A Single-phase Grounding Fault Judgment Method Based on Steady-state Current Characteristics in Distribution

Xu Yuhang¹, Li Tongning¹, Lin Yibin¹, Lu Chaoteng¹, Lu Huiji¹ and Zhang Wei²

¹ State Grid Xiamen Electric Power Supply Company, 361000 Xiamen, Fujian, P. R. China
² Jicheng Electronics Co., Ltd, 250100, Jinan, Shandong, P. R. China

E-mail: zhangweieslab@163.com

Abstract. In order to solve the problem of single-phase grounding fault judgment in non-solid-earthed distribution network, the power flow in non-solid-earthed distribution is analyzed. The steady-state current value in the upstream fault phase will be abruptly changed, and the current in the downstream fault phase will keep the load current constant. The steady-state current values in other non-faulty phases and non-faulty lines do not change abruptly. A single-phase grounding fault judgment method based on steady-state current characteristics is proposed. The power supply path real-time current matrix, the power supply path history current matrix, the power supply path mutation current matrix and the power supply path mutation current logical matrix are established. The problem of the single-phase grounding fault judgment is transformed into the matrix operation problem. The detailed calculation formulas are given. The simulation results show that the method proposed in this paper has a good adaptability to the permanent grounding fault and it is worth popularizing.

1. Introduction

FA (Feeder Automation), as an important means to improve the reliability of power supply, has been widely deployed in the current DMS (Distribution Management System), and it plays an important role in distribution fault location. However, at present, the feeder automation system can only deal with the short-circuit fault location, but there is no better way to deal with the single-phase grounding fault judgment in non-solid-earthed distribution network [1-3].

The neutral grounding mode of 10kV distribution network in China mainly includes two kinds of neutral unearthed and neutral earthed via Peterson coil. When the single-phase grounding fault occurs, these grounding modes can limit the short-circuit current to a smaller value. But because of the step voltage, it often leads to human and livestock casualties. If the neutral grounding mode is changed into neutral earthed through small resistance, when the single-phase grounding fault occurs, the substation outlet circuit breaker will trip. Although this method can isolate the fault, the reliability of power supply is seriously reduced due to frequent tripping of the outlet switch. Therefore, the non-solid-earthed operation mode is desirable in most areas of our country, but it also needs to be removed as soon as possible [4-6].

Passive method and active method are two commonly used methods for single-phase grounding fault location in non-solid-earthed distribution [7-8]. However, the installation of special terminal equipment is required for both the active and passive methods to meet the special sampling requirements. The current distribution network has installed a large number of sampling terminal...
equipment, such as FTU(Feeder Terminal Unit), DTU(Distribution Terminal Unit), fault indicator, etc., most of these devices do not have a special sampling and determination requirements. If a special sampling decision device is installed, most of the equipment needs to be installed under the condition of power failure, and the reliability of power supply is further reduced. Therefore, the best possible use of existing equipment and sampling data to solve the problem of single-phase grounding fault judgment, try not to install special equipment, to avoid duplication of waste of resources, these practices can be better to build a conservation-oriented society.

Based on the characteristics of single-phase grounding fault location, this paper analyzes the power flow in non-solid-earthed distribution, and presents a single-phase grounding fault judgment method based on steady-state current characteristics.

2. Steady-state characteristic analysis of single-phase grounding fault

In the non-solid-earthed distribution, whether the grounding transformer is grounded via Peterson coil or not, its influence on distribution network is the same, which is to reduce the fault short-circuit current. Figure 1 is the distribution of capacitance current and load current in the non-solid-earthed distribution network. Wherein, the G1 is the equivalent power supply of the system, #1~#4 is the bus, and the ABC are the three phases of bus #3. TRA1 is Y/Y/D type three winding transformer, and rated voltage is 110kV/35kV/10kV. TRA2 is Y/Y type two winding transformer, rated voltage is 10kV/400V, and it can be used as grounding transformer. Feeder1 and Feeder2 are two feeders. Load1 and Load2 are equivalent loads. FP is the fault point.

![Figure 1. The non-solid-earthed distribution power flow.](image)

When the A phase of the feeder Feeder2 is single-phase grounding fault at the FP point, the B phase and C phase capacitive current phasors $I_{CB1}$, $I_{CC1}$ and $I_{CB2}$, $I_{CC2}$ in the non-fault line Feeder1 and the fault line Feeder2 flow from the bus to the feeder and flow to the fault point. As shown in figure dline1~dline4. TRA1 transformer low side because it is triangular wiring, so the winding between the ground capacitance is small, negligible, and the capacitor current between the windings have been incorporated into the load current, as shown phasors $I_{AT}$, $I_{BT}$, $I_{CT}$ in Figure 1. TRA2 ground transformer due to neutral point is not grounded, so the capacitance current is also negligible. The total capacitance current flowing through the fault point is the zero sequence current $I_{02}$, which is the sum of the four capacitor currents whose direction flows from the fault point to the bus.

