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Faulted feeder identification and location for a single line-to-ground fault in ungrounded distribution system based on principal frequency component

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Abstract: When a single line-to-ground fault occurs in the ungrounded distribution system, the steady-state fault current is relatively small for fault analysis and the transient fault current is observable, which can be used for faulted feeder identification and location. The principal frequency component retains most of the characteristics of the transient current. The principal frequency is related to the distance from the fault point to the substation and can be used for fault location. This paper analyzes the sequence network model of a single line-to-ground fault in the distribution network, and gives a method for principal frequency calculation. Depending on the characteristics of the maximum amplitude of the principal frequency component of the faulted feeder, the method of faulted feeder identification is given. Based on the complementary characteristics of the phase angle of the principal frequency component of the fault current and the phase angle at the substation bus, the faulted section location is carried out. MATLAB simulation is used to verify the effectiveness of the faulted feeder identification and location method.

Key words: fault identification, fault location, single line-to-ground fault, principal frequency component

1. Introduction

In distribution systems of China, the three-wire, ungrounded (isolated) neutral system is widely used [1]. The advantage of an ungrounded system is that when a single line-to-ground (SLG) fault occurs on the distribution feeder, the fault current is small, and it can generally operate for 2 hours with a fault [2–4]. There are three types of methods to deal with SLG faults of the ungrounded system: 1) steady state methods, using the amplitude and phase information of fault current power frequency (50 Hz) to select the faulted feeder [5–6]; 2) additional resistance methods, putting a resistance into the neutral point for a short time, making the ground point produce a fault current about 40 ampere for fault judgment [7–8]; 3) transient methods, directly use the transient information of voltage and current generated by fault to judge the faulted feeder [9–10]. In recent years, the transient signal methods have been extensively used because of its stable fault signal, obvious amplitude, and no need of primary equipment cooperation, low cost, safety and reliability.

Analyzing the transient characteristics of an SLG fault, it is found that the transient process contains varies frequency [11–12]. The principal frequency component has the largest energy, which can be used to represent the characteristics of the transient process. The faulted feeder can be selected by using the amplitude and phase information of the principal frequency current. The principal frequency current can be used to calculate the distance between the fault point and substation bus. In this paper, the transient equivalent circuit of an SLG fault is analyzed, and the calculation method of the principal frequency is given. Then the phase information of the principal frequency is used for the faulted feeder identification, and the fault distance is located by the principal frequency value. This method improves the accuracy of faulted feeder identification and location for SLG faults.

2. Principal frequency of fault current

2.1. Distribution network

The medium voltage (MV) distribution network in China generally refers to the 10 kV voltage level network, whose function is to distribute power to users safely, reliably, economically and reasonably. The MV distribution network generally consists of a mixture of overhead lines and underground cables. The MV distribution feeder is led out from the substation bus to the normally open switch or various terminal equipment (electrical equipment, distributed power supply, etc.) connected to another distribution feeder [13]. In normal operation, the distribution feeder is radiated, that is, there is only one power source for a specific user.

Distribution feeders generally use overhead lines or underground cables. Overhead lines are single conductors, and split conductors are generally not used. The structures of overhead lines and underground cables are not tolerated, and the corresponding line parameters are also different. The overhead and cable lines are not rotating components, and their positive sequence impedance is the same as negative sequence impedance.

2.2. Equivalent circuit

When an SLG fault occurs in a distribution feeder, the voltage of the fault point to the ground becomes zero, which is equivalent to inserting the virtual power supply E_1 with equal amplitude and opposite polarity at the fault point [14]. The three-phase network is decomposed into positive-sequence, negative-sequence, and zero-sequence networks. These networks are connected and the corresponding fault currents are decoupled into positive-, negative-, and zero-sequence currents that are computed for fault conditions [15]. The zero sequence current of the fault is shown in

Fig. 1(a) and it contains multiple frequency components in the half cycle (10 ms) of the fault, as shown in Fig. 1(b). The frequency component of the faulted power E_1 is very rich, and it resonates with the faulted line. The amplitude of the component at the resonance frequency is the largest as shown in Fig. 1(b). In reference [16], the transient of an SLG fault in the distribution network is analyzed, and it is considered that the principal frequency with maximum amplitude and most energy can be solved according to the second-order equivalent circuit as shown in Fig. 2. That is, the resonance frequency can be calculate using Fig. 2(b).

