Research on Line Selection Method of Single-phase Earth Fault Based on Improved Dynamic Time Bending Distance Similarity Word

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Abstract. The problem of fault line selection for the distribution network of neutral point via arc suppression coil grounding has not been solved for a long time. Based on this, a single-phase ground fault line selection method based on dynamic time bending distance similarity is proposed. Firstly, the single-phase ground fault feature analysis of the distribution network of the zero-mode network is used to determine the electrical characteristic quantity of the single-phase ground fault line selection. Then, the faulty electrical feature quantity is improved by the dynamic time bending distance algorithm to form the distance matrix. The similarity data processing is performed on the matrix to obtain a line selection vector, and then the fault line is selected. Finally, the single-phase ground fault system model of 10kV distribution network is constructed by Matlab/Simulink. The correctness and feasibility of single-phase ground fault line selection method based on the dynamic time bending distance similarity is verified by simulation under different fault conditions.

1. Introduction

If a single-phase ground fault occurs in a system grounded by an arc suppression coil, if the faulty branch is not effectively detected, the continuous fault may develop into a more severe two-phase or three-phase short circuit. The technical issues of line selection have always been the hotspots and difficulties of research.

According to the signal source used, the existing line selection methods include injection signal method [1, 2], fault signal method [3, 4] and information fusion method [5, 6]. The injection signal method is complicated in signal source design and control by applying signal selection lines to the grid. The fault signal method uses the steady-state or transient characteristics of the system single-phase ground to detect the fault branch. The information fusion method is based on the fusion of multiple signals and methods. The validity of the effective domain and its combination of the fusion method remains to be studied [7]. The fault signal method includes a steady state line selection method and a transient line selection method. The steady-state signal used by the steady-state line selection method is weak; and there is a dead zone in the over-compensated arc-suppression coil grounding system; the method is limited in application. The fault transient signal contains a lot of fault features, and if it can be fully utilized, it is beneficial to line selection.
The transient process mechanism is complex and the state is random. Especially under the condition of small fault angle or high resistance grounding, the reliability of the existing transient line selection cannot be guaranteed. Therefore, this paper proposes a single-phase ground fault line selection method based on dynamic time bending distance similarity. The single-phase ground fault characteristics of the distribution network of the zero-mode network are analyzed, and the line selection criterion is constructed by using the improved dynamic time bending distance. Simulations verify the effectiveness of the method.

2. Analysis of single-phase ground fault characteristics of distribution network with zero-mode network

The single-phase ground fault occurs in the system, and the balance of the three-phase system is broken, so that the zero-sequence voltage appears in the system, so whether the zero-sequence voltage appears in the power distribution system can be used as the starting criterion for the fault line selection. The system for grounding the arc suppression coil is modeled and analyzed; the zero-mode network model for single-phase ground fault is shown in Figure 1.

![Figure 1. Single-phase grounded 0-mode equivalent network](image)

Single-phase grounding fault occurs in the resonant grounding system of the distribution network. Due to the influence of line resistance, inductance and capacitance in the centralized parameters, high-frequency oscillations are attenuated in the fault transient process. In order to describe the theorem of the physical process, each can be The zero mode current of the branch is divided into the attenuated DC component \(i_0\), the fundamental frequency current component \(i_1\), the higher harmonic current component \(i_m\) and the high frequency attenuation current component \(i_\alpha\). The zero mode currents of the respective components are respectively (1)–(4) shown.

\[
i_0 = I_0 e^{-\beta t}
\]  

(1)
\[ i_1 = \sqrt{2} I_1 \sin(2\pi f_1 t + \varphi_1) \] (2)

\[ i_m = \sum_{m=2}^{q} \sqrt{2} I_m \sin(2\pi f_m t + \varphi_m) \] (3)

\[ i_n = \sum_{2}^{p} e^{-\beta_n \rho} \sqrt{2} I_n \sin(2\pi f_n t + \varphi_n) \] (4)

The zero sequence full current is:

\[ i = i_0 + i_t + i_m + i_n \] (5)

Among them, the amplitude of the DC component of \( I_0 \), \( \beta_0 \) represents the attenuation factor of the DC component, \( I_1 \), \( \varphi_1 \), and \( f_1 \) represent the effective value, initial phase, and frequency of the fundamental wave; \( I_m \), \( \varphi_m \), and \( f_m \) represent the effective values of the nth harmonic. The initial phase, frequency, \( \beta_n \), \( I_n \), \( f_n \), \( \varphi_n \) represent the attenuation factor, effective value, frequency, and initial phase angle of the nth high frequency component.

