Fault Line Selection of Non-solidly Grounding System Based on EMD and Correlation Analysis of Zero Sequence Current Break-variable

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Abstract. When a single-phase grounding fault occurs in non-solidly grounding system, the zero sequence transient current is nonlinear and non-stationary. Especially when the resonant system is grounded with high resistance, the transient quantity is weak, which brings challenges to data processing. Therefore, empirical mode decomposition (EMD) is proposed to decompose the transient quantity and obtain different intrinsic mode functions (IMF). The IMF with the largest discrimination is selected as the characteristic quantity for correlation analysis. At the same time, considering the existence of unbalanced current in the actual system, in order to avoid the influence of unbalanced current, a single-phase grounding fault line selection algorithm based on EMD decomposition and correlation analysis of zero sequence current break-variable is proposed. Finally, the effectiveness of the method is verified by simulation and field test waveforms.

1. Introduction
Non-solidly grounding system is mainly used in medium and low voltage distribution network in China. When single-phase grounding fault occurs, long-term operation will develop into more serious power and fire accidents. At present, there are many line selection algorithms for small current single-phase grounding fault, which mainly use transient and steady-state signals.

The algorithms based on steady-state signal mainly include 5th harmonic method, admittance method, active component method, negative sequence component method [1-6]. The steady-state algorithm performs well when single-phase grounding occurs in ungrounded and low-resistance grounded systems and the transition resistance is small, and may fail in systems with large harmonic content, large grounding transition resistance or arc suppression coil compensation. The algorithms based on transient signals include ratio of amplitude to phase method, energy of transient zero sequence method, first half wave method and zero current projection method [7-11].

At present, judging from the effects of engineering practice, transient signals have great advantages in distinguishing single-phase ground faults, and good results have also been achieved. At present, the processing methods of transient data mainly include wavelet filtering, band-pass filtering, empirical mode [12-14]. The denoising effect of wavelet filter will be greatly different due to the difference of wavelet basis and scale function. At present, there is no reliable theoretical basis for the selection of...
basis function, and the decomposition process will also be affected by the characteristics of the function itself. There are many kinds of band-pass filters, and the design parameters are complex and the adaptive effect is poor. EMD is an adaptive time-frequency analysis method, which is suitable for non-stationary nonlinear signals and adaptively decomposes the intrinsic mode function (IMF) with frequency from high to low according to the local characteristics of the signal. In some related researches, EMD is used to decompose the transient zero sequence current after fault, and different IMFs are obtained. The component with the largest discrimination is selected from IMFs for correlation analysis, which can effectively identify the fault line. In this paper, considering the influence of unbalanced current, EMD decomposition of zero sequence current break-variable can effectively avoid the influence of unbalanced current, improve the correlation coefficient of line selection and reduce the probability of wrong selection.

2. Fundamental principles

2.1. Transient zero sequence current characteristics of ground fault in non-solidly grounding system

Figure 1. shows the equivalent circuit of high-resistance grounding fault in non-solidly grounding system. This model illustrates the transient zero-sequence current characteristics of a single-phase grounding fault [15].

![Figure 1. Equivalent network of grounding fault in non-solidly grounding system.](image)

Suppose the system has n overhead line feeders (the n-th line is the fault line), in the figure, C_j (j = 1, 2,...n) is the zero sequence distributed capacitance of the j-th line to the ground; iC_j is Zero-sequence capacitance current to ground; i_j is the zero-sequence current at the outlet of the j-th line; i_f is the zero-sequence fault current at the fault point; u_f is the virtual power supply at the fault point, which is equal to the inverted voltage before the fault point; L is the equivalent inductance of the line from the fault point to the bus; R is the equivalent resistance of the line from the fault point to the bus; L_p is the equivalent inductance of the arc suppression coil.

A single-phase grounding fault occurs in the line, which is equivalent to generating a faulty virtual power source at the fault point. The zero sequence current if generated from the fault point flows to the bus bar. For n-1 non-faulty lines, the outlet current of the line is its own line to ground capacitive current, and the direction is from the bus to the line. Since the parameters of the non-faulty lines are similar, the similarity of the corresponding zero-sequence current is high. This transient feature has been proven effective in both resonant grounded and ungrounded systems.

