Research on fault line selection method for distribution network in small current grounding system

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Abstract. When a single-phase-to-ground fault occurs in the distribution network, there is a wealth of information in the transient process of the fault line, from which the fault line selection criterion can be extracted. In this paper, based on the analysis of the related principle of wavelet transform and the concept of entropy, the comprehensive wavelet entropy is defined, and the principle and process of fault line selection are put forward by analyzing the variation coefficients of a group of comprehensive wavelet entropy. Finally, the simulation software is used to verify the fault line selection method under different fault conditions to prove its applicability and feasibility.

1. Introduction
Through the statistical analysis of the fault data of the distribution network, it is known that compared with other types of faults, single-phase ground faults account for 80% of the total fault events. Generally speaking, when a single-phase ground fault occurs in the distribution network, the fault current generated by the system is relatively small, which will not cause much damage to the load carried by the line [3-7]. However, with the continuous improvement of the urban distribution network structure, the new lines are mainly cable lines, so that the impedance in the system decreases, the system ground capacitance increases, and the fault current increases in the case of single-phase-to-ground fault in the distribution network. When a metal single-phase ground fault occurs in the distribution network line, the ground fault point will flow through a large current, and even produce arc grounding overvoltage. Therefore, when a single-phase ground fault occurs in the distribution network, the fast and accurate identification of the fault line is very important for the stable operation of the distribution network. In this paper, taking the arc suppression coil grounding system as an example, the principle of line selection in the case of single-phase ground fault is analyzed, and its feasibility is verified by simulation.

2. Method of fault line selection

2.1. Analysis of the principle of fault line selection
For the urban distribution network, when there are more distribution lines or more cable lines, the ground capacitance of the whole system is relatively large, and the short-circuit current generated by the system may exceed the value that can be extinguished automatically when a single-phase ground fault occurs. At this time, it is necessary to be equipped with arc suppression coil to reduce it to the allowable value[9].
The structure block diagram of single-phase-to-ground fault in distribution network is shown in Figure 1.

Figure 1. Structure block diagram of single-phase-to-ground fault in distribution network

When a single-phase-to-ground fault occurs in the distribution network, there is a great difference in zero-sequence current between fault lines and non-fault lines, so the difference of zero-sequence current is selected as the data source of fault line selection. The wavelet packet transform has high time resolution in the high frequency range, and the relative entropy can be used as a measure of the difference between the two signals. The greater the difference, the greater the relative entropy. Therefore, with the combination of wavelet packet transform and relative entropy, the comprehensive wavelet entropy which can quantify the difference of zero sequence current between one line and other lines in distribution network is defined.

The zero sequence current of each power frequency cycle before and after the fault is selected for analysis. By collecting the zero sequence current in different lines after the fault of the distribution network, the wavelet packet transform is carried out. When the number of decomposition layers is $j$, $2^j$ frequency bands are generated, corresponding to the 0 to $(2^j-1)$ nodes generated in the $j$-layer decomposition.

For a medium voltage distribution network with $l$ lines, the energy of line $s$ $(1 \leq s \leq l)$ in the $m$ $(1 \leq m \leq 2^j)$ band is defined as $E_{sm}$:

$$E_{sm} = \sum_{i=1}^{n} \left( w_m^j(i) \right)^2$$  \hspace{1cm} (1)

In the equation, $w_m^j(i)$ is the reconstruction coefficient of the $m$-band under the $j$-layer decomposition of the signal after wavelet packet transform, and $n$ is the total number of sampling points.

For the $l$ lines that exist in the distribution network, the total energy $E_m$ in the $m$-band is defined as shown in the following equation:

$$E_m = \sum_{s=1}^{l} E_{sm}$$  \hspace{1cm} (2)

Then the ratio of the energy of the line $s$ in the $m$-band $E_{sm}$ to the total energy of all lines in the $m$-band $E_m$ in the distribution network is defined as follows:

$$P_{sm} = E_{sm} (E_m)^{-1}$$  \hspace{1cm} (3)

According to the introduction of the relative entropy in the previous article, the relative entropy of the line $s$ relative to the line $h$ $(1 \leq h \leq l)$ can be defined $K_{sh}$:

$$K_{sh} = \sum_{m=1}^{2^j-1} \left| p_{h,m} \frac{p_{sm}}{p_{hm}} \right|$$  \hspace{1cm} (4)

Considering the relative relationship between the two signals and the symmetry of the relative entropy between the two lines, the comprehensive wavelet entropy of the line $s$ relative to the rest of the distribution network is defined as $K_s$:

$$K_s = \sum_{h=1}^{l} (K_{sh} + K_{hs})$$  \hspace{1cm} (5)
After the fault occurs, the zero-sequence current in fault and non-fault lines shows great differences in amplitude and polarity, and the entropy value of the corresponding comprehensive wavelet entropy between them will be relatively large, while for non-fault lines, the difference between zero-sequence currents between different lines is relatively less severe and the similarity is higher, and the entropy value between them will be much smaller than the former.

