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Application of Six-Sequence Fault Components in Fault Location for Joint Parallel Transmission Line

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Abstract: A new fault location method based on six-sequence fault components was developed for parallel lines based on the fault analysis of a joint parallel transmission line. In the six-sequence fault network, the ratio of the root-mean square value of the fault current from two terminals is the function of the line impedance, the system impedance, and the fault distance away from the buses. A fault location equation is given to relate these factors. For extremely long transmission lines, the distributed capacitance is divided by the fault point and allocated to the two terminals of the transmission line in a lumped parameter to eliminate the influence of the distributed capacitance on the location accuracy. There is no limit on fault type and synchronization of the sampling data. Simulation results show that the location accuracy is high with an average error about 2%, and it is not influenced by factors such as the load current, the operating mode of the power system, or the fault resistance.

Key words: fault location; joint parallel line; six-sequence components; two-terminal

Introduction

Fault location for transmission line can be classified into one-terminal method[1-6] and two-terminal method[7-11]. The location method that uses one-terminal information is very difficult to overcome the influence of the change of the remote-terminal system impedance and the fault resistance on location accuracy. Suonan et al.[5] proposed a method that makes full use of the sound line of the joint parallel line to obtain the information of the remote terminal. This method is effective for single line faults, but not so effective for overline (one line to another line) faults.

The fault location method that uses two-terminal information is not influenced by these factors and is accurate in theory, but the asynchronous problem of the data in these two terminals is difficult to be solved. Jiang et al.[9] proposes a new method for fault location in parallel double-circuit multi-terminal transmission lines. Although one equation can be used for all types of faults, and classification of faults and selection of fault phase are not required, the proposed methods do not have enough accuracy when the fault occurs across both circuits of a parallel double-circuit line. Saha et al.[10] and Ge[11] proposed a method based on the phase measurement unit device. However, this method is not economic and the accuracy of fault location is not very high.

A power system is generally a symmetrical three-phase system. If the symmetrical component method is used to decompose the asymmetrical phase measurement, all the calculations can be carried out according to single-phase condition for the asymmetry caused by asymmetrical fault and asymmetrical load. For the extremely long transmission line, especially for the joint parallel lines, there is zero sequence mutual reactance, as well as positive and negative sequence mutual reactance between phases[12]. Application of the traditional symmetrical component method is difficult, so the

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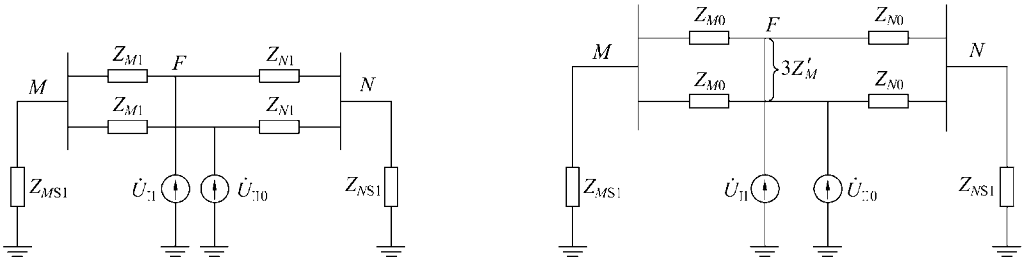
six-sequence-component method is applied to implement fault location for a joint parallel transmission line.

1 Six-Sequence Fault Component

1.1 Concept of six-sequence fault component

The six-sequence component can be produced from symmetrical component. For the joint parallel line, assume that the system meets the symmetrical condition, namely, the phase mutual impedance between phases of one line is same and the phase mutual impedance between two lines is same. Then, the six phase voltages and currents can be expressed as the superposition of the six-sequence symmetrical voltages and currents.

According to the superposition theory, sudden-changing components of all the sequence components can be obtained, and all the corresponded six-sequence components networks are passive networks. The positive, negative, and zero sequence networks for joint parallel line are shown in Fig. 1. In Fig. 1, M and N are buses of the power system; F is the fault point; $Z_{M\text{si}}$, $Z_{N\text{si}}$ are the equivalent source impedance of side M and N; i=1,2,0, representing positive, negative, and zero sequence; Z'_M is the mutual impedance between the two lines of the parallel lines.



(a) Positive sequence fault network (b) Zero sequence fault network

Fig. 1 Positive, negative, and zero sudden-change component networks of joint parallel lines

1.2 Sequence parameters of joint parallel line in six-sequence network system

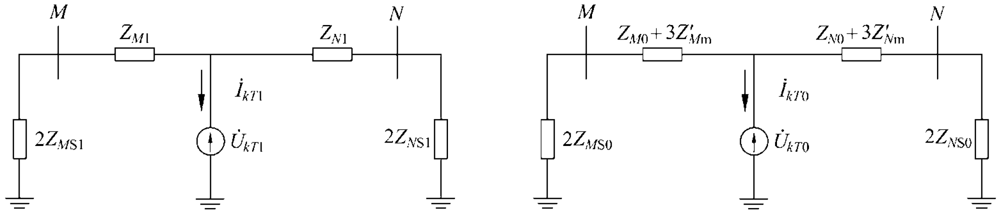
The sequence impedance in six-sequence network is related with the positive, negative, and zero sequence impedance in traditional symmetrical network. The same-sequence positive impedance and same-sequence negative impedance of the joint parallel line are equal to the traditional positive sequence impedance, and the inverted-sequence impedance of the joint parallel line is equal to the traditional positive impedance. As there is zero sequence mutual impedance between the two lines, the same-sequence zero impedance is equal to the traditional zero sequence impedance plus the triple mutual impedance, and the inverted-sequence zero impedance is equal to the traditional zero sequence impedance subtract the triple mutual impedance. The distributed capacitance in the six-sequence network is also changed correspondingly. The corresponding parameters of the joint parallel line can be seen in Ref. [12]. Various sequence networks for six-sequence components are shown in Fig. 2. T_1, T_2, and T_0 are the same-sequence positive, negative, zero network, respectively; F_1, F_2, and F_0 are inverted-sequence positive, negative, zero network, respectively.

