Single-phase Ground Fault Line Selection for Distribution Network Based on Frequency Domain Parameter Identification Method

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1. Introduction
Most domestic distribution networks use small current grounding. After a single-phase ground fault occurs in a small-current grounding grid, the current flowing through the faulty and non-faulty lines is only a change in the capacitance current to ground, and its value is relatively small, especially when the neutral point is grounded via the arc-suppression coil and over-compensated. When working in mode, it is difficult to distinguish between faulty lines and non-faulty lines by using changes in power frequency components[1].

The traditional method of line selection is mostly based on fault steady-state signals, due to factors such as small fault current and arc instability of the small current grounding system, the actual line selection effect is not good; especially for the arc suppression coil grounding system, the above method fails[2].

The transient signal-based line selection method makes full use of the transient signal after the fault to improve the line selection performance, and analyzes the fault model by using the transient signal, which provides favorable conditions for extracting fault features[3-5]. Therefore, this paper proposes a transient quantity based line selection method——model parameter identification method. The method has strong resistance to transition resistance and is not affected by the arc suppression coil and the intermittent arc, but the differential equation coefficient therein amplifies the influence of the high frequency component and requires high sampling rate. If the frequency information in the transient process can be accurately extracted, the differential equation can be avoided, and the method will have better line selection effect.
According to the basic idea of frequency domain parameter identification, this paper first introduces the basic principle of the singular entropy matrix beam method. Then, using the frequency point information extracted by the matrix beam method, and the frequency domain equation of the fault model is established. Finally, the capacitance of the transmission line to ground is solved. The line selection is performed according to the positive and negative of the capacitance value. The correctness and effectiveness of the proposed method are verified by ATP-EMTP simulation and MATLAB simulation.

2. Frequency domain model parameter identification method
The singular entropy matrix beam method used in this paper uses a set of complex exponential signal sums to fit the sampled data. It has the characteristics of being unrestricted by the model order, high noise resistance, good stability and high computational efficiency. The signal has obvious advantages, and solves the problem that the previous frequency domain parameter identification method using discrete Fourier transform cannot be realized.

2.1 The basic principle of singular entropy matrix beam algorithm
The singular entropy matrix beam algorithm has the same extraction steps as the matrix beam method except for the order of the modal order. Usually, let the signal consist of M exponential functions:

\[ y(t) = \sum_{i=1}^{M} R_i e^{s_i t} \]  

where: \( y(t) \) is the observed value; \( R_i \) is the complex amplitude; \( s_i = -\alpha_i + j\omega_i \), \( \alpha_i \) is the attenuation factor, and \( \omega_i \) is the angular frequency. After sampling, at time \( k \), the time variable \( t \) is replaced by \( kT_s \), where \( T_s \) is the sampling interval, then equation (1) can be rewritten as:

\[ y(kT_s) = \sum_{i=1}^{M} R_i z_i^k \]  

\[ z_i = e^{s_i T_s} = e^{(-\alpha_i + j\omega_i)T_s} \]  

For convenience of expression, \( y(k) \) is used to represent \( y(kT_s) \), and construct the Hankel matrix \( Y \) for

\[ Y = \begin{bmatrix}
  y(1) & y(2) & \cdots & y(L+1) \\
  y(2) & y(3) & \cdots & y(L+2) \\
  \vdots & \vdots & \ddots & \vdots \\
  y(N-L) & y(N-L+1) & \cdots & y(N)
\end{bmatrix} \]  

where: \( L \) is the beam parameter, which is generally selected between \( N/3 \) and \( N/2 \), which plays an important role in eliminating the influence of noise.

Perform singular value decomposition on matrix \( Y \):

\[ Y = U \Sigma V^H \]  

where: \( U \) and \( V \) are unitary matrices, respectively containing eigenvectors of \( YY^H \) and \( Y^H Y \); \( \Sigma \) is a diagonal matrix containing matrix \( Y \) singular values.

The matrix \( \Sigma \) obtained by Hankel's singular decomposition, whose elements \( d_i (i=1,2,\ldots,m) \) are non-negative and arranged in descending order, that is \( d_1 \geq d_2 \geq \ldots \geq d_m \geq 0 \). Where \( m=\min\{N-L,L+1\} \), let

\[ \beta_i = \log \left( \frac{d_i}{\sum_{j=1}^{m} d_j} \right) \]  

then the singular spectrum obtained by the singular value decomposition of the Hankel matrix is the sequence of \( \beta_i (i=1,2,\ldots,m) \).