By analyzing the zero-mode network, it can be obtained that the zero-mode current has the following characteristics:

1. In the resonant grounding system of the distribution network, due to the compensation of the steady-state amount of the arc-suppressing coil, the steady-state component of the faulty branch is not satisfied with the maximum amplitude compared with the steady-state component of the non-faulty branch, which makes the steady-state amount based on The line selection method basically fails in the resonant grounding system.

2. In the resonant grounding system, the transient zero-mode current contains a DC component and a large number of high-frequency components. At this time, the arc-suppression coil has substantially no compensation for the zero-mode current flowing into the faulty branch. Therefore, the faulty branch The transient zero mode current is greater than the transient zero mode current of the non-faulty branch, and its direction is from the line to the bus, and the zero sequence current of the non-faulty branch flows from the bus to the line.

3. Line selection for improving dynamic time bending distance similarity

3.1 Signal identification method for dynamic time bending distance similarity

There is a difference between the transient zero-sequence current waveforms of the faulty line and the non-faulty line. The improved dynamic bending distance algorithm can obtain the mutual distance between the transient zero-mode currents of each line. The DTW algorithm is a signal identification method successfully applied in the field of speech recognition, and has strong resistance to synchronization error and sensitivity. DTW seeks the best correspondence by appropriately scaling and nonlinearly curling two data sequences, so that the sum of the corresponding distances of the two sequences is the minimum DTW distance. The DTW distance can be used to measure the similarity between two time series.

The DTW searches the relationship between the two time series X and Y, uses the dynamic programming idea to adjust the correspondence between the two sequences, and obtains an optimal path, so that two sequences along the path Minimum distance between.

The sampling signal \( y_1(t) = \{y_1(t_1), y_1(t_1), \cdots, y_1(t_m)\} \), \( y_2(t) = \{y_2(t_1), y_2(t_1), \cdots, y_2(t_n)\} \), where \( m \) and \( n \) are the sequence lengths. As shown in Figure 3.6, the curved path can represent the path formed by the black point, that is, \( P = \{p_1, p_2, \cdots, p_s\} \), where \( p_s \) is the coordinate of the sth point of the path,
that is, $p_s = (i_s, j_s)$, indicating that the $i_s$ th point of the sequence $y_1(t)$ corresponds to the $j_s$ th point of the sequence $y_2(t)$, you can get all the corresponding distance matrix $D$ of the two sequences:

$$D = \begin{bmatrix}
d(y_1(t_1), y_2(t_1)) & d(y_1(t_1), y_2(t_2)) & \cdots & d(y_1(t_1), y_2(t_n)) \\
d(y_1(t_2), y_2(t_1)) & d(y_1(t_2), y_2(t_2)) & \cdots & d(y_1(t_2), y_2(t_n)) \\
\vdots & \vdots & \ddots & \vdots \\
d(y_1(t_m), y_2(t_1)) & d(y_1(t_m), y_2(t_2)) & \cdots & d(y_1(t_m), y_2(t_n))
\end{bmatrix}$$

(6)

In the formula, the element $d(y_1(t_m), y_2(t_n)) = (y_1(t_m) - y_2(t_n))^2$ in $D$ represents the square of the distance between the sequence points $y_1(t_m)$ and $y_2(t_n)$. The existence sequence $p = \{p_1, p_2, \cdots, p_k, \cdots p_3\}$ is used to represent a curved path, $s$ represents the total number of elements in $l$, and $p_k$ represents the $k$ th element in the curved path.