For a set of one-dimensional data with \( n \) elements \( \{x_1, x_2, \cdots, x_n\} \), when analyzing this set of data, if a small amount of data does not conform to the overall distribution trend of \( n \) elements as a whole, that is, it is different from most of the elements in the data set, then these minorities can be considered abnormal relative to \( n \) elements as a whole. For the characteristics shown by different aspects of a group of data, there are different digital characteristics of the data.

The data mean represents the centralized location of a set of data, and the equation is as follows:

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i
\]  
(6)

The variance represents a measure of the dispersion of data values, and the equation is as follows:

\[
s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2
\]  
(7)

Then the coefficient of variation of the relative dispersion of a group of data is equation as follows:

\[
CV = 100 \frac{s}{\bar{x}} \% 
\]  
(8)

In the analysis of a group of data, the degree of data dispersion can be judged by setting an appropriate coefficient of variation threshold. When the value of the data group is greater than the preset value, it is considered that the dispersion phase of this group of data is relatively large, in which there are outliers.

2.2. Fault line selection criterion and process

In several power frequency periods after the occurrence of single-phase ground fault in distribution network, there is an obvious difference in the change of zero-sequence current between fault lines and non-fault lines, while the change of zero-sequence current between non-fault lines is relatively similar. This difference characteristic is used to calculate the corresponding value of the line, and then judge the degree of difference between different lines. After the occurrence of the line fault, the corresponding value of the non-fault line will be relatively small, while the corresponding value of the fault line is much larger. A group of K value data corresponding to the distribution network line after the fault is analyzed, and the coefficient of variation of the K value data set is calculated. then it is compared with the set threshold to judge that the fault occurs in the bus or line. When the fault occurs at the bus position, the coefficient of variation of each line corresponding to the K value data group is less than the threshold, for the line fault, the coefficient of variation of the data group is greater than the threshold, and the maximum value in the K value data set is an abnormal value. The line corresponding to this abnormal value is the fault line, so as to realize the fault line selection.

The steps of the line selection method are as follows:

(1) Set the zero sequence voltage threshold of the bus, taking into account the deviation according to the actual situation, the determination of the numerical value can ensure that the line selection device does not operate in the actual operation state, and only if the collected zero sequence voltage of the bus exceeds the setting, it is considered that a single-phase ground fault occurs and enters the line selection program.

(2) When the fault occurs in the distribution network, the zero sequence current of each line within 0.04 seconds before and after the power frequency period is collected, and the sampling frequency is set to 6400Hz, that is, 256 data of the zero sequence current signal in the line are collected.

(3) For the zero sequence current collected by each line, the wavelet packet transform with the wavelet function of db10, decomposition layer 4 is carried out, the low frequency band corresponding to the 0th node with power frequency component is removed, the wavelet packet reconstruction coefficient of each remaining frequency band is extracted, and the energy in the remaining 15 frequency
bands corresponding to each line is calculated.

4. The energy of distribution network lines in 15 frequency bands is summed up respectively, the total energy of each line in the corresponding frequency band is obtained, and the ratio of each line in a certain frequency band to the corresponding total energy is obtained.

5. The relative entropy of any line in the distribution network relative to another line is calculated, and the corresponding comprehensive wavelet entropy of each line is obtained according to the equation (5).

6. According to the calculation, the comprehensive wavelet entropy corresponding to a total of $l$ lines is obtained. For the data group with $l$ values, the coefficient of variation ($CV_l$) is calculated and compared with the threshold of the coefficient of variation ($CV_N=60\%$). If the CV value is less than the $CV_N$ value, the fault occurs in the bus, on the contrary, the fault occurs in the distribution line.

7. After judging that the fault occurs on the line, the maximum value in the corresponding K value data set of each line is selected as the abnormal value, and the corresponding line is the fault line.

