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Fault Line Selection Method Based on Zero Sequence Current Phase Angle Offset

Abstract: - Aiming at the problem that the fault characteristic quantity of high resistance grounding fault in small current grounding system is small and the fault line can not be selected accurately, a fault line selection method based on zero sequence current phase angle offset is proposed. After the fault is detected, the current signal is injected. By measuring the zero-sequence current at the beginning of each line before and after the injection signal, and calculating the phase angle of the zero-sequence current change before and after the injection signal and the ratio of the zero-sequence current before the injection signal, the line selection and section of the grounding fault can be realized. This method has strong anti-transition resistance ability, is not affected by the system parameters in theory, has high accuracy, simple calculation method, fast speed, and has strong engineering practicability.

Keywords: Distribution Network (DN), Single-phase Grounding Fault (SGF), Fault Line Selection (FLS), Injection Current Signal (ICS).

I. INTRODUCTION

As an important public infrastructure of the country, the distribution network plays an important role in ensuring power supply, supporting economic and social development, and improving people's livelihood. The topology and operation environment of distribution network are complex, and the incidence of single-phase grounding fault is high. Through the incomplete statistics of the national grid data, the single-phase grounding fault accounts for more than 80 % of the total number of faults [1]-[4]. The fault characteristics of the high-resistance grounding fault are weak, and the fault current is usually only a few amperes or even less than one ampere, which leads to the difficulty of section positioning when the high-resistance grounding fault occurs in the system. The safety of the distribution network and people's lives and property is seriously threatened, and the social impact is huge. Therefore, it is of great significance to study the high resistance grounding fault line selection of distribution network.

The current line selection methods can be roughly divided into two categories. One is to use the method of steady-state or transient quantity to find the characteristic difference for line selection. Using the method of fault steady-state or transient characteristic quantity, the characteristic quantity will decrease with the increase of transition resistance. Therefore, when a high-resistance grounding fault occurs in the system, such methods will fail and cannot effectively detect high-resistance grounding faults [5]-[7]. The second is the injection signal method, which is famous for the 'S' injection method [8]-[9]. This method has a high dependence on the accuracy of the system detection. Reference [10] proposed a fault processing method of injecting a single characteristic signal into the distribution network by adjusting the inverter strategy. However, when the high resistance is grounded, the characteristic signal flows through the transition resistance, and the shunt effect of the capacitor leads to the decrease of the energy of the characteristic signal and the decrease of the discrimination accuracy. In reference [11], the short-term injection of capacitive current is used to increase the steady-state characteristic quantity of the fault, which improves the accuracy of the fault line selection and location criterion based on the steady-state characteristics of the fault and the ability to resist the transition resistance. However, this method is only applicable to the neutral point ungrounded system. In recent years, with the development of computer technology, the research on fault location using intelligent algorithms is increasing [12]-[13]. However, the physical meaning of such methods is unknown, and the problem of section location of high resistance grounding fault is not fundamentally solved, and the interpretation is poor. Aiming at such problems, a flexible grounding device is designed in literature [14]-[15]. The device can inject power frequency current with adjustable [1]amplitude and phase angle into the neutral point of the distribution network through the inverter, and has excellent grounding fault detection functions

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such as identifying fault types, distinguishing fault phases, and selecting fault lines. At present, due to the advanced and practical nature of the flexible grounding device to deal with grounding faults, the device has been widely used.

Based on this, aiming at the problems of weak resistance to transition resistance and strong dependence on equipment detection accuracy in existing technologies, this paper proposes a fault line selection method based on zero-sequence current phase angle offset. In this method, the zero-sequence current at the head of the line is measured by injecting the current signal into the neutral point. According to the difference between the zero-sequence current variation before and after the signal injection and the ratio of the zero-sequence current before the signal injection, the fast and accurate fault line selection is realized.

II. ANALYSIS OF SINGLE-PHASE GROUNDING FAULT STRUCTURE AND FAULT ZERO-SEQUENCE CURRENT

A. *Topology Analysis of Single-phase Grounding Fault Structure*

Fig.1 is a single-phase grounding fault model of a 10kV flexible grounding system with n lines, where $\dot{E}_A$、$\dot{E}_B$、$\dot{E}_C$ is a three-phase symmetrical power supply, Z_0 is the neutral point grounding resistance, C_x is the single-phase ground capacitance of the x line, R_f is the fault resistance, $\dot{I}_s$ is the injected current signal, and $\dot{U}_0$ is the neutral point voltage.