There are multiple curved paths that satisfy the constraint, and the shortest DTW distances that can define the sequences $y_1(t)$ and $y_2(t)$ are:

$$D_{rw}(y_1(t), y_2(t)) = \sqrt{\min_{l_1=1}^{s} \sum_{k=1}^{s} p_k}$$

(7)

By obtaining the cumulative distance matrix in the curved window, the DTW distance can be quickly obtained, which is simple to calculate and easy to implement by the microcomputer, and can avoid the local optimal solution of the curved path.

3.2 Improvement of Signal Identification Method for Dynamic Time Bending Distance Similarity

In practical engineering applications, due to the large number of samples, the cumulative distance matrix method needs to calculate nDT times for the DTW distance. On the other hand, due to the different impedance angles of the lines, there is a certain phase difference between the non-faulty zero-sequence current waveforms between different lines. Although the DTW distance has a certain resistance to synchronization error, it is bound by its path boundary and phase deviation. Will still affect the final distance value, which will reduce the accuracy of fault line selection.

In this paper, the DTW distance algorithm is improved for the defects of the DTW distance algorithm in signal identification. By adding a solution region to the distance square matrix D and setting a curved window in the solution region, the error caused by the phase can be corrected to a certain extent, and the calculation amount is greatly reduced.

The solution area is a t-valence matrix. Since the single-phase grounded transient information is distributed at the front end of the series, the specified solution area can only select the elements in D with the first row or the first column sliding frame. A curved window with a width r is set for the solution area, and only the cumulative distance matrix within the window is obtained. Phase deviation can be corrected quickly. The improved DTM distance algorithm needs to limit the minimum order in the solution area to prevent information loss caused by transition correction. The value of the bending window width r needs to be integrated with the ability to withstand synchronization error and calculation time. Processing selects the curved window. An improved DTW distance is obtained between the two lines, and a matrix W for characterizing the similarity of the transient zero-sequence current waveform is constructed.
Where: element $w_{ij}$ is the improved DTW distance value for the transient zero-sequence current waveform of line $i$ and line $j$. In order to simplify the steps, the correlation coefficient between the lines is obtained through the matrix $W$ as a vector of the line selection. The correlation coefficient expression is:

$$
\rho = \frac{\sum_{n=1}^{N} x(n)y(n)}{\sqrt{\sum_{n=1}^{N} x^2(n)\sum_{n=1}^{N} y^2(n)}}
$$

Where $x(n)$, $y(n)$ are the improved DTW distance values for the transient zero-sequence current waveforms of line $i$ and line $j$, respectively. The fault line selection vector is normalized. get:

$$
\rho = \frac{1}{\rho_{\text{max}}} [\rho_{11}, \rho_{12}, \ldots, \rho_{1N}]
$$

In the fault line selection, the value of $\rho$ is between 0-1, the correlation coefficient of DTW distance between non-faulty line and non-faulty line is close to 1, and the correlation coefficient between fault line and fault line is close to 0.

3.3 Line selection criterion for improving dynamic time bending distance similarity

The correlation coefficient of the DTW distance between the non-faulty line and the non-faulty line is close to 1, and the correlation coefficient of the DTW distance between the faulty line and the faulty line is close to zero.

3.4 Line selection process for improving dynamic time bending distance similarity

According to the characteristics of the single-phase ground fault of the distribution network of the zero-mode network and the line selection method for improving the similarity of the dynamic time bending distance, the flow of the line selection for improving the dynamic time bending distance similarity is finally given.

(1) Analyze the characteristics of single-phase ground fault of distribution network in zero-mode network, and determine the electrical characteristic quantity of single-phase ground fault line selection;

(2) Improved dynamic time bending distance algorithm for fault electrical feature quantity to form distance matrix;

(3) Perform similarity data processing on the distance matrix to obtain a line selection vector;

(4) Select the fault line according to the line selection vector;
(5) If the correlation coefficient of the DTW distance between the non-faulty line and the non-faulty line is close to 1, the line operates normally; if the correlation coefficient of the DTW distance between the faulty line and the faulty line is close to 0, then the line has a single phase Ground Fault.

Algorithm flow chart shown in Figure 2.