Figure 2 shows that every network in the six-sequence network is independent. According to the given fault terminal condition, six-sequence compound network can be formed and can obviously indicate the relationship of the amplitude and phases of various sequence components. Applying the six-sequence components in fault analysis of joint parallel line is the same as the traditional symmetrical components.

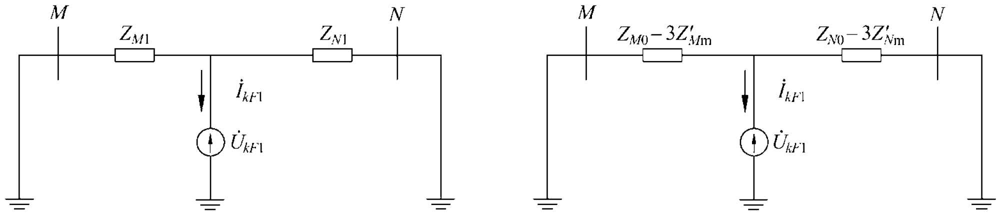
2 Fault Location Scheme for Joint Parallel Line Based on Six-Sequence Components

2.1 Solving of system impedance

All the sequence networks in Fig. 2 are passive network. In Fig. 2b, the subscript "m" represents the zero mututal reactance between the circuits. If the distributed capacitance is considered, the sequence network of joint parallel lines for fault mutation components of one line can be obtained as shown in Fig. 3. In Fig. 3, L is the total length of the transmission line, and D is the distance between Bus M and the fault point F.



(a) T_1, T_2 network (b) T_0 network



(c) F_1, F_2 network (d) F_0 network

Fig. 2 Six-sequence network of mutation components

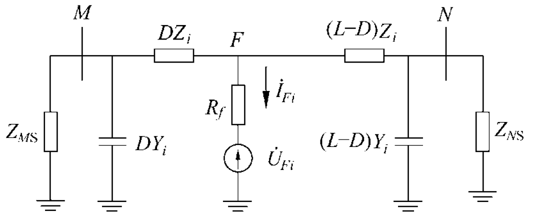


Fig. 3 Sequence network of joint parallel lines for fault mutation components

Firstly, the sudden-change of the fault component is obtained. The output of electromagnetic transient program(EMTP) or fault recorder can record the prefault and postfault voltages and currents of Buses *M* and *N*. Subtracting prefault components from postfault components can obtain sudden-changes of fault components. Assume that the sudden-changes of phase measurements are $\mathrm{d}\dot{U}_{Mj}$, $\mathrm{d}\dot{I}_{Mj}$, $\mathrm{d}\dot{U}_{Nj}$, and $\mathrm{d}\dot{I}_{Nj}$, which can be transformed into six-sequence components according to the six-sequence-component method[12]:

$$\begin{cases} \Delta\dot{U}_{Mi} = \boldsymbol{T}^{-1}\cdot \mathrm{d}\dot{U}_{Mj}, \\ \Delta\dot{I}_{Mi} = \boldsymbol{T}^{-1}\cdot \mathrm{d}\dot{I}_{Mj}, \\ \Delta\dot{U}_{Ni} = \boldsymbol{T}^{-1}\cdot \mathrm{d}\dot{U}_{Nj}, \\ \Delta\dot{I}_{Ni} = \boldsymbol{T}^{-1}\cdot \mathrm{d}\dot{I}_{Nj}, \end{cases}$$

where *i* indicates the *i*-th sequence, i.e., positive, negative, and zero sequence of same-sequence and positive, negative, and zero sequence of inverted-sequence; *j* indicates the *j*-th line; $\boldsymbol{T}$ is transformation matrix for six-sequence components [12].

Every sequence system's impedance of two terminals of the transmission line by the sudden-change sequence voltage and current is:

$$Z'_{MSi} = \frac{\Delta\dot{U}_{Mi}}{\Delta\dot{I}_{Mi}},\quad Z'_{NSi} = \frac{\Delta\dot{U}_{Ni}}{\Delta\dot{I}_{Ni}} \tag{1}$$

2.2 Modifying of sequence system impedance

The system impedance of the six-sequence network is not completely equal to the impedance calculated from Eq. (1) because of the characteristic of the six-sequence network.

In the joint parallel line system, since the same-sequence positive current doubles the current of the line out of the joint parallel line system, the same-sequence positive system impedance must be doubled.

The inverted-sequence negative current is the circulating current of the joint parallel transmission line, and hence, the inverted-sequence negative current is zero for the line out of the joint parallel line system. The inverted-sequence system impedance must be zero.

Due to the zero sequence mutual impedance between two lines, the same-sequence zero impedance is equal to the traditional zero sequence impedance plus triple zero sequence mutual impedance, and the inverted-sequence zero impedance is equal to the traditional zero sequence impedance subtracting triple zero sequence mutual impedance. The zero sequence system impedance must be modified by the zero sequence mutual impedance of the line and is not definite.

When six-sequence components are used to implement fault location, components except zero sequence components are applied.

2.3 Fault location scheme

In Fig. 3, the sequence currents that are flowing in the fault resistance can be solved from the sudden-change sequence voltