impossible to judge the fault section by zero-sequence current flows. Segmental and reasonable FTU setting is helpful to observe the phase relationship between zero-sequence current and voltage under different conditions.

According to the flow pattern of zero-sequence current calculated in Chapter 2, FTU is set every 2.5 km to detect the flow direction of zero-sequence current and its phase relationship with zero-sequence voltage, and an FTU is added to the contact line for judgment. The setting of FTU and the regulation of positive direction are shown in figure 4.

Figure 4. FTU settings, section naming and positive direction provisions.

3.2 Method of section location

The method of locating fault section is:

(1) The method of judging whether the fault locate on the virtual line is to set FTU on the line outside the virtual line near the bus. If the phase of zero sequence current component measured by FTU is ahead
of the zero-sequence voltage, then the fault occurs in the virtual line; otherwise, it occurs outside the virtual line.

(2) If the result turn out to be current-leading-voltage relation, the upstream line will be regard as fault occurrence area, and vice versa, the downstream line will be regard as fault occurrence area.

The upstream of the FTU setting in the contact line is defined as line 1, and downstream as line 2. Since the fault occurs outside the virtual line is easy to judge, it will not be analyzed below.

4. Simulation verification
The closed-loop network model is built up as shown in figure 6. Asymmetric grounding fault simulation is carried out in each section. The simulation data in 0.3-0.5s are recorded and zero-sequence current flow direction and the phase relationship between the current and voltage are obtained with the use of MATLAB.

Figure 6. ATP model of typical line 1.

With the fault occurring in the different section, there will be at least two cases of phase change of zero sequence current. The general case with the highest frequency and the special case with the lowest frequency are selected to verify the accuracy of the location method.

4.1 Simulation of the general situation
The general situation refers to the general performance when grounding fault occurs in each section. Its zero-sequence current characteristics will change with other factors. The section naming of the model in ATP corresponds to the naming used in this analysis as shown in table 1.

Table 1. Naming rules.

| sectionI | sectionII | sectionIII | sectionIV | sectionV | sectionVI | sectionVII | sectionVIII |
|----------|-----------|------------|-----------|----------|-----------|------------|------------|
| XX0030-  | XX0001-   | XX0025-    | XX0014-   | XX0030-  | XX0020-   | XX0021-    | XX0008-    |
| XX0017   | XX0013    | XX0019     | XX0033    | XX0009   | XX0007    | XX0016     | XX0034     |

Tables 2 and table 3 show the locating criteria for asymmetric faults occurring in sections I, IV. These two sections are representative and can well reflect the general applicability of locating methods.

Table 2. Fault occur in sectionI.

| FTU   | State of FTU | I | II | III | IV | V | VI | VII | VIII |
|-------|--------------|---|----|-----|----|---|----|-----|------|
| ①    | Ahead        | ✓ |    |     |    |   |    |     |      |
| ②    | Ahead        | ✓ | ✓  |     |    |   |    |     |      |
| ③    | Ahead        | ✓ | ✓  | ✓   |    |   |    | ✓   |      |
| ④    | Ahead        | ✓ | ✓  | ✓   | ✓  |   |    |     |      |
| ⑤    | Ahead        | ✓ | ✓  | ✓   | ✓  | ✓ |    |     |      |
4.2 Simulation of the special situation

Special situation refers to that when the circuit length outside the virtual line changes, or when grounding faults occur at different locations in the same section, it may affect the current of the virtual line.

Special case 1: When grounding fault occurs at the end of section IV, which close to the contact line, the current states measured by each FTU are shown in Table 4. The current phase of FTU \( \text{④}\)–\(\text{⑥}\) is completely opposite of table 3. However, the state of FTU \(\text{⑦}\) is ahead, which determines the location of fault section is section IV rather than section VIII.

Table 4. Fault occur at the very end of section IV.

| FTU | State of FTU | I   | II  | III | IV  | V   | VI  | VII | VIII |
|-----|--------------|-----|-----|-----|-----|-----|-----|-----|------|
| ①   | Lag          | √   | √   | √   |     |     |     |     |      |
| ②   | Lag          |     |     |     | √   | √   |     |     |      |
| ③   | Lag          |     |     |     | √   |     |     |     |      |
| ④   | Ahead        |     |     |     |     |     |     | √   |      |
| ⑤   | Ahead        |     |     |     |     |     | √   | √   |      |
| ⑥   | Ahead        |     |     |     |     |     |     |     | √    |
| ⑦   | Ahead        | √   | √   | √   | √   |     |     |     |      |

Special case 2: When the length of the line outside the virtual line changes, it means that the length increases from 100 km to 5000 km for instance in this simulation. When the grounding fault occurs in section I, the zero-sequence current state measured by each FTU are shown in table 5. The current phases of FTU \(\text{④}\)–\(\text{⑥}\) in table 5 are completely opposite of table 2. The state of FTU \(\text{⑦}\) is ahead, which determines the location of fault section is section I rather than section VIII.

Table 5. Fault occur in section I.

| FTU | State of FTU | I   | II  | III | IV  | V   | VI  | VII | VIII |
|-----|--------------|-----|-----|-----|-----|-----|-----|-----|------|
| ①   | Ahead        | √   |     |     |     |     |     |     |      |
| ②   | Ahead        | √   | √   |     |     |     |     |     |      |
| ③   | Ahead        | √   | √   |     |     |     |     |     |      |
| ④   | Lag          |     |     |     | √   | √   | √   |     |      |
| ⑤   | Lag          |     |     |     |     |     |     |     | √    |
| ⑥   | Lag          |     |     |     |     |     |     |     |      |
| ⑦   | Ahead        | √   | √   | √   | √   |     |     |     |      |

5. Conclusion

With the rapid development of distribution network structure, the requirement of the subordinate and important users for dual power supply is getting higher and higher. Closed-loop network power supply mode has become a typical connection mode. The research of fault location is extremely necessary. Based on the basic circuit knowledge, this paper studies the flow pattern of zero-sequence current after
grounding fault occur, summarizes a set of concise, practical and reliable criterion principles, and makes a lot of experiments on ATP to verify the reliability of criterion. In order to take all the cases into account and further verify the scientificty of the criterion, simulation verification under special circumstances is also made. This method fills a blank field of fault section location in the neural point non-effectively grounded distribution network under closed-loop operation mode.

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