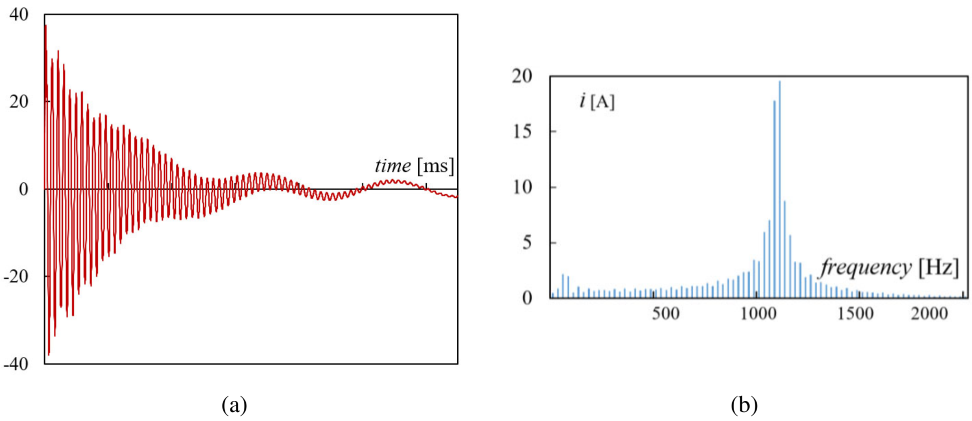

Fig. 1. Zero sequence current of an SLG: i versus time (a); i versus frequency (b)

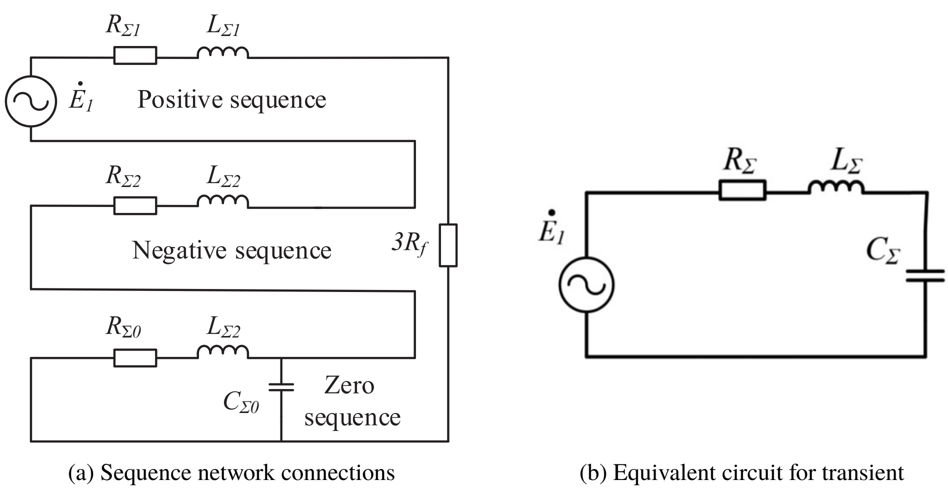

Fig. 2. Equivalent circuit for transient calculation of an SLG fault

In Fig. 2, power source $E_1 = -V_m \sin(\omega_0 t + \varphi)$, $R_{\Sigma 1}$, $R_{\Sigma 2}$, $R_{\Sigma 0}$ are respectively the resistance of positive-sequence, negative-sequence and zero-sequence, $L_{\Sigma 1}$, $L_{\Sigma 2}$, $L_{\Sigma 0}$ are the equivalent inductance of positive-sequence, negative-sequence and zero-sequence, $C_{\Sigma 0}$ is the equivalent capacitance of zero-sequence.

$$\left.\begin{aligned} R_\Sigma &= 3R_f + 2R_{T1} + 2R_{u1}l_f + R_{u0}l_f \\ L_\Sigma &= 2L_{T1} + 2L_{u1}l_f + L_{u0}l_f \\ C_\Sigma &= C_{u0}l_\Sigma \end{aligned}\right\}, \tag{1}$$

where: R_f is the grounding fault resistance, R_{u1}, L_{u1} are respectively the positive-sequence resistance and inductance in per unit length, R_{u0}, L_{u0} are respectively the zero-sequence resistance and inductance in per unit length, l_f is the feeder length of the fault point upstream, that is, the distance from the substation to the fault point.