In order to investigate the change of signal information with the singular spectrum order, the k-order singular entropy is defined:
where $\Delta E_i$ is the increment of the i-order singular entropy and there is

$$\Delta E_i = -\frac{d_i}{\sum_{j=1}^{m} d_j} \lg \left( \frac{d_i}{\sum_{j=1}^{m} d_j} \right)$$

As the effective information content of the signal tends to be saturated, the singular entropy increment will quickly converge to the bounded value. At this moment, the feature information has remained basically intact, and the order $n$ of the singular spectrum at this time is the signal modal order.

After determining the maximum modal order $n$, the new matrix $\Sigma'$ is formed by the first $n$ non-zero singular values of $\Sigma$.

$$\Sigma' = \begin{bmatrix} \sigma_1 & 0 & 0 & \cdots & 0 \\ 0 & \sigma_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \sigma_n \\ 0_{(N-L-n)} \end{bmatrix}$$

The matrix $V$ obtained by singular decomposition of the Hankel matrix $Y$ takes out $n$ dominant right singular vectors to form a $(L+1) \times n$-order matrix $V'$, and performs correlation processing on $V'$ to obtain two new matrices $V_1, V_2$. Where $V_1$ is the $L \times n$ order matrix obtained by deleting the last row from $V'$, and $V_2$ is the $L \times n$ order matrix obtained by deleting the first row from $V'$. Thus, two $(N-L) \times L$-order matrices $Y_1$ and $Y_2$ can be constructed as:

$$Y_1 = U \Sigma' V_1^T$$

$$Y_2 = U \Sigma' V_2^T$$

$Y_1$ and $Y_2$ are already the response of the noise reduction process, and it is considered that $Y_1$ and $Y_2$ are obtained by the system real response $x(t)$, that is

$$Y_1 = \begin{bmatrix} y(0) & y(1) & \cdots & y(L-1) \\ y(1) & y(2) & \cdots & y(L) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L-1) & y(N-L) & \cdots & y(N-2) \\ y(L) & y(L) & \cdots & y(L) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-1) & y(N-L+1) & \cdots & y(N-1) \end{bmatrix}$$

$$Y_2 = \begin{bmatrix} y(0) & y(1) & \cdots & y(L-1) \\ y(1) & y(2) & \cdots & y(L) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L-1) & y(N-L) & \cdots & y(N-2) \\ y(L) & y(L) & \cdots & y(L+1) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-1) & y(N-L+1) & \cdots & y(N-1) \end{bmatrix}$$

It is known from the principle of matrix beam that the pole $z_i (i=1,2,\ldots,n)$ of the signal is exactly the generalized eigenvalue of the matrix beam $Y_2-\lambda Y_1$, so that the problem of solving the signal pole can be transformed into the generalized feature of the solution matrix beam $Y_2-\lambda Y_1$. The problem of value, that is, solving the eigenvalues of the matrix $Y_1^T Y_2$, is to solve the following eigenvalue problem:

$$Y_1^T Y_2 - z_i I = 0$$

where $I$ is a unit array. Once $M$ and $z_i$ are known, $R_i$ can be obtained by least squares using the following formula:
Further, the amplitude $A_i$, the phase $\theta_i$, the attenuation factor $\alpha_i$, and the angular frequency $\omega_i$ can be obtained as follows:

\[
\begin{align*}
A_i &= |R_i| \\
\theta_i &= \arctan \left( \frac{\text{Im}(R_i)}{\text{Re}(R_i)} \right) \\
\alpha_i &= \frac{-\text{Re}(\ln z_i)}{T_i} \\
\omega_i &= \frac{\text{Im}(\ln z_i)}{T_i}
\end{align*}
\] (16)

2.2 Establish the frequency domain equation of the fault model

A small-current grounding system with multiple outgoing lines, the zero-sequence network when single-phase grounding occurs is shown in Figure 1. In the figure: $U_{f0}$ is the voltage drop of the virtual power supply on the zero-sequence network at the fault point; $R_{0i}$, $L_{0i}$, $C_{0i1}$, and $C_{0i2}$ are the zero-sequence resistance, zero-sequence inductance, bus-side and load-side zero-sequence capacitance of line $i$, respectively. If $i$ is a faulty line, the above amount represents the value from the fault point to the bus. When the switch $K$ is opened, the system is not grounded; the switch $K$ is closed, and the system is grounded via the arc suppression coil.