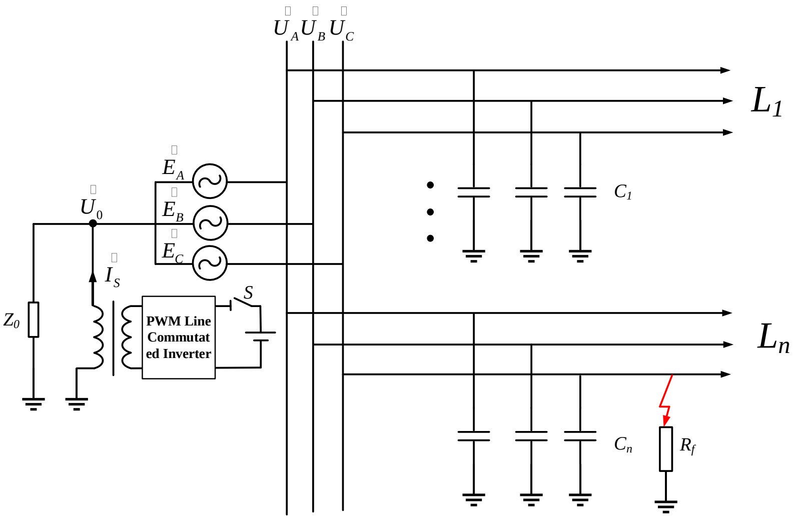

Fig. 1 Single-phase grounding fault model of flexible grounding distribution network

The injection signal device consists of a DC power supply, a PWM inverter and an isolation transformer. S is the control switch. The impedance of the single-phase grounding fault model is decomposed according to the line, and the zero-sequence equivalent circuit of the distribution network fault is analyzed as shown in Figure 2.

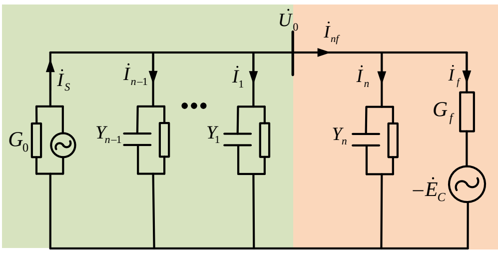

Fig.2 Zero-sequence equivalent model of single-phase grounding fault in flexible grounding distribution network

Among them, Y_i (i=1,2...,n-1) is the line section admittance, G_0 is the neutral point-to-ground conductance, G_f is the fault conductance, $\dot{I}_i$ (i=1,2...,n-1) is the zero sequence current at the head of the line, $\dot{I}_{nf}$ is the zero sequence current of the fault line, $\dot{I}_n$ is the fault relative to the ground admittance current, $\dot{I}_f$ is fault current.

B. The change trend of zero sequence current of each line before and after signal injection

When a single-phase ground fault is detected in the distribution network, it is assumed that the fault line is the nth. According to the node voltage method, the neutral point voltage of the system $\dot{U}_0$ is.

$$\dot{U}_0 = \frac{-\dot{E}_C G_f}{G_0 + \sum_{i=1}^{n} Y_i + G_f} \tag{1}$$

It can be seen from Eq. (1) that the neutral point voltage of the system is related to the transition resistance and the system admittance. Combined with Figure 2, the zero-sequence current at the head end of the healthy line and the fault line is shown in Formulas (2) and (3):

$$\dot{I}_i = \dot{U}_0 Y_i \left(i = 1, 2, \cdots, n-1\right) \tag{2}$$

$$\dot{I}_{n.f} = \dot{U}_0 Y_n + \dot{E}_C G_f \tag{3}$$

From Eq. (2) and Eq. (3), it can be seen that the current at the head of the line is related to the neutral point voltage and the fault phase voltage and transition resistance. There are differences in the size of zero sequence current between fault line and non-fault line.