2.3. Transient analysis

Applying superposition theorem, the virtual power supply E_1 is superposed with the grid power supply to generate the voltage and current in the non-fault state, that is, the load component; the fault components generated by the virtual power supply E_1 acting on the grid separately, including zero-sequence voltage and current components. E_1 is suddenly added to the distribution network at the fault moment, which is equivalent to adding an impact component in the original circuit, forming a resonant current under the influence of the inductance and capacitance of the distribution feeder. Set $E_1 = -V_m \sin(\omega_0 t + \varphi)$, take the voltage v_c on the capacitance as the variable, and establish the differential equation according to Fig. 2.

$$\left.\begin{aligned} L_\Sigma C_\Sigma \frac{\mathrm{d}^2 v_c}{\mathrm{d}t^2} + R_\Sigma C_\Sigma \frac{\mathrm{d}v_c}{\mathrm{d}t} + v_c = E_1 \\ i = C_\Sigma \frac{\mathrm{d}v_c}{\mathrm{d}t} \\ V_c(0\_) = 0 \\ i(0\_) = 0 \end{aligned}\right\}. \tag{2}$$

Equation (2) is a second-order differential equation. When $R < 2 \times (L_\Sigma/C_\Sigma)^{1/2}$, the roots are complex. Transient current oscillations occur in a network as Fig. 2. The characteristic impedance, $Z_0 = (Lu/Cu)^{1/2} \approx (L_\Sigma/C_\Sigma)^{1/2}$, for the overhead distribution feeders, it is about 300~400 Ω. So, if the grounding resistance is less than 800 Ω, the SLG fault may cause the current on the faulted feeder to oscillate.

2.4. Principal frequency

When the fault current of the distribution feeder oscillates, as Fig. 2(b), its principal frequency can be expressed as:

$$\omega_p = \sqrt{\frac{1}{L_\Sigma C_\Sigma} - \left(\frac{R_\Sigma}{2L_\Sigma}\right)^2}. \tag{3}$$

If R_Σ is small enough, its effect on frequency is relatively small, R_Σ can be omitted. Generally, when $R_f < 40\ \Omega$, the effect of R_Σ can be ignored. The principal frequency can be simplified to

$$\omega_p = \sqrt{\frac{1}{L_\Sigma C_\Sigma}} = \frac{1}{\sqrt{\left(2L_{T1} + 2L_{u1}l_f + L_{u0}l_f\right) C_\Sigma}} . \tag{4}$$

It can be seen from (4) that the larger the distributed capacitance of the system to ground and the farther the fault point is from the bus, the smaller the principal frequency. For a certain system, the C_Σ of the distributed capacitance to the ground is certain, which will not change with the change of the fault point. The principal frequency varies with the distance between the fault point and the substation bus. Using this property, the fault point can be located.

3. Faulted feeder identification

3.1. Method of faulted feeder identification

When an SLG fault occurs in a distribution feeder, the zero sequence current of the faulted feeder flows from the feeder to the substation bus, while the zero sequence current of the unfaulted feeder flows from the bus to the feeder. This principle is mostly used in faulted feeder identification, and generally uses zero-sequence current steady state information or transient state information. The steady state quantity is generally small and difficult to judge. In recent years, the transient information method has been widely used. After an SLG fault, the information of zero sequence current in a half cycle (10 ms) is very rich, and the amplitude ratio is generally large, which can reach tens to hundreds amperes, so it is easy to judge the fault.

The frequency component of fault information is complex, which will inevitably cause certain interference. Therefore, this paper uses the method of principal frequency to judge fault. By the Fourier transform, the principal frequency, amplitude and phase of fault information are extracted, and this information is used for fault judgment. The steps are as follows:

1. When the zero sequence voltage is detected to exceed the set value on the substation bus, the feeder identification algorithm is started;
2. For the zero sequence current of all the connected feeders on the substation bus, each of them is Fourier decomposed to extract the frequency value and phase information with the largest amplitude;
3. Compare the extracted amplitude information on all feeders, select the maximum value as the amplitude of the principal frequency, which is the principal frequency, and the feeder is the faulted feeder;
4. Verify that the phase angle of the principal frequency component of the zero sequence current of the faulted feeder is complementary to that of other feeder.