Under the basic idea of frequency domain parameter identification, for the ungrounded system and the arc suppression coil grounding system, the transmission line is equivalent to the $\Pi$ model, so that its zero sequence resistance is $R_0$, the zero sequence inductance is $L_0$, and the bus side is zero sequence. The capacitor is $C_{01}$ and the load-side zero-sequence capacitor is $C_{02}$. Generally, we believe that the load zero-sequence impedance is infinite, negligible, and the actual distribution network lines are mostly "tree-shaped" structures with many branches. When the lines are equivalent to the $\Pi$ model, these branch lines and load transformers, load switches distributed capacitance of the components such as the rear line has a certain influence on the ground branch on the line load side, and cannot be ignored. Therefore, we equivalent these effects to a capacitor whose magnitude is unknown and superimposed on the ground capacitance of the load side of the line $\Pi$ model. The capacitance to the ground on the bus side is taken as a known amount, and its value is generally taken as half of the capacitance of the line itself to the ground. Thus, the capacitance values of the two sides of the line's $\Pi$ model are no longer equal, and $C_{01} \ll C_{02}$. This improved model is closer to the actual system and more accurate.

We can get the impedance of the frequency point $\omega$ under the improved $\Pi$ model:
finishing is available:

\[ Z(\omega) = \frac{U(\omega)}{I(\omega)} = \frac{R_0 + j\omega L_0 + \frac{1}{j\omega C_{02}}}{j\omega C_{01}R_0 - \omega^2 L_0 C_{01} + \frac{C_{01}}{C_{02}} + 1} \]

then the real part \( U_R(\omega) \) and the imaginary part \( U_I(\omega) \) of the frequency point \( \omega \) are:

\[ U_R(\omega) = R_0 I_R(\omega) - \omega L_0 I_I(\omega) + \frac{I_I(\omega)}{\omega C_{02}} - \frac{C_{01}}{C_{02}} U_R(\omega) + \omega R_0 C_{01} U_I(\omega) + \omega^2 L_0 C_{01} U_R(\omega) \]

\[ U_I(\omega) = R_0 I_I(\omega) + \omega L_0 I_R(\omega) - \frac{I_R(\omega)}{\omega C_{02}} - \frac{C_{01}}{C_{02}} U_I(\omega) - \omega R_0 C_{01} U_R(\omega) + \omega^2 L_0 C_{01} U_I(\omega) \]

where: \( I_R(\omega) \) and \( I_I(\omega) \) are the real and imaginary parts of the current at frequency \( \omega \), respectively.

For the convenience of the following description, the real part and the imaginary part of the voltage of the \( n \)th frequency point \( \omega_n \) are denoted as \( U_{nR} \) and \( U_{nI} \), respectively; the real part and the imaginary part of the current are denoted as \( I_{nR} \) and \( I_{nI} \), respectively. For different frequency points, you can write the following frequency domain equations:

\[ U = \begin{bmatrix} U_{1R} & U_{1I} & U_{2R} & U_{2I} & \cdots & U_{nR} & U_{nI} \end{bmatrix}^T = Dc \]

\[ D = \begin{bmatrix} 1_R & -\omega i_{11} & -\frac{i_{12}}{\omega} & -U_{1R} & \omega U_{1I} & \omega^2 U_{1R} \\
1_{11} & \omega i_{1R} & -\frac{i_{12}}{\omega} & -U_{1I} & -\omega U_{1R} & \omega^2 U_{1I} \\
1_{2R} & -\omega i_{21} & -\frac{i_{12}}{\omega} & -U_{2R} & \omega U_{2I} & \omega^2 U_{2R} \\
1_{21} & \omega i_{2R} & -\frac{i_{12}}{\omega} & -U_{2I} & -\omega U_{2R} & \omega^2 U_{2I} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1_{nR} & -\omega i_{n1} & -\frac{i_{12}}{\omega} & -U_{nR} & \omega U_{nI} & \omega^2 U_{nR} \\
1_{n1} & \omega i_{nR} & -\frac{i_{12}}{\omega} & -U_{nI} & -\omega U_{nR} & \omega^2 U_{nI} \end{bmatrix} \]

\[ c = \begin{bmatrix} R_0 & L_0 & \frac{1}{C_{02}} & C_{01} & R_0 C_{01} & L_0 C_{01} \end{bmatrix}^T \]

Solve the frequency domain equations and select the line-to-ground zero-sequence capacitors for line selection.