Switch S control injection current signal $\dot{I}_S$, The system neutral point voltage will change. According to the circuit superposition theorem, when the flexible device acts alone, the system neutral point voltage is :

$$\dot{U}'_{01} = \frac{\dot{I}_s}{G_0 + \sum_{i=1}^{n} Y_i + G_f} \tag{4}$$

When the system works alone, the neutral point voltage of the system is the neutral point voltage before the signal is injected.

$$\dot{U}'_{02} = \frac{-\dot{E}_C G_f}{G_0 + \sum_{i=1}^{n} Y_i + G_f} \tag{5}$$

It can be obtained that the neutral point voltage of the distribution network after the current signal is injected when the single-phase grounding fault occurs in the distribution network is :

$$\dot{U}'_0 = \dot{U}'_{01} + \dot{U}'_{02} = \frac{\dot{I}_s - \dot{E}_C G_f}{G_0 + \sum_{i=1}^{n} Y_i + G_f} \tag{6}$$

It can be seen from Equation (6) that after the current signal is injected, the neutral point voltage is not only related to the transition resistance and the system 's admittance to the ground, but also related to the amplitude and phase of the injected current. The greater the amplitude of the injected current signal, the greater the change of the neutral point voltage of the system, and the greater the change of the zero-sequence current at the head of each line.

After the current signal is injected, the zero-sequence current at the head end of the healthy line and the fault line is shown in Formulas (7) and (8):

$$\dot{I}_i = \dot{U}'_0 Y_i \left(i = 1, 2, \cdots, n-1\right) \tag{7}$$

$$\dot{I}_{n.f} = \dot{U}'_0 Y_n + \dot{E}_C G_f \tag{8}$$

III. FAULT LINE SELECTION CRITERION BASED ON THE CHANGE OF ZERO SEQUENCE CURRENT BEFORE AND AFTER CURRENT SIGNAL INJECTION

The criterion of the fault line is based on the phase angle of the ratio of the zero-sequence current variation to the zero-sequence current before the injection signal, and is subtracted in turn. The multi-branch distribution network of n fault line sections described in this paper is taken as an example.

Before and after the current signal is injected, the zero-sequence current variation of the fault line and the non-fault line is:

$$\Delta\dot{I}_i = (\dot{U}'_0 - \dot{U}_0) Y_i \left(i = 1, 2, \cdots n-1\right) \tag{9}$$

$$\Delta \dot{I}_{n.f} = (\dot{U}_0' - \dot{U}_0)Y_n \tag{10}$$

The phase angle difference between the ratio of the zero-sequence current variation before and after the injection current signal to the zero-sequence current before the injection signal is defined as K.

$$K_i = \arg\left(\frac{\Delta \dot{I}_i}{\dot{I}_i}\right) = \arg\left(\frac{\left(\dot{U}_0' - \dot{U}_0\right)Y_{0i}}{\dot{U}_0 Y_{0i}}\right) = \arg\left(\frac{\left(\dot{U}_0' - \dot{U}_0\right)}{\dot{U}_0}\right)\left(i = 1, 2, \cdots n-1\right) \tag{11}$$

$$K_{n.f} = \arg\left(\frac{\Delta \dot{I}_{n.f}}{\dot{I}_{n.f}}\right) = \arg\left(\frac{\left(\dot{U}_0' - \dot{U}_0\right)Y_n}{\dot{U}_0 Y_n + \dot{E}_C G_f}\right) \tag{12}$$

It can be seen from Eq. (11) and Eq. (12) that the calculated K value has nothing to do with the system line-to-ground admittance parameters, so this method is theoretically not affected by the three-phase unbalance of the system.

Calculate the difference of K between the lines, defined as p,

$$\begin{cases} p_i = \left|K_i - K_{i+1}\right|\left(i = 1, 2...., n-1\right) \\ p_n = \left|K_n - K_1\right|\left(i = n\right) \end{cases} \tag{13}$$

Since the calculated K value of the non-fault line is independent of its ground impedance, only related to the zero-sequence voltage, and the zero-sequence voltage of the line is consistent, the difference of the p value between the non-fault lines is zero, and the p value between the non-fault line and the fault line is not zero. Therefore, the criterion of the line selection method used in this method is:

$$p_i > \overline{p}, p_{i+1} > \overline{p} \tag{14}$$

In this, $\overline{p}$ is the average of the p values for all lines, with $\overline{p} = \frac{1}{n}\sum_{i=1}^{n} p_i$.