3.2. Simulation verification

A typical 10 kV distribution network is built and simulated with MATLAB. The method described in Section 3.1 is used for feeder identification to determine the effectiveness of the faulted feeder identification method. The distribution transformer is 110 kV/10 kV, with a capacity of 20 MVA and a short-circuit impedance of 10.5%. There are six distribution feeders on the bus, with a total length of 65 km. The length of each feeder is 3 km, 6 km, 15 km, 9 km, 12 km and 20 km, respectively, as shown in Fig. 3. The 15 km feeder is selected as the fault test, and the single-phase ground fault is set at 5 km. Taking JKLGJ-150, a typical three-wire with an average wire spacing of 1.25 m, as an example, the positive (negative) sequence parameters per unit length are as follows:

Table 1. JKLGJ-150 distribution feeder parameters

Sequence	***Ru*** **(Ω/km)**	***Lu*** **(mH/km)**	***Cu*** **(pF/km)**
Positive (negative)	0.222	1.09	10.76
Zero	0.367	5.06	4.13

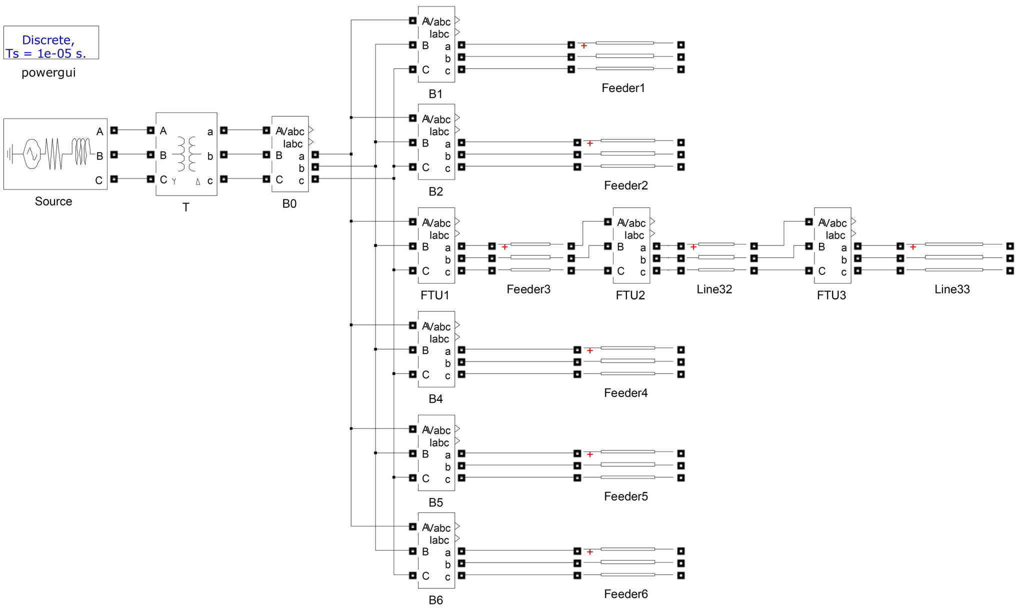

Fig. 3. Distribution feeder simulation in MATLAB

The total length of all six distribution feeders on the bus of the substation is 65 km, and the transformer $L_{T1} = 6.07$ mH. It can be calculated that when the fault point is 10 km away from the bus, the principal frequency is 1057 Hz. The fault current of Feeder 1, Feeder 2 and Feeder 3 is shown in Fig. 4.

It can be clearly seen from Fig. 4 that the amplitude of Feeder 3 is significantly larger than that of Feeder 1 and Feeder 2, and it can be judged that Feeder 3 is the faulted feeder. The frequency value information, amplitude and phase information with the largest amplitude are extracted from each feeder, as shown in Table 2.