2.3 Applicable frequency bands for frequency domain parameter identification methods

In the establishment of the fault model, the theory is equivalent to the \( \Pi \) model, and the actual line is the distributed parameter model, which has a certain impact on the frequency band selection of parameter identification. Therefore, it is necessary to redefine the applicable frequency band of the frequency domain parameter identification method to process the frequency points.

Based on the literature [4], the parameters of Table 1 are used as the applicable frequency bands of the model.

2.4 Line selection criteria

In this paper, the calculated capacitance value is used as the line selection criterion, as follows: (1) if the capacitance value of a calculated line is negative, and the other line capacitance values are positive, then the line is determined to be a fault line; (2) if the capacitance of all lines is calculated. If the value is positive, it is determined to be a bus fault.
3. ATP-based fault simulation

The simulation system model is shown in Figure 2. The unit zero sequence line parameters are \( R_0=1.53\Omega, \ L_0=2.7\text{mH}, \ C_0=0.007\mu\text{F} \); the unit positive sequence line parameter is \( R_1=1.53\Omega, \ L_1=1.37\text{mH}, \ C_1=0.016\mu\text{F} \). When the switch \( K \) is closed, the system is grounded via the arc suppression coil, and the compensation degree is 8%; when disconnected, the system is not grounded. The sampling frequency is 10 kHz.

Using this model, a large number of detailed simulations of different transition resistances, different initial phase angles and different fault point locations in arc-suppressed coil grounding systems are presented. The simulation results are shown in Table 2, Table 3, and Table 4, respectively.

| Table 1. Cutoff frequency of lines of different lengths |
|-----------------------------------------------|
| **Line length (km)** | **Cutoff frequency (Hz)** |
| --- | --- |
| <10 | 5000 |
| 10~20 | 3000 |
| 20~30 | 2000 |
| 30~40 | 1500 |

| Table 2. Simulation results with different transition resistance |
|-----------------------------------------------|
| **Line name** | **0Ω** | **50Ω** | **100Ω** |
| | C/μF | C/μF | C/μF |
| --- | --- | --- | --- |
| Line 1 | -0.352 | -0.349 | -0.353 |
| Line 2 | 0.064 | 0.070 | 0.068 |
| Line 3 | 0.087 | 0.085 | 0.090 |
| Line 4 | 0.201 | 0.194 | 0.195 |

| Table 3. Simulation results under different initial phase angles |
|-----------------------------------------------|
| **Line name** | **0°** | **45°** | **90°** |
| | C/μF | C/μF | C/μF |
| --- | --- | --- | --- |
| Line 1 | -0.218 | -0.187 | -0.235 |
| Line 2 | 0.056 | 0.044 | 0.049 |
| Line 3 | 0.097 | 0.092 | 0.088 |
| Line 4 | 0.065 | 0.051 | 0.098 |

| Table 4. Simulation results at different fault point locations |
|-----------------------------------------------|
| **Line name** | **head** | **middle** | **end** |
| | C/μF | C/μF | C/μF |
| --- | --- | --- | --- |
| Line 1 | -0.314 | -0.287 | -0.232 |
| Line 2 | 0.042 | 0.034 | 0.037 |
| Line 3 | 0.051 | 0.048 | 0.053 |
| Line 4 | 0.221 | 0.205 | 0.142 |
4. Conclusion
This paper proposes a frequency domain method based on parameter identification for single-phase ground fault line selection in distribution network. This method has the following features:

(1) The singular entropy matrix beam method is used to analyze the transient signal after the fault, which can accurately extract the frequency information of the zero sequence voltage and zero sequence current after the fault, thus ensuring the reliability of the data.

(2) The method is to identify the parameters of the line model in the sense of least squares. It’s sampling rate is low and the calculation accuracy is high.

(3) The method in this paper can make full use of transient information to ensure the sensitivity and reliability of line selection.

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