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To cite this article: Siwen Cheng and Zhouxing Fu 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **267** 042130

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

Siwen Cheng¹, Zhouxing Fu^{1*}

¹College of Electrical and Control Engineering, Xi'an University of Science and Technology, Xi'an, ShaanXi, 710000, China

*Corresponding author's e-mail: 598929526@qq.com

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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:

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

where: $y(t)$ is the observed value; R_i is the complex amplitude; $s_i = -\alpha_i + j\omega_i$, α_i is the attenuation factor, and ω_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:

$$y(kT_s) = \sum_{i=1}^M R_i z_i^k \quad (2)$$

$$z_i = e^{s_i T_s} = e^{(-\alpha_i + j\omega_i) T_s} \quad (3)$$

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

$$Y = \begin{bmatrix} y(1) & y(2) & \cdots & y(L+1) \\ y(2) & y(3) & \cdots & y(L+2) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L) & y(N-L+1) & \cdots & y(N) \end{bmatrix} \quad (4)$$

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 :

$$Y = U \Sigma V^H \quad (5)$$

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

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

$$\beta_i = \lg \left(\frac{d_i}{\sum_{j=1}^m d_j} \right) \quad (6)$$

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

In order to investigate the change of signal information with the singular spectrum order, the k -order singular entropy is defined:

$$E_k = \sum_{i=1}^k \Delta E_i \quad (k \leq m) \quad (7)$$

where ΔE_i is the increment of the i -order singular entropy and there is

$$\Delta E_i = - \frac{d_i}{\sum_{j=1}^m d_j} \lg \left(\frac{d_i}{\sum_{j=1}^m d_j} \right) \quad (8)$$

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 Σ' is formed by the first n non-zero singular values of Σ .

$$\Sigma' = \begin{bmatrix} \sigma_1 & 0 & 0 & \cdots & 0 \\ 0 & \sigma_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \sigma_n \\ & & 0_{(N-L-n)} & & \end{bmatrix} \quad (9)$$

where Σ' is a $(N-L) \times n$ -order matrix, the first n singular values form a diagonal matrix of $n \times n$, and the latter $(N-L-n)$ acts as a $(N-L-n) \times n$ matrix composed of 0 elements. The Σ' matrix effectively reduces the effects of noise.

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:

$$Y_1 = U \Sigma' V_1^T \quad (10)$$

$$Y_2 = U \Sigma' V_2^T \quad (11)$$

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

$$Y_1 = \begin{bmatrix} y(0) & y(1) & \cdots & y(L-1) \\ y(1) & y(2) & \cdots & y(L) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L-1) & y(N-L) & \cdots & y(N-2) \end{bmatrix} \quad (12)$$

$$Y_2 = \begin{bmatrix} y(1) & y(2) & \cdots & y(L) \\ y(2) & y(3) & \cdots & y(L+1) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L) & y(N-L+1) & \cdots & y(N-1) \end{bmatrix} \quad (13)$$

It is known from the principle of matrix beam that the pole $z_i (i=1,2,\dots,n)$ 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 $Y_1^+ Y_2$, is to solve the following eigenvalue problem:

$$Y_1^+ Y_2 - z_i I = 0 \quad (14)$$

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:

$$\begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ z_1 & z_2 & \cdots & z_n \\ \vdots & \vdots & \ddots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \cdots & z_n^{N-1} \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} \quad (15)$$

Further, the amplitude A_i , the phase θ_i , the attenuation factor α_i , and the angular frequency ω_i can be obtained as follows:

$$\begin{cases} A_i = |R_i| \\ \theta_i = \arctan\left(\frac{\text{Im } R_i}{\text{Re } R_i}\right) \\ \alpha_i = \frac{-\text{Re}(\ln z_i)}{T_s} \\ \omega_i = \frac{\text{Im}(\ln z_i)}{T_s} \end{cases} \quad (16)$$

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.