In the feeder Feeder1 and Feeder2, the load current of each phase is denoted by $I_{A1}$, $I_{B1}$, $I_{C1}$, $I_{A2}$, $I_{B2}$, $I_{C2}$ respectively, as shown in the figure. When the fault occurs, due to symmetry, the load current of each phase does not change.

As can be seen from Figure 1, the current $I_{A2}$ flowing through the fault phase A in the upstream region of the fault point FP is a superposition of the load current $I_{A2}$ and the zero sequence current $I_{02}$. And the current flowing through the downstream of the fault point is only the load current $I_{A2}$. The current flowing through the BC phase of the fault line is the same as before and after the fault, and the
value is the load current. The current of ABC three-phase flow in non fault line Feeder1 has no change before and after the fault, and its value is the load current.

For cable lines or cable and overhead hybrid lines, the line capacitance current will be much larger than the overhead line capacitance current, and the substation 10kV feeder is generally more than a dozen, in addition feeder branch more effective length. Therefore, in the city or suburban distribution network with cable line and cable overhead hybrid line, the ground current flowing through the fault point will not be neglected relative to the load current when the single-phase grounding fault occurs.

3. A single-phase grounding fault judgment method based on steady state current characteristics

3.1. Establishment of fault judgment model
According to the above analysis, when the single-phase grounding fault occurs, only the steady-state current of the fault phase load superimposed on the fault feeder upstream to the substation switch will change, while the steady-state current of the other paths will not change. Therefore, the problem of fault judgment is to find the power supply path from the substation switch to the fault point.

Figure 2 is the distribution network typical feeder; # 1 is the substation bus; S1 is substation outlet switch; A–K are sectional switches which is installed with FTU, DTU, fault indicator and other acquisition devices. DT1 ~ DT5 are distribution transformers.

![Figure 2](image)

Figure 2. The distribution network typical feeder.

As can be seen from Figure 2, there are 5 power supply paths from substation outlet switch S1 to terminal distribution transformer DT1~DT5, which are respectively Lline1~Lline5, as shown by the dashed line in Figure 2. The single-phase grounding fault will also take place on one of the 5 power supply paths. When a single-phase grounding fault occurs, the steady-state current value of one of the five power supply paths will change, and the changed path is the fault path.

Starting from the distribution transformer, it is traced back in the opposite direction of the flow direction until the substation outlet switch, which is defined as a set of power supply path switches. Each of the power supply path switches is generated a power supply path sequence table according to the order of the current flows. The power supply path sequence table of the power supply path switch in Figure 2 is shown in Table 1.

| Path | Path1 | Path2 | Path3 | Path4 | Path5 |
|------|-------|-------|-------|-------|-------|
| Switch | S1,A,B,C | S1,A,B,D,E,H,K | S1,A,B,D,E,G | S1,A,B,D,F,J | S1,A,B,D,F,I |

The power supply path real-time current matrix is established to describe the real-time operation state of a distribution feeder A, B and C three-phase. The A phase power supply path real-time current matrix $RCM_A$ is described as follows:
Wherein, \( i = 1, 2, n, n \) is the number of feeder power supply paths, that is, the number of distribution transformers; \( j = 1, 2, \ldots, m, m \) is the number of switches included in the maximum power supply path; \( ra_{ij} \) is the real-time current value of the \( j \) switch in the \( i \) power supply path. If the switch does not exist, it is represented as -1. \( RCM_B \) and \( RCM_C \) are used to describe the real-time current matrix of B and C phase power supply path. The specific method is similar to \( RCM_A \), and no longer is described.