3. Simulation analysis

In this paper, the fault line selection model of distribution network is established by matlab, and the above line selection principle is verified by simulation. The simulation verification is carried out according to different fault distance, different fault initial angle, different fault excessive resistance and the case of bus fault. The simulation results are shown in Table 1. The simulation results show that when a single-phase ground fault occurs in the arc suppression coil grounding system, the comprehensive wavelet entropy K value of the fault line is the maximum value of the K value data set. According to the calculated coefficient of variation, compared with setting the threshold of coefficient of variation, we can accurately distinguish that the fault occurs in the bus or the line. The fault detection result is consistent with the fault line set by the simulation model.

Fig. 2 (a) shows the K value of each line when the transition resistance is 5 ohms in the fault line L6. Fig. 2 (b) shows the K value of each line when the fault distance of L1 line is 2km. Fig. 2 (c) shows the K value diagram of each line when the initial fault angle is 0 in L6. Figure 2 (d) shows the corresponding K value of each line when the bus bar fails.
Figure 2. K value diagram of each line under different fault conditions

Table 1. Formatting sections, subsections and subsubsections.

| Fault line | $R_f$ /Ω | $\phi$ /° | $X_f$ /km | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $CV$ | Fault line selection result |
|-----------|---------|---------|---------|-------|-------|-------|-------|-------|-------|------|--------------------------|
| L6        | 5       | 90      | 8       | 15.94 | 24.65 | 16.71 | 23.82 | 16.23 | 70.19 | 75.46% | L6            |
|           | 50      | 90      | 8       | 16.45 | 22.30 | 16.67 | 24.20 | 16.38 | 80.43 | 85.78% | L6            |
|           | 200     | 90      | 8       | 16.68 | 22.00 | 16.78 | 24.09 | 16.61 | 79.21 | 84.48% | L6            |
|           | 500     | 90      | 8       | 16.58 | 22.15 | 16.71 | 23.77 | 16.62 | 76.30 | 82.04% | L6            |
|           | 200     | 45      | 1       | 78.96 | 24.14 | 16.51 | 22.51 | 19.93 | 20.65 | 78.50% | L1            |
| L1        | 200     | 45      | 3       | 77.32 | 23.53 | 16.99 | 22.65 | 17.33 | 20.95 | 78.66% | L1            |
|           | 200     | 45      | 4       | 76.50 | 23.31 | 17.28 | 22.85 | 16.70 | 20.74 | 78.33% | L1            |
|           | 500     | 30      | 4       | 17.70 | 21.41 | 16.85 | 22.92 | 17.70 | 85.41 | 89.31% | L6            |
| L6        | 500     | 60      | 4       | 17.34 | 20.91 | 17.22 | 23.49 | 17.35 | 81.35 | 86.03% | L6            |
|           | 500     | 90      | 4       | 16.79 | 22.08 | 16.85 | 23.87 | 16.79 | 77.41 | 82.62% | L6            |
| Busbar    | 5       | 90      | -       | 7.44  | 12.49 | 8.78  | 10.75 | 7.43  | 9.04  | 21.22% | Busbar        |
|           | 200     | 45      | -       | 9.29  | 10.39 | 11.40 | 9.92  | 9.28  | 13.13 | 14.03% | Busbar        |
|           | 500     | 0       | -       | 9.75  | 11.49 | 12.89 | 11.25 | 9.74  | 9.48  | 12.47% | Busbar        |

4. Conclusion
When a single-phase-to-ground fault occurs in the distribution network, due to the influence of fault conditions and system operation mode and other factors, it is more difficult to extract obvious features from the line steady-state signal, which increases the difficulty of fault line selection. In view of this difficulty, this paper analyzes the transient signals generated during the fault of the distribution network, extracts the fault features from the transient zero-sequence current, and adopts a single-phase-to-ground fault line selection method based on the comprehensive wavelet entropy variation coefficient. By analyzing the corresponding values of different lines, the coefficient of variation of the value data group is calculated, and by comparing it with the set variation coefficient threshold, we can judge whether there is an outlier in the data group, and then judge whether the fault occurs in the bus or the line. If the coefficient of variation of the calculated value data set is greater than the set threshold, the grounding fault occurs in the line, and the maximum value in the value data set is the singular value, and the corresponding line has a fault. If the calculated coefficient of variation is less than the threshold, it is a bus grounding fault. According to the proposed line selection steps, the line selection method is simulated and verified under different fault conditions. The simulation results show that the above method is feasible and has certain anti-jamming ability.
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