When the p value of the i line is greater than $\overline{p}$ and the p value of the i+1 line is greater than $\overline{p}$, the fault line is judged to be the i+1 line.

IV. GROUNDING FAULT LINE SELECTION PROCESS DESIGN

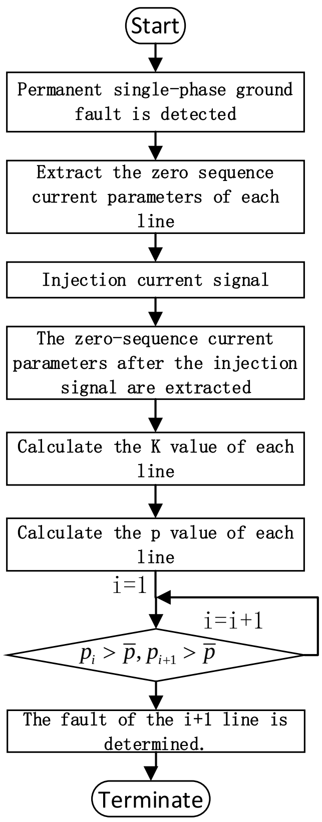

Fig.3 Grounding fault detection flow chart

After the single-phase grounding fault is detected in the system, the phase angle of the ratio of the zero-sequence current variation at the head of the line to the zero-sequence current before the injection signal is calculated according to the zero-sequence current at the head of the line before and after the injection signal. Then, the p value is obtained by subtraction in turn, and the obtained p value is judged. When it is satisfied $\left|p_i\right| > \bar{p}, \left|p_{i+1}\right| > \bar{p}$, it is judged that the i+1the line is faulty.

V. SIMULATION VERIFICATION

The PSCAD/EMTDC simulation software is used to build the simulation model of the fault section of the distribution network as shown in Figure 4. The simulation model contains 5 feeders l_1, l_2, l_3, l_4 and l_5, where the fault occurs l_4. The line l_2 and l_4 are cable lines, and the remaining lines are overhead lines. The three-phase ground parameters of the lines are different. The neutral point-to-ground resistance of the system is 10Ω, and the feeder simulation parameters are shown in Table 1.

Table 1 Parameters of line selection simulation model

	Earth Capacitance /*uf*			Resistance to Earth /Ω		
	A	B	C	A	B	C
Line 1	0.029	0.020	0.0225	4244132	4244132	4244132
Line 2	2.5	2.4	2.6	44210	44210	44210
Line 3	0.05	0.055	0.06	2122066	2122066	2122066
Line 4	4.20	4.12	4.22	25263	25263	25263
Line 5	0.085	0.095	0.089	1116877	1116877	1116877

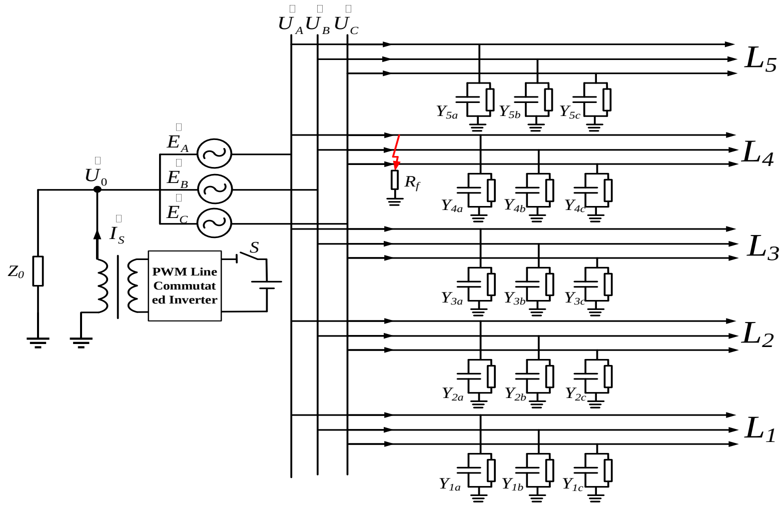

Fig.4 Distribution network fault line selection simulation topology

It is assumed that the fault occurs on line 4, the fault resistance is 3000 Ω, the simulation is set to inject the power frequency current A, and the frequency f is 50 Hz. The grounding fault of the system occurs in 0.2 s, and the current signal is injected in 0.4 s. The amplitude and phase angle changes of zero sequence current and neutral point voltage before and after injection are obtained as shown in table 2:

Table 2 Changes of amplitude and phase angle of neutral point voltage

	Before Injection		After Injection	
	Amplitude	Phase Angle	Amplitude	Phase Angle
U_0/kV	3.3132	6.62	3.6265	-0.46
I_{01}/A	8.95e-5	96.65	9.62e-5	90.53
I_{02}/A	7.84e-3	97.36	8.54e-3	90.09
I_{03}/A	1.58e-4	98.47	1.73e-4	90.52
I_{04}/A	8.25e-3	95.98	9.14e-3	82.82
I_{05}/A	2.66e-4	92.91	2.90e-4	85.42

According to the zero-sequence current data before and after the injection signal, the change value $\Delta\dot{I}_i$, K and p values of the zero-sequence current of each line are calculated. The calculated values are shown in Table 3 :

Table 3 Calculation value of zero sequence current characteristic quantity

	$\Delta\dot{I}_i$	K_i	p_i
U_0	0.53∠-50.79 kV	-57.41	
Line 1	1.19e-5∠37.60 A	-59.05	0.66
Line 2	1.25e-3∠37.65 A	-59.71	0.16
Line 3	0.27e-4∠37.60 A	-59.87	12.79
Line 4	2.18e-3∠23.32 A	-72.66	13.24
Line 5	0.44e-4∠33.49 A	-59.42	0.37

The calculated data in Table 3 can be shown in Figure 5:

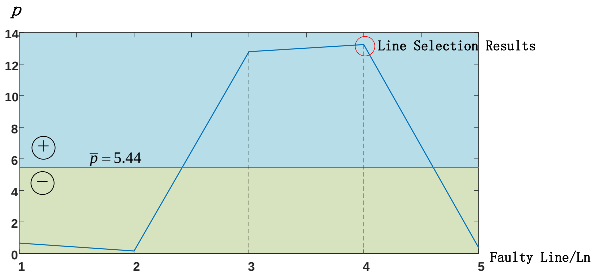

Fig.5 Zero-sequence current p-value line chart

The calculation can be obtained $\overline{p}$ = 5.44, and then enter the criterion link. According to the criterion proposed in this paper, it is obvious that the fault line occurs in the fourth line, which is consistent with the simulation setting result.

Change the transition resistance and the fault line, repeat the simulation steps, and get the line selection results as shown in Table 4:

Table 4 Line selection results table under different fault conditions

Fault Resistance Value	Faulty Line	p					Line Selection Results
		p_1	p_2	p_3	p_4	p_5	
R_f=3000Ω	L3	0.37	8.61	9.78	0.11	1.65	L3
	L4	0.66	0.16	12.79	13.24	0.37	L4
R_f=5000Ω	L1	7.65	0.23	0.41	0.23	7.24	L1
	L2	9.52	9.84	0.21	0.39	0.14	L2
R_f=10000Ω	L5	0.55	0.48	0.32	5.20	5.45	L5
	L2	7.68	7.84	0.76	0.38	0.54	L2

The above theoretical analysis and simulation results show that when the fault occurs on the overhead line and the cable line respectively, the method proposed in this paper can effectively select the fault line. The simulation is carried out under the conditions of fault resistance of 3000Ω, 5000Ω and 10kΩ respectively. The simulation results verify that the method still maintains good line selection accuracy under high resistance fault conditions.

VI. CONCLUSION

Based on the problem that the fault signal is weak and the line selection is difficult when the high resistance grounding fault occurs in the system, in order to improve the accuracy of the existing distribution network grounding fault line selection, this paper proposes a fault line selection method based on the phase angle offset of the fault zero sequence current, and obtains the following conclusions:

1) By injecting the signal, the zero-sequence current of the head end and section of each line before and after the injection signal is extracted, and the phase angle of the ratio of the zero-sequence current change to the zero-sequence current before the injection signal is calculated to realize the fault line selection function.

2) The proposed line selection method is theoretically not affected by the imbalance of the system parameters, and has high accuracy, which overcomes the difficulty of weak high-resistance fault characteristics.

3) The proposed line selection criterion does not need complex calculation, and it is fast and easy to be applied in engineering.

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