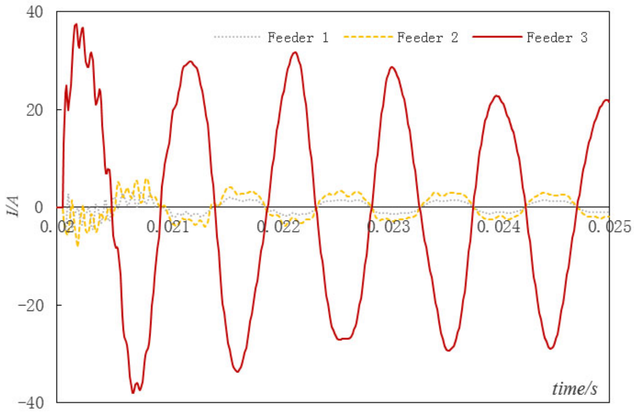

Fig. 4. Comparison of zero sequence current between faulted and unfaulted feeder

Table 2. Current frequency information of feeders

	***f*1**			***f*2**			***f*3**		
	***f* (Hz)**	***I* (A)**	**φ (°)**	***f* (Hz)**	***I* (A)**	**φ (°)**	***f* (Hz)**	***I* (A)**	**φ (°)**
Feeder 1	1 050	0.87	213.8	1 100	0.45	95.5	1 000	0.27	244.5
Feeder 2	1 050	1.75	214.0	1 100	0.92	95.6	1 000	0.55	244.7
Feeder 3	1 050	15.54	34.0	1 100	8.18	−84.3	1 000	4.82	64.6
Feeder 4	1 050	2.64	214.1	1 100	1.40	95.7	1 000	0.83	244.7
Feeder 5	1 050	3.63	214.0	1 100	1.91	95.7	1 000	1.13	244.7
Feeder 6	1 050	6.61	214.0	1 100	3.50	95.8	1 000	2.04	244.6

It can be seen from Table 2 that 1050 Hz is selected as the principal frequency, and the amplitude of faulted Feeder 3 is obviously larger than that of unfaulted Feeder 1 and Feeder 2. The ratio of the current amplitude of the unfaulted feeder is roughly equal to the ratio of the capacitance of the feeder, such as Feeder 1 and Feeder 2. The difference phase angle of each frequency between Feeder 3 (faulted) and Feeder 1, Feeder 2 (unfaulted) is about 180°. The phase angles of Feeder 1 and Feeder 2 of the unfaulted feeder are not much different, within 10°. Faulted feeder identification can be realized by using amplitude information and phase angle information.

4. Fault location

4.1. Fault location principle

Some feeder terminal units (FTUs) are installed along distribution feeders, and the FTUs detect single-phase current and zero-sequence current of the distribution feeders. When an SLG fault occurs in the distribution feeder, if the fault point is on the feeder between the two FTUs, the direction of zero sequence fault current is opposite; if the fault point is on the feeder outside the two FTUs, the direction of fault currents is the same. The principle is also applicable to the fault current of the principal frequency and can be used for fault location.

In the simulation system as in Section 3.2, three FTUs are successively installed on Feeder 3 at the exit of Feeder 3 (0 km away from the bus), 5 km away from the bus and 10 km away from the bus. The fault occurs at 10 km (in front of the third distribution terminal). The fault currents detected by the three FTUs are shown in Fig. 5.

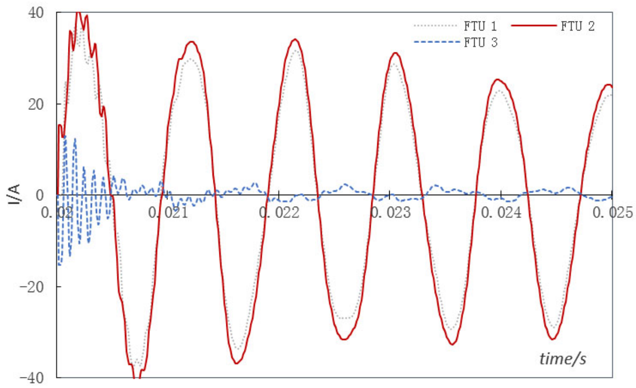

Fig. 5. Zero sequence current of fault point upstream and downstream

4.2. Frequency based fault location method

From the calculation of the principal frequency in Section 2.4, it can be known that the principal frequency of the zero sequence current after the SLG fault is related to the capacitance of the distribution network and the inductance of the feeder from the fault point to the bus. When the feeder is made of a single material (i.e. L_{u1} is the fixed value), the inductance of the feeder is directly proportional to the length of the feeder. Using this feature, the distance between fault points can be calculated.