The power supply path history current matrix is established to describe the history operation state of a distribution feeder A, B and C three-phase. The A phase power supply path history current matrix \( HCM_A \) is described as follows:

\[
HCM_A = \begin{bmatrix}
ha_{a_{11}} & ha_{a_{12}} & \cdots & ha_{a_{ij}} & \cdots & ha_{a_{im}} \\
ha_{a_{11}} & ha_{a_{12}} & \cdots & ha_{a_{ij}} & \cdots & ha_{a_{im}} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
ha_{a_{i1}} & ha_{a_{i2}} & \cdots & ha_{a_{ij}} & \cdots & ha_{a_{im}} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
ha_{a_{n1}} & ha_{a_{n2}} & \cdots & ha_{a_{ij}} & \cdots & ha_{a_{im}}
\end{bmatrix}
\]  

(2)

Wherein, \( ha_{ij} \) is the certain historical moment current value of the \( j \) switch in the \( i \) power supply path. If the switch does not exist, it is represented as -1. The historical moment can be set according to the terminal type. If the sampling devices are high-precision real-time devices with short sampling interval such as FTU and DTU, the historical moment may be set to 2 to 5 minutes before the current moment. If the sampling devices are sampling devices with a longer sampling interval such as fault indicator, the historical moment can be set as 5 to 10 minutes before the current moment. If the sampling devices are mixed configurations of FTU, DTU and fault indicator, the historical moment can be set as 5 to 10 minutes before the current moment, so as to ensure that all data are sent to DMS. \( HCM_B \) and \( HCM_C \) are used to describe the history current matrix of B and C phase power supply path. The specific method is similar to \( HCM_A \), and no longer is described.

### 3.2. A single-phase grounding fault judgment method

When the grounding fault occurs, the substation bus will be generated zero sequence voltage. In this case, the steady-state current mutation caused by the fault can be calculated by using the power supply path real-time current matrix after the fault and the power supply path history current matrix before the fault, and the detailed description is as follows:

\[
ACM_A = RCM_A - HCM_A 
\]  

(3)

\[
ACLM_A = \begin{bmatrix}
la_{a_{12}} & la_{a_{12}} & \cdots & la_{a_{ij}} & \cdots & la_{a_{im}} \\
la_{a_{21}} & la_{a_{22}} & \cdots & la_{a_{ij}} & \cdots & la_{a_{im}} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
la_{a_{i1}} & la_{a_{i2}} & \cdots & la_{a_{ij}} & \cdots & la_{a_{im}} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
la_{a_{n1}} & la_{a_{n2}} & \cdots & la_{a_{ij}} & \cdots & la_{a_{im}}
\end{bmatrix} 
\]

\[
l_{a_{ij}} = \begin{cases}
1 & aa_{ij} \geq \alpha Ma \\
0 & aa_{ij} < \alpha Ma
\end{cases}
\]  

(4)
Wherein, $ACM_A$ is A-phase power supply path mutation current matrix, and it is also $n$ row $m$ column matrix. For the convenience of calculation, the mutation of the A phase current is expressed by the power supply path mutation current logic matrix $ACLM_A$. $la_{ij}$ is the mutation current logic value of the $j$ switch in the $i$ power supply path. $aa_{ij}$ is the $i$ row and $j$ column element of the A-phase power supply path mutation current matrix $ACM_A$. $Ma$ is the capacitance current threshold, which can be determined according to the maximum steady-state current change of all the substations after a grounding fault within one year of the substation. $\alpha$ is the threshold coefficient, the value range is $(0,1)$.

If the grounding fault occurs in phase A, the power supply path mutation current logic matrix $ACLM_A$ is a matrix of 0 and 1. The path with the most mutation current switch in all the power supply paths is the fault path, that is, the power supply path represented by the row with the most logic value 1 in all the rows in the matrix is the fault path. The detailed description is as follows:

$$RF_A = \text{Max}[sla_1, sla_2, \ldots, sla_i, sla_n] \quad sla_i = \sum_{j=1}^{m} la_{ij}$$

Where, $sla_i$ is the sum of all the elements in line $i$. $RF_A$ is the judgment result of A-phase grounding fault, if its value is $sla_i$ and not 0, it means that the ground fault point is after the $sla_i$ switch of A-phase $k$ ($k = 1,2,\ldots,n$) power supply path. In summary, the specific steps to determine the grounding fault are as follows:

Step 1: According to substation bus voltage information to determine whether a grounding fault occurs. If the grounding fault occurs then go to step 2, if the ground fault does not occur then terminate;

Step 2: Select any substation feeder, and generate A-phase, B-phase and C-phase power supply path mutation current logic matrix according to the formula (1) ~ (4).

Step 3: The results of the grounding fault judgment of the three phases are calculated respectively according to the formula (5). If judgment result value is $sla_i$ and not 0, it means that the ground fault point is after the $sla_i$ switch of A-phase $k$ power supply path. If the judgment result value is 0, it indicates that there is no grounding fault on the feeder.