2.2. Principle of empirical mode decomposition

The empirical mode decomposition method was proposed by Nordon E Huang et al. The traditional filtering method is greatly affected by the basis function and the decomposition scale. The EMD algorithm decomposes the local characteristics of the signal and extracts the high frequency components of the signal, avoiding the difference between the basis function and the decomposition scale. Influencing, it has strong adaptability at the same time, which can reduce the noise and extract the signal without distortion.
EMD can decompose the signal into several IMF and remainder terms. The decomposed IMF satisfies two conditions: the number of extreme points and zero crossing points is different by one or the same; the mean value of each point of the upper and lower envelope obtained by cubic spline interpolation is zero. The specific implementation steps are as follows\cite{16}:

1) All extreme points and zeros of original signal \( x(t) \) are determined. The upper and lower envelope of \( x(t) \) is calculated by cubic spline interpolation, \( m_{11}(t) \) is the average of the upper and lower envelope, and \( m_{11}(t) \) separates from the original signal \( x(t) \), the results are as follows:

\[
h_{11}(t) = x(t) - m_{11}(t)
\]

2) Determine whether the new signal \( h_{11}(t) \) satisfies the two conditions of IMF. The conditions can be appropriately relaxed in practical engineering use. If not, repeat the above operation for \( h_{11}(t) \) until the conditions are met to obtain the first-order component of IMF:

\[
c_1(t) = IMF_1(t)
\]

3) Then separate the first-order intrinsic mode functions \( c_1(t) \) from the original signal \( x(t) \) to get:

\[
r_1(t) = x(t) - c_1(t)
\]

4) Then repeat the above process with \( r_1(t) \) as a new signal, and continue to obtain the second-order intrinsic mode functions \( c_2(t) \). Repeat the above operations, and stop the decomposition when \( r_N(t) \) is less than the set threshold.

5) Finally, the original signal \( r_{-1}(t) \) can be decomposed into:

\[
x(t) = \sum_{i=1}^{N} c_i(t) + r_N(t)
\]

In the formula, \( r_N(t) \) is the remainder, representing the trend of the signal, \( c_i(t) \) is the intrinsic mode functions of each order, representing the frequency from high to low. Therefore, the feature quantity can be extracted.

2.3. Principle of correlation analysis

The similarity of two waveforms can be described by correlation coefficient. EMD decomposition of zero sequence current of each feeder is used to obtain the IMF with the largest discrimination, namely the characteristic IMF, and then the correlation coefficient between the characteristic IMF is calculated:

\[
\rho = \frac{\sum_{n=1}^{N} IMF_{01}(n)IMF_{02}(n)}{\left(\sum_{n=1}^{N} IMF_{01}^2(n)\right)^{1/2}\left(\sum_{n=1}^{N} IMF_{02}^2(n)\right)^{1/2}}
\]

Due to the influence of asymmetric load and unbalanced line parameters in the real operation of power grid, there is unbalanced current in the feeder, which may lead to the failure of transient correlation line selection in high resistance grounding. In order to eliminate the influence of unbalanced current, the transient current of the last cycle is used to make a difference with the transient current of the previous cycle to get the zero sequence current break-variable, and then EMD is used to decompose the current break-variable to get its characteristic IMF. Finally, the characteristic IMF correlation coefficient of each line zero sequence current break-variable is calculated.

The correlation coefficient \( \rho \) represents the similarity between the two characteristic IMFs. When the trends between the two are similar, \( \rho \) approaches 1; when the two trends are different, or even opposite, \( \rho \) approaches -1. According to the analysis in Section 2.1, the correlation between zero sequence currents of non fault lines is close to 1 in ideal state; The correlation coefficient of zero sequence current between fault line and non fault line is close to -1.
3. Simulation verification

3.1. Modelling and simulation
In this paper, the MATLAB simulation model is built according to figure 1, and $N = 4$ is selected. The length of the four lines is 10km, 8km, 5km and 3km respectively; the line parameter is $r_1=0.315 \, \Omega/km$, $x_1=0.414 \, \Omega/km$, $b_1=4.328 \, S/km$; $r_0=0.412 \, \Omega/km$, $x_0=2.618 \, \Omega/km$, $b_0=0.847 \, S/km$. The fault occurred in line 4, and the effect of unbalanced current was verified by adding asymmetric capacitance to line 3. The simulation sampling frequency is set to 10kHz; the main transformer samples Y/Yn type, the transformation ratio is 110kv/10kv, the rated capacity is 100MVA, the no-load loss is 0.1kW, and the short-circuit loss is 1.97kW. The arc suppression coil adopts over-compensation 5%, and the system-to-ground capacitance current is 14A.

3.2. Extraction of intrinsic mode function
The fault is simulated by Simulink module, and the waveform data of four lines are saved to the workspace space of MATLAB. The obtained discrete data is decomposed by EMD to obtain characteristic IMF of each line. Taking the single-phase grounding fault with 500 Ω transition resistance in line 4 as an example, the fault line and a non-fault line are selected, and the original zero sequence current and corresponding IMF components are as follows:

![IMF components](image)

Figure 2. IMF components corresponding to zero sequence currents of different lines.