From (4) we compute:

$$l_f = \frac{1}{4\pi^2 f_p^2 C_\Sigma \left(2L_{1u} + L_{0u}\right)} - \frac{2L_{T1}}{2L_{1u} + L_{0u}}\,. \tag{5}$$

The steps are as follows:

1. The length of each outgoing feeder and the capacitance per unit length (C_{u0}) are known, and the total equivalent capacitance C_Σ can be calculated by $C_\Sigma = C_{u0} l_\Sigma$;
2. Calculate the principal frequency of the fault feeder f_p;
3. Calculate the fault distance l_f according to (5).

For the fault example shown in Section 3.2, the total length of the feeders is 65 km, $C_\Sigma = 268.5$ nF, equivalent inductance of the transformer $L_{T1} = 0.006066$ H, positive sequence inductance of the feeder per unit length $L_{u1} = 1.09$ mH/km, zero sequence $L_{u0} = 4.13$ mH/km. After an SLG fault, the principal frequency of the fault is calculated to be 1050 Hz. The fault distance l_f calculated by (5) is 10.14 km, and the actual fault distance is 10 km. So the error is 1.4%. In the medium voltage distribution network, the line is generally shorter than 30 km. Therefore, the error of fault location is less than 10%, that is, no more than 3 km, which can bring great help to line patrol workers. In the case of simple feeder structure, this method has certain accuracy and can meet the requirements.

4.3. Location method based on phase angle comparison

After the principal frequency is extracted from the FTU, the fault section can also be located by using the phase angle relationship of the principal frequency. The steps are as follows:

1. The Fourier transform is applied to the zero sequence current waveform data of the FTU at 0 km at the faulted feeder. The frequency with the largest amplitude is selected as the principal frequency f_p, and the initial phase at the fault time of the principal frequency is recorded as φ_0;
2. According to the distance from the substation, the frequency of the zero sequence current waveform data collected by each FTU is transformed, and the initial phase value φ_n at the fault moment when the FTU(n) detects the principal frequency f_p is extracted;
3. If $|\varphi_0 - \varphi_n| < 120°$, then the faulted section is at the downstream the FTU(n); if $|\varphi_0 - \varphi_n| > 120°$, then the fault is at the upstream of the FTU(n), and confirms that the fault section is between the FTU(n–1) and the FTU(n);
4. If $|\varphi_0 - \varphi_n| > 120°$ does not appear until the end of the FTU, then the faulted section is considered to be at the downstream last FTU, i.e. the end of the feeder.

In the fault shown in Fig. 5, the principal frequency is 1050 Hz. Three FTUs are installed on the distribution feeder in turn, and the detected phase angle of the principal frequency is shown in Table 3.

Table 3. Current frequency information of feeders

	f (Hz)	I (A)	φ (°)
FTU 0	1050	15.54	34.0
FTU 1	1050	16.8	34.0
FTU 2	1050	0.69	215.1

From the data shown in Table 3, it can be seen that the phase angle difference between FTU 0 and FTU 1 is less than 120°, so the FTU 1 is at the upstream of the fault point. The phase angle difference between FTU 0 and FTU 2 is more than 120°, so the FTU 2 is at the downstream. Therefore, it can be judged that the fault is between FTU 1 and FTU 2.

5. Conclusions

When a single line-to-ground fault occurs in an ungrounded neutral system, the principal transient frequency component of the fault current contains most of the transient information. The value of the principal frequency is related to the grounding capacitance of the distribution system and the distance from the fault point to the substation bus, and the distance can be used for fault location. The amplitude of the principal frequency component of zero-sequence current in the faulted feeder is obviously larger than that of other normal feeder, which can be used for fault feeder identification. Upstream and downstream the fault point, the phase angle of the principal frequency component is complementary. Using this feature, the faulted section can be located.

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