Line Selection for Single-Phase Ground Fault Based on Grey Relation Analysis in Small Current Grounding System

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Abstract
The neutral point un-grounding method and the arc-suppression coil grounded method are generally used in power distribution networks in China. In the system, the rate of single-phase-to-earth fault is always the highest. Based on various existing principles of line selection for small current grounding systems, this paper proposes a line selection method based on correlation analysis. When single-phase ground fault occurs in the distribution system, this method utilizes the zero sequence current (especially transient current) relation degree of faulted feeder and normal feeder to distinguish the faulted feeder. An improved algorithm is given based on traditional relation analysis, with which the difference of the fault and the normal feeders can be enlarged. The corresponding simulation and calculation are also carried out by PSCAD. Simulation results show that the selective protection principle based on the method has larger margin between the action values of the fault and sound feeders. It is also not affected by the value of grounding resistance, the degree of fault phase and different grounding patterns.

Key words: Small Current Grounding System, Single-Phase Ground Fault, Fault Line Selection

1. INTRODUCTION
The neutral point un-grounding method and the arc-suppression coil grounding method are generally used in MV power distribution networks in China. In these small current grounding systems, the fault rate of single-phase-to-earth fault is always the highest, accounting for more than 80% of the incidents (Yang X H, 2006; Lin J, 2004). Until now, no reliable method has been found to easily discriminate a faulted feeder from a normal one when single-phase-to-earth faults occur. Scholars both at home and abroad have done a lot of work on how to identify the faulted feeder. Two main kinds of fault line selection principles have been developed, one based on steady signals and the other on transient signals. Fault line selection methods based on transient signals achieve the function through extracting high frequency components from the fault signals, and wavelet analysis is one of these techniques (Chen, 2006; Liang, 2012; Zhao, 2006; Liang, 2015). It judges the faulted feeder through analysis of transient signals in the zero sequence current and is sensitive to sudden and weak signal changes. It can effectively improve the sensitivity of judgments, but an increased transition resistance at the grounding point will decrease the size of the sudden change in the zero sequence current and the size of the sudden change is also small when steady grounded. So it is possible to “judge lose”. In addition, calculations based on transient wavelet analysis of a single-phase-to-earth fault are complex. Consequently, there would be many difficulties if this technique were to be used in production scale projects.

As a method dealing with nondeterministic, grey theory was put forward in the 1980’s. After 20 years of development, the method has been applied in the domain of forecasting, system control and identification and so on. As an important part of grey theory, grey relation analysis also has been widely used in various applications (Yang, 2005).

2. ANALYSISOFZEROSEQUENCE TRANSIENT CURRENT FOR SINGLE-PHASE-TO-EARTH FAULT
Figure 1 shows the equivalent circuit diagram in order to calculate zero sequence current of single-phase-to-earth fault. C is the grounding capacitance of the grid’s three phases, \( L_0 \) is the equivalent inductance of the elements such as three-phase lines and power transformers in the zero-sequence circuit; \( R_0 \) is the equivalent resistance including grounding resistance and arc resistance of the fault point in zero-sequence circuit. \( R_L \), \( L \) separately represents the equivalent resistance and inductance of arc-suppression coil. \( U_0 \) is the zero-sequence voltage.
In the moment when single-phase-to-earth fault occurs in the compensation grid, the equivalent circuit can be used as shown in Figure 1 for calculation of transient current in small current single-phase-to-earth fault. Therefore, the transient grounding currents is

\[
i_a = i_c + i_z = (I_{cn} - I_{zn}) \cos(\omega t + \phi) + I_{cn}(\frac{\omega_0}{\omega} \sin \phi \sin \omega t - \cos \phi \cos \omega t)e^{-\frac{\tau_c}{\omega}} + I_{zn} \cos \phi e^{-\frac{\tau_z}{\omega}} (1)
\]

Where \(\omega\) is the basic frequency, \(\omega_0\) is the self-vibration angular frequency of free-oscillating current components, \(\phi\) is the initial phase of zero-sequence voltage, \(\tau_z\), \(\tau_c\) is separately the time constant of the inductance and capacitance circuit. The first term in equation (1) is the difference between capacitive current and inductive current; The rest is the transient components of the grounding current, and its value is equal to the sum of transient capacitive current component and the transient DC component of inductive current(Zhang, 2006; Pang, 2009; Liang, 2015). In the moment when single-phase-to-earth fault occurs, the maximum transient inductive current appears when the ground fault occurred in the phase voltage zero-crossing moments. When the ground fault occurs in the maximum instantaneous phase voltage, the inductive current is close to 0. Because the value of \(\omega_0/\omega\) is very high (can reach scores), so in the initial moment of failure, transient ground current is mainly transient capacitive current, and the size of transient current is related to the initial phase angle.