It can be seen from Figure 2(a) that the high-frequency signal can be separated after multiple cycles, and the original signal becomes more and more smooth. Comparing Figure 2(a) and Figure 2(b), it can be seen that IMF2 has obvious characteristic components, which can be used to distinguish faulty and non-faulty lines.

3.3. Correlation analysis and comparison
Aiming at the single-phase grounding fault of neutral point ungrounded and resonant grounded system, the working conditions of system without unbalanced current and with unbalanced current are simulated respectively. The unbalanced current working condition is realized by adding unbalanced capacitor to line 2. According to Section 2.2, the IMF component with the largest characteristic quantity is selected first, and then the correlation analysis is carried out, as follows:

![Correlation analysis](image)

Figure 3. Characteristic IMF components of zero sequence current without unbalanced current.
The data in Table 1 correspond to the correlation of IMF components of lines 1-4 in Figure 3-5. It can be seen from the data in Table 1 that: 1) when there is no unbalanced current in the non-solidly grounding system, the correlation of the characteristic IMF component of the zero sequence current of each non-fault line is close to 1, and the correlation of the characteristic IMF component of the zero sequence current of the fault line and the non-fault line is close to -1; 2) when there is unbalanced current in the non-solidly grounding system, the correlation of the characteristic IMF component of the zero sequence current break-variable of each line is higher than the correlation of the characteristic IMF component of the zero sequence current of each line. At the same time, the characteristic IMF component correlation of the zero sequence current break-variable between non-fault lines is closer to 1.

4. Field test waveforms analysis

In order to verify the reliability of the algorithm, a group of real fault data of XXX city 110kV/10kV Huilong station is used for verification.

Figure 6(a) shows the zero sequence current waveforms of three lines under the same bus when grounding fault occurs. From the waveforms, it can be seen that the system has unbalanced current and
is resonant grounded. Due to arc suppression coil compensation, the phase angle of zero sequence current of fault line 1 begins to approach non fault lines 1 and 2 about 30ms after the fault occurs. And the phase of line 3 is different from that of line 2 in the first half cycle after the fault, so the direct correlation analysis of zero sequence current may lead to misjudgment of line 3. Figure 6(b) and Figure 6(c) are the characteristic IMF curves obtained after EMD decomposition of zero sequence current and zero sequence current break-variable respectively. From the waveform, it can be seen that the characteristics of the first half wave of fault after decomposition are more obvious. See Table 2 for specific data.

![Figure 6](image)

(a) Zero sequence current  (b) Characteristic IMF of zero sequence current

(c) Characteristic IMF of break-variable of zero sequence current

Figure 6. Real fault zero sequence current waveform and different IMF components.

| Method | $\rho_{12}$ | $\rho_{13}$ | $\rho_{23}$ |
|--------|-------------|-------------|-------------|
| Method 1 | -0.2588     | 0.6883      | -0.1642     |
| Method 2 | -0.3116     | -0.5396     | 0.0151      |
| Method 3 | -0.7637     | -0.4672     | 0.2871      |

Table 2. Real fault correlation calculated by different methods.

Table 2 shows the results of correlation analysis for different methods. Method 1 is to calculate the correlation of the first half wave of the transient zero sequence current, method 2 is to calculate the correlation of the characteristic IMF component of the zero sequence current, and method 3 is to calculate the correlation of the characteristic IMF component of the break-variable of the zero sequence current. The data verify the effectiveness of the algorithm. It can be seen from Table 2 that directly using zero sequence current to calculate the correlation will misjudge line 2 fault; The overall data effect of method 3 is better than that of method 2, which verifies the effectiveness of the EMD decomposition and correlation analysis algorithm proposed in this paper.

5. Conclusion

This paper proposes a single-phase ground fault line selection algorithm based on the EMD decomposition and related analysis of the zero-sequence current break-variable. Through simulation and field real fault data analysis, it can be known that:

1) EMD can effectively extract the IMF components used for fault judgment, with simple calculation and strong self-adaptation;

2) When the non-solidly current grounding system does not contain unbalanced current, after the EMD decomposition of the zero sequence current, the correlation coefficient between the IMF components of the zero sequence current of the non-faulty line is close to 1, and the correlation coefficient of the IMF components of the zero sequence current of the faulty line and the non-faulty line close to -1;
When the non-soldily current grounding system contains unbalanced current, the EMD decomposition of the zero sequence current is better than the EMD decomposition of the zero sequence current directly. The correlation between the non fault lines is greater, and the correlation between the fault line and the non fault line is smaller, which is more conducive to select the fault line and reduce the probability of misjudgment.

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