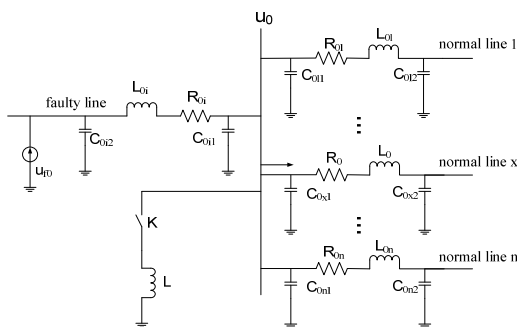


Figure 1. Single-phase ground fault zero-sequence network

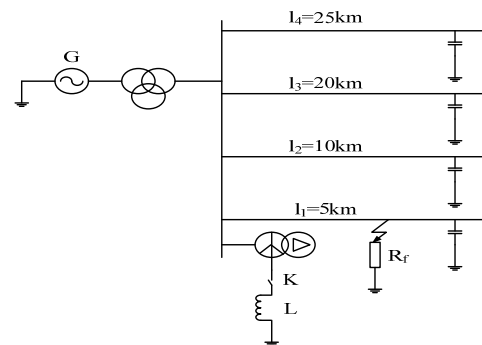


Figure 2. Schematic diagram of the simulation system

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 Π 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 Π 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 Π 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 Π model are no longer equal, and $C_{01} < C_{02}$. This improved model is closer to the actual system and more accurate.

We can get the impedance of the frequency point ω under the improved Π model:

$$Z(\omega) = \frac{U(\omega)}{I(\omega)} = \frac{R_0 + j\omega L_0 + \frac{1}{j\omega C_{02}}}{j\omega C_{01} R_0 - \omega^2 L_0 C_{01} + \frac{C_{01}}{C_{02}} + 1} \quad (17)$$

finishing is available:

$$U(\omega) = (R_0 + j\omega L_0 + \frac{1}{j\omega C_{02}})I(\omega) - (\frac{C_{01}}{C_{02}} + j\omega R_0 C_{01} - \omega^2 L_0 C_{01})U(\omega) \quad (18)$$

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

$$U_R(\omega) = R_0 I_R(\omega) - \omega L_0 I_I(\omega) + \frac{I_I(\omega)}{\omega C_{02}} - \frac{C_{01}}{C_{02}} U_R(\omega) + \omega R_0 C_{01} U_I(\omega) + \omega^2 L_0 C_{01} U_R(\omega) \quad (19)$$

$$U_I(\omega) = R_0 I_I(\omega) + \omega L_0 I_R(\omega) - \frac{I_R(\omega)}{\omega C_{02}} - \frac{C_{01}}{C_{02}} U_I(\omega) - \omega R_0 C_{01} U_R(\omega) + \omega^2 L_0 C_{01} U_I(\omega) \quad (20)$$

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

For the convenience of the following description, the real part and the imaginary part of the voltage of the n th frequency point ω_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:

$$U = [U_{1R} \quad U_{1I} \quad U_{2R} \quad U_{2I} \quad \cdots \quad U_{nR} \quad U_{nI}]^T = D \cdot c \quad (21)$$

$$D = \begin{bmatrix} I_{1R} & -\omega I_{1I} & \frac{I_{1I}}{\omega} & -U_{1R} & \omega U_{1I} & \omega^2 U_{1R} \\ I_{1I} & \omega I_{1R} & -\frac{I_{1R}}{\omega} & -U_{1I} & -\omega U_{1R} & \omega^2 U_{1I} \\ I_{2R} & -\omega I_{2I} & \frac{I_{2I}}{\omega} & -U_{2R} & \omega U_{2I} & \omega^2 U_{2R} \\ I_{2I} & \omega I_{2R} & -\frac{I_{2R}}{\omega} & -U_{2I} & -\omega U_{2R} & \omega^2 U_{2I} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ I_{nR} & -\omega I_{nI} & \frac{I_{nI}}{\omega} & -U_{nR} & \omega U_{nI} & \omega^2 U_{nR} \\ I_{nI} & \omega I_{nR} & -\frac{I_{nR}}{\omega} & -U_{nI} & -\omega U_{nR} & \omega^2 U_{nI} \end{bmatrix} \quad (22)$$

$$c = \left[R_0 \quad L_0 \quad \frac{1}{C_{02}} \quad \frac{C_{01}}{C_{02}} \quad R_0 C_{01} \quad L_0 C_{01} \right]^T \quad (23)$$

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 Π 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	0 Ω	50 Ω	100 Ω	Line selection result
	C/ μF	C/ μF	C/ μF	
Line 1	-0.352	-0.349	-0.353	Line 1
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 $^\circ$	45 $^\circ$	90 $^\circ$	Line selection result
	C/ μF	C/ μF	C/ μF	
Line 1	-0.218	-0.187	-0.235	Line 1
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	Line selection result
	C/ μF	C/ μF	C/ μF	
Line 1	-0.314	-0.287	-0.232	Line 1
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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