A good line selection method should be adapted to different conditions, and the algorithm should have strong robustness. It can not only make the right choice in the arc-type grounding, high resistance grounding conditions, but also free from the impact of load current, unbalanced current and current transformer saturation. After discussing the analysis of traditional grey relation briefly, this paper proposes a fault line selection method for the small current system based on the grey relation analysis of transient zero sequence current. This method utilizes the zero sequence transient current relation degree of faulted feeder and normal feeder to construct a self-adaptive fault line selection method. This method can overcome the current unbalance of the system, the interference of arc and noises. It can also overcome the effects of capacitive current of normal long feeders when fault occurred on short line, and distinguish bus ground faults, without setting and judgement of the polarity or direction. It has a strong self-adaptability.

3. TRADITIONAL GREY THEORY

Grey relation analysis method presented by grey system theory can identify the relevance of the various factors to be analyzed in incomplete information from elements at random sequences through a set of data processing. The so-called grey relation analysis is an analysis method based on microcomputer macrogeometric approach of behavioral factors sequences. The method is carried out in order to identify and analyze the degree of influence between factors, or the contribution measure of factors to the main actions. Grey relation refers to the uncertain relation between things, or uncertain relation between system factors and main behavioral factors. It measures the relative degree of factors based on the similar or dissimilar degree of the factors’ development trend(Wu, 2007).

Suppose there are two series, one is \(X_i(t)\) (presents parent sequences or the reference sequence), the other one is \(X_j(t)\) (presents sub-sequences or the comparison sequence). If there are two curves, separately representing the process of change of two things under one variable (time t), then the proximity is a quantity that contains the information of zero-order slope difference of \(X_i(t) - X_j(t)\) between curves. Thus, in the traditional grey relation analysis, the correlation coefficient is defined as follows:

\[
\xi_{ij} [X_i(t), X_j(t)] = \frac{\min\{X_i(t) - X_j(t)\} + \rho \max\{X_i(t) - X_j(t)\}} {\max\{X_i(t) - X_j(t)\} + \rho \max\{X_i(t) - X_j(t)\}}
\]
In equation (3), the distinguishing coefficient is set to $\rho = 0.5$. Get the correlation between the reference sequence $X_i$, and the comparison sequence $X_j$, defined as follows:

$$r_{ij} = \frac{1}{N} \sum_{k=1}^{N} \xi_{ij}(k)$$  \hspace{1cm} (4)

Where $r_{ij}$ is the relation degree between the reference sequence $r_i$ and the comparison sequence $r_j$. All the $r_{ij}$ compose a matrix, constitute a correlation matrix $R$.

$$R = \begin{bmatrix}
1 & r_{12} & r_{13} & \ldots & r_{1n} \\
r_{21} & 1 & r_{23} & \ldots & r_{2n} \\
r_{31} & r_{32} & 1 & \ldots & r_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
r_{n1} & r_{n2} & r_{n3} & \ldots & 1
\end{bmatrix}$$  \hspace{1cm} (5)

4. FAULT LINE SELECTION METHOD FOR THE SMALL CURRENT SYSTEM BASED ON THE GREY THEROY

The traditional fault line selection methods in the small current system, regardless of the use of steady signals or transient signals, are trying to find signal singularity between fault line and normal line. They ignored the fault and normal lines, as well as the correlation between them. This paper uses grey relation theory to find the correlation between lines and thus find the fault line from the strength of the relation degree that is the singularity of the information.

The correlation in equation (3) considers just the relation between the static differences of things, if from the dynamic point of view, such as the rate of change and the slope of the waveform curve, using the acquaintance of change trends of the curves’ geometric shape for correlation calculations. A typical representative is an absolute correlation:

$$\xi_{ij}(k) = \frac{1}{1 + |X_i(t) - X_j(t)|}$$  \hspace{1cm} (6)

Then the correlation between the reference sequence $X_i$ and the comparison sequence $X_j$ is:

$$r_{ij} = \frac{1}{N} \sum_{k=1}^{N} \frac{1}{1 + |X_i(t) - X_j(t)|}$$  \hspace{1cm} (7)

Suppose the substation bus has outlet lines of $n$, and the label respectively is $1, 2, \ldots, n$, achieving fault zero-sequence currents from zero-sequence current transformers at the exit of feeders, then the zero-sequence current of each outlet line is $i_1, i_2, \ldots, i_n$.

The basic approach of fault line selection method based on grey theory for small current system is to sample each branch at a highspeed in a cycle time after a fault happened, zero-sequence voltage increased to a certain threshold value can be used as the start signal, in order to obtain more comprehensive information on the transient information, the sampling frequency of 12kHz is selected, available to obtain the synchronous sampling sequences of each branch current at different times, $i_1(t) = \{i_1(0), i_1(1), \ldots, i_1(m)\}$, $i_2(t) = \{i_2(0), i_2(1), \ldots, i_2(m)\}$, $\ldots$, $i_n(t) = \{i_n(0), i_n(1), \ldots, i_n(m)\}$.

Using equation (7) to calculate the grey correlation between slip lines, $n$ slip require to be calculated $C_n^2$ times, then the matrix similar to formula (5) can be got:

$$R = \begin{bmatrix}
0 & r_{12} & r_{13} & \ldots & r_{1n} \\
r_{21} & 0 & r_{23} & \ldots & r_{2n} \\
r_{31} & r_{32} & 0 & \ldots & r_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
r_{n1} & r_{n2} & r_{n3} & \ldots & 0
\end{bmatrix}$$  \hspace{1cm} (8)

$$\bar{R} = \frac{1}{n} \sum_{j=1}^{n} r_{ij}$$  \hspace{1cm} (9)

$$\Delta\bar{R} = \sum_{j=1}^{n} |\bar{R} - \bar{R}_j|$$  \hspace{1cm} (10)
From the matrix $R$ we can see, each element $r_{ij}$ represents the relation degree between two lines, so $\bar{R}$ of each branch with other can be calculated. And then calculate the sum of the mutual difference between average relation grades. $\bar{R}$ inequation (10) can be used inequation (11) to zoom in the difference between average relation grade of fault and normal lines. Because $\bar{R}$ of the normal lines are basically the same, from the above equation we can see that for a distribution network with branches of $n$, the $y_i$ of normal lines are approximately equal to $n-2$; while $y_i$ of the fault line is approximately equal to $(n-1)^2$. This shows that as long as the feedernumber of the system is greater than 3, the fault line can be clearly distinguished, and more reliable with more feeders.

5. SIMULATION AND EXPERIMENTAL ANALYSIS

5.1. Model Construction of Single-phase-to-earth Fault in Distribution Network and Simulation

In this paper, PSCAD (EMTDC) simulations of single-phase-to-earth fault in a variety of conditions in small current network were carried out. The simulation model used as shown in Figure 2, this is a simple 6kV system with five outlet lines, the neutral point arc-suppression coil paralleled with resistance grounding method was used, with arc-suppression coil resonance degree adjustable.

Parameters are as follows: voltage level at power supply side is 35kV, through 35kV/6kV, Y/d type connected power transformer to supply the branches, rated capacity of the transformer is 10MVA, power factor is 0.8, 3 cables and two overhead lines, total capacitive current is 50A, assuming the grid to ground asymmetry grade is 1% in normal working hours. Line parameters are as follows: line distributed capacitance described with lumped parameter, to-ground capacitance of Cable1 is 18μF, to-ground capacitance of Cable2 is 12μF, to-ground capacitance of Line3 is 4μF, to-ground capacitance of Line4 is 3μF, to-ground capacitance of Cable5 is 9μF. Using excessive compensation, arc-suppression coil parameters: resistance is 6.777Ω, inductance is 0.20816H.