Step 4: Repeat step 2 to 3 until all substations have been fully analyzed, and then all the grounding fault feeders and grounding fault points can be determined.

### 4. Case analysis

As shown in Figure 2, it is assumed that a permanent fault of A-phase occurs between the switches H and K. Through the PSCAD simulation system, the three-phase simulation current waveform of substation outlet switch S1 is shown in Figure 3. The horizontal axis is time, the unit is $s$; the longitudinal axis is current, and the unit is $A$.

![Figure 3](image)

**Figure 3.** The three-phase current simulation waveform

The real-time measured data $RD$ of each switch after the fault occurred and the historical measured data $HD$ of 5 minutes before the fault occurred are shown in Table 2.
Table 2. The switch measurement value before and after fault (A)

|   | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
|RD| 101.6| 101.6| 101.6| 23.3| 78.3| 57.3| 21.0| 22.3| 35.0| 7.9| 13.1| 27.8|
|HD| 94.4| 94.4| 94.4| 24.1| 70.3| 49.9| 20.6| 22.1| 27.8| 7.9| 12.7| 27.8|

According to the formula (1)–(4), $Ma$ is 8, $\alpha$ is 0.5, then the A-phase power supply path mutation current logic matrix $ACLM_A$ is:

$$ACLM_A = \begin{bmatrix}
7.2 & 7.2 & 7.2 & -0.8 & 0 & 0 & 0 \\
7.2 & 7.2 & 7.2 & 8 & 7.4 & 7.2 & 0 \\
7.2 & 7.2 & 7.2 & 8 & 7.4 & 0.2 & 0 \\
7.2 & 7.2 & 7.2 & 8 & 0.4 & 0.4 & 0 \\
7.2 & 7.2 & 7.2 & 8 & 0.4 & 0 & 0 \\
\end{bmatrix}$$

$$RF_A = \text{Max}[3,6,5,4,4] = 6$$

The analysis process of phase B and phase C is similar and will not be repeated here. Therefore, the grounding fault occurs after the 6th switching device of the A-phase 2nd power supply path. According to Table 1, the fault occurs between the H switch and the K switch.

5. Conclusion

According to the above analysis, it can be seen that in the non-solid-earthed distribution network, when the single-phase grounding fault occurs, the current in the upstream fault phase is abruptly changed due to the superposition of the normal load current and the capacitance current, and the current in the downstream fault phase will keep the load current constant. For other non-fault phase and non-fault feeder current in the upstream or downstream of the fault point, the steady-state current values are load current without mutation.

A single-phase grounding fault judgment method based on steady-state current characteristics is proposed. The power supply path real-time current matrix, the power supply path history current matrix, the power supply path mutation current matrix and the power supply path mutation current logical matrix are established. The problem of the single-phase grounding fault judgment is transformed into the matrix operation problem. The simulation results show that the method proposed in this paper has a good adaptability to the permanent grounding fault and it is worth popularizing.

References

[1] Senger E.C. Manassero G. Jr.Goldenberg 2005 Automated fault location system for primary distribution networks(American: IEEE Transactions on Power Delivery) chapter 2.
[2] Cliff J Williams 2009 A 15 Year Roadmap to Advanced Distribution Automation (International Seminar On New Technology And Applications Of Distribution Automation).
[3] Ni Guang-kui Yang Yi-han Bao Hai 2009 Design of New Fault Indicator of Earthling Fault (China: Modern Electric Power) chapter 6 pp 35-38.
[4] CHEN Bobo,QU Weifeng, YANG Hongyu. 2016 Research on single phase grounding arc model and line selection for neutral ineffectively grounding system (China: Power System Protection and Control), chapter 16 pp 1-7.
[5] LAI Ping, ZHOU Xiangling, QIU Dan.2015 Research on transient-current frequency analysis and faulty line detecting method in indirectly grounding power system(China: Power System Protection and Control), chapter 4 pp 51-57.
[6] ZHANG Wei 2013 An intelligent distributed feeder automation fault judgment (China: Power System Protection and Control) chapter 5 pp 108-113.
[7] YanFeng,YangQixun,QiZheng. 2004 Study on fault location for distribution network based on travelling wave theory(China: Proceedings of the CSEE), chapter 9 pp 38-43.
[8] XUE Yongduan,LI Juan,XU Bingyin. 2015 Transient Equivalent Circuit and Transient Analysis of Single-phase Earth Fault in Arc Suppression Coil Grounded System(China: Proceedings of the CSEE), chapter 22 pp 5703-5714.