![Algorithm flow chart](image)

Figure 2. Flow chart of line selection algorithm for improving dynamic time bending distance similarity

4. Numerical simulation

Using Matlab/Simulink to establish a single-phase ground fault system model for 10kV distribution network, through simulation verification of single-phase ground fault under different fault conditions (fault point position, grounding resistance, compensation type), using simulation data analysis and verification line selection method Correctness and feasibility.

4.1 Construction of simulation model

Simulation verification for the line selection method. The simulation model is shown in Figure 3. This paper is verified by the following simulation analysis:

Load parameter: Active power is $P = 10000\text{W}$, Inductive reactive power is $Q_L = 4000\text{var}$, Capacitive reactive power is $Q_C = 0\text{var}$. 
Single-phase ground faults with various conditions are set by simulation models, including different initial angles of faults (0°, 30°, 45°, 60°, 90°), different grounding resistance (20Ω, 50Ω, 100Ω, 500Ω, 1000Ω), Compensation status of zero sequence reactor inductance value (Overcompensation $p=10\%$, Full compensation $p=0\%$, Under compensation $p=-20\%$), Different fault lines (L1, L2, L3), Verification of the validity and reliability of the line selection method proposed above for improving the dynamic time bending distance similarity.

![Figure 3. Single-phase ground fault line selection simulation model](image)

4.2 Simulation verification under overcompensated conditions

(1) Simulation results of different initial angles of failure under overcompensation mode

10kV power distribution system, line L1 is faulted by C phase grounding, Resonant system overcompensation is $p=10\%$. Zero sequence inductance is $L=5.062H$, Grounding resistance is $R_f=50Ω$. Set different initial phase angles of the fault to verify that the line selection method is not affected by the initial phase angle of the fault.

Table 1. Line selection results under different initial angles of overcompensation ($R_f=50Ω$)

| Fault line | Fault angle $\phi/\circ$ | Line selection vector | critical result |
|------------|--------------------------|-----------------------|----------------|
| Line L1    | 0                        | [0.012 0.998 0.909 0.968] | L1             |
| Line L1    | 30                       | [0.021 0.995 0.967 0.926] | L1             |
| Line L1    | 60                       | [0.053 0.943 0.973 0.936] | L1             |
| Line L1    | 90                       | [0.069 0.987 0.975 0.928] | L1             |

(2) Simulation results of different grounding resistances in overcompensated mode

10kV power distribution system, line L1 is faulted by C phase grounding, Resonant system overcompensation $p=10\%$, Zero sequence inductance is $L=5.062H$, Fault initial phase angle $\phi=45°$, Set different grounding resistances to verify that this line selection method is not affected by the grounding resistance.

Table 2. Line selection results based on overcompensation for different grounding resistances ($\phi=45°$)

| Fault line | Grounding resistance $R_f/Ω$ | Line selection vector | critical result |
|------------|-----------------------------|-----------------------|----------------|
| Line L1    | 50                          | [0.014 0.995 0.943 0.912] | L1             |
| Line L1    | 500                         | [0.026 0.945 0.936 0.926] | L1             |
| Line L1    | 1000                        | [0.051 0.973 0.942 0.971] | L1             |
| Line L1    | 10000                       | [0.071 0.947 0.899 0.903] | L1             |

Conclusion: Under the condition of overcompensation mode, the simulation results show that the line selection method for improving the dynamic time bending distance similarity is not affected by the grounding resistance and the initial angle of the fault, which verifies the effectiveness of the method.
4.3 Simulation verification under under-compensation/resonance compensation conditions

Through a large number of simulations, the results show that the line selection method for improving the dynamic time bending distance similarity is not affected by the compensation type. Under different compensation conditions, this line selection method is not affected by grounding resistance and initial angle of failure.

5. Conclusion

This paper mainly studies the single-phase ground fault line selection method based on dynamic time bending distance similarity. The single-phase ground fault characteristics of the distribution network of the zero-mode network are analyzed, and the line selection criterion is constructed by using the improved dynamic time bending distance. Through the simulation under different fault conditions, the correctness and feasibility of the single-phase ground fault line selection method based on dynamic time bending distance similarity are verified. The line selection method is not compensated, the initial angle of failure, Effect of transition resistance.

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