![Figure 2. The sketch map of single-phase-to-ground fault in the distribution network](image)

Metallic single-phase ground fault, and by the 1000Ω resistance grounding situations were simulated in the neutral point arc-suppression coil paralleled with resistance grounding mode, also metallic single-phase ground fault of one line in the neutral point arc-suppression coil grounding mode and metallic single-phase ground fault in neutral point insulated mode were simulated. The zero-sequence current waveforms got with different initial phase angle were shown in Figure 3. The figure shows that the zero-sequence current in the first half-wave is mainly high frequency signals, and the frequency mainly concentrated in 1kHz ~ 2kHz and the high frequency components are close to zero after a half-cycle after fault occurred. From the simulation waveforms, it can be seen directly that the similarity between zero-sequence current waveforms of fault line and normal line is low within the first cycle after the fault occurred, while the similarity between zero-sequence current waveforms of normal lines is high.

From the transient process of single-phase ground fault point of view, the transient component of a ground current is much larger than the steady value, transient process of fault voltage and fault current has a very short duration, but is rich in characteristic quantities. Under normal circumstances, the transient capacitive current can be seen as a sum of capacitor charging and discharging currents between non-fault phase and the fault phase. The frequency of fault-phase capacitor discharging current is as high as several kHz, which is flowing through the bus to the point of failure, and the attenuation is very fast. In the non-fault phase, the capacitor charging current flows mainly through the power supply to form a loop, its attenuation is slow and the oscillating frequency is low (Hao, 2007; Liang, 2009; Zhang, 2012; Zhang, 2007).
(a) Metallic ground fault when Phase voltage is the maximum in neutral point grounding by ASC mode

(b) Metallic single-phase ground fault when Phase angle of phase voltage is 30° in neutral point grounding by ASC mode

(c) Metallic single-phase ground fault when Phase angle of phase voltage is 60° in neutral point grounding by ASC mode

(d) Metallic single-phase ground fault when Phase angle of phase voltage is 0 in neutral point grounding by ASC mode
As shown in Figure 3, in addition to the arrows marked fault zero-sequence current signals, other curves are fault current signals of non-fault lines. It can be seen clearly from the figure that the single-phase ground fault occurred when the fault phase voltage is 0, zero-sequence current of each branch does not present the situation of polarity different as the first half-wave theory, and the zero-sequence transient current curves are basically the same trend when the bus is grounded. When the fault phase voltage is a certain value when the single-phase ground fault occurs, the slope of zero-sequence transient current curves of fault line and non-fault line has the opposite polarity.

5.2. Experimental Data Analysis and Calculation

This paper shows ground fault experiments in three different kinds of typical conditions: bus ground fault, ground fault occurs respectively when fault phase voltage phase is $0^\circ$, $30^\circ$, $60^\circ$, $90^\circ$. In the neutral point arc-suppression coil paralleled with resistance grounding mode, regulating arc-suppression coil to be over compensated 15% with damping resistance and without damping resistance, $L_3$ is respectively metallic grounded, by $1000\Omega$ resistance grounded, using formula (9) to calculate the average relation grade of each branch, and then using formula (10) and (11) for amplification. Because of the limited space, the tables in this paper only give out the data of four branches.

(1) Ground fault occurred in the neutral point grounded by ASC with parallel resistance while the ASC is over compensated mode, the calculation results were shown as Table 1.

**Table 1.** Calculation results of neutral point grounded by ASC with parallel resistance while the ASC is over compensated

<table>
<thead>
<tr>
<th>Resistance/(\Omega)</th>
<th>Phase angle</th>
<th>(\Delta R_1)</th>
<th>(\Delta R_2)</th>
<th>(\Delta R_3)</th>
<th>(y_1)</th>
<th>(y_2)</th>
<th>(y_3)</th>
<th>(y_4)</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over Compensated With damping</td>
<td>10</td>
<td>0°</td>
<td>0.728</td>
<td>0.736</td>
<td>1.812</td>
<td>0.702</td>
<td>4.04</td>
<td>4.18</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30°</td>
<td>0.615</td>
<td>0.629</td>
<td>1.797</td>
<td>0.634</td>
<td>4.12</td>
<td>4.09</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°</td>
<td>0.571</td>
<td>0.548</td>
<td>1.932</td>
<td>0.504</td>
<td>4.25</td>
<td>4.35</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90°</td>
<td>0.582</td>
<td>0.551</td>
<td>1.971</td>
<td>0.569</td>
<td>4.15</td>
<td>4.21</td>
<td>15.8</td>
</tr>
<tr>
<td>1000</td>
<td>0°</td>
<td>0.618</td>
<td>0.606</td>
<td>1.912</td>
<td>0.605</td>
<td>3.96</td>
<td>3.98</td>
<td>12.7</td>
<td>3.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30°</td>
<td>0.518</td>
<td>0.545</td>
<td>1.938</td>
<td>0.511</td>
<td>4.14</td>
<td>4.29</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°</td>
<td>0.525</td>
<td>0.531</td>
<td>1.984</td>
<td>0.502</td>
<td>4.16</td>
<td>4.27</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90°</td>
<td>0.579</td>
<td>0.617</td>
<td>1.991</td>
<td>0.662</td>
<td>4.14</td>
<td>4.28</td>
<td>15.9</td>
</tr>
</tbody>
</table>

(2) Ground fault occurred in the neutral point grounded by ASC while the ASC is over compensated mode, the calculation results were shown as Table 2.

See from Table (1), Table (2), it is clearly that using this method can accurately select the fault line regardless of whether the neutral point arc-suppression coil with or without paralleled (in Series) resistance. And, regardless of fault feeder or non-fault feeder, its fault judgment quantity is the difference between the feeder’s information and all the other feeders’ information, using the sum of their absolute values, it is informative, containing information of all the feeders. (1) Bus grounded, in the neutral point grounded by ASC with parallel resistance while the ASC is over compensated mode, bus grounded by $1000\Omega$ resistance, the calculation results were shown as Table 3. y of the lines are basically the same, doesn’t like the situation $y_1$ has significant difference shown in Table 1, Table 2. Therefore, in the starting moment when zero-sequence voltage rises, if there is only little difference between the calculated $y_1$, it can consider the bus ground fault, not reporting a result of grounded line.
Table 2. Calculation results of neutral point grounded by ASC while the ASC is over compensated

<table>
<thead>
<tr>
<th>resistance/Ω</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.505</td>
<td>0.516</td>
<td>1.842</td>
<td>0.521</td>
</tr>
<tr>
<td>1000</td>
<td>0.606</td>
<td>0.591</td>
<td>1.612</td>
<td>0.585</td>
</tr>
</tbody>
</table>

Table 3. Calculation results of single phase of bus is grounded

<table>
<thead>
<tr>
<th>Phase angle</th>
<th>0°</th>
<th>30°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.505</td>
<td>0.516</td>
<td>1.842</td>
<td>0.521</td>
<td>1.842</td>
</tr>
<tr>
<td>0.606</td>
<td>0.591</td>
<td>1.612</td>
<td>0.585</td>
<td>1.612</td>
</tr>
</tbody>
</table>

Conclusion: This method can overcome the effects of capacitive current of normal long feeders when fault occurred on short line; and in different operating mode, grounded at different moments of the fault phase, we found that this method is basically unaffected by their impacts after changing Compensation Degree, fault lines, fault point location, load and such parameters.

Change the size of the grounded resistance when fault occurs at the moment when the phase voltage value is the maximum, the method can clearly separate the fault line. When fault occurs at the moment when the phase voltage is nearly zero, capacitive current’s amplitude changes obviously with different grounded resistances, but it can still distinguish the fault line, the simulation results verified that the new method is correct and effective. When introduce interference signals, the interference signals will be filtered by the algorithm, so the anti-interference capability has been considerably increased, at the same time it widened the gap between the fault line and the non-fault lines, so that the protection margin was increased significantly.

6. CONCLUSIONS

Based on the characteristics of single-phase ground fault in distribution systems and the zero sequence transient current waveforms relation degree of faulted feeder and normal feeder, this paper proposes a fault line selection method for small grounding current systems based on grey theory. Simulation is carried out by using PSCAD and related mathematical tools. The results verify that the method is correct and feasible.

The method is characterized as follows:

1. The computational complexity of this method is small, significantly improve the previous fault line selection methods based on the transient theory, results can be obtained by high-speed AD sampling and computing, it has great feasibility.

2. The simulation results show that the average relation grade between the lines can be quickly and accurately obtained in a variety of conditions, and then the difference be enlarged to obtain the corresponding criterion.

3. When fault occurs at the moment that the phase voltage is nearly zero, the transient component amplitude is very small, causing difficulties for fault line selection, this method can effectively overcome the impact of a small transient current in that circumstance to achieve the proper selection.

4. The method has strong anti-interference ability, and is not affected by the ground phase of fault phase, grounding mode and resistance. It is a promising grounding line selection method for small current systems.

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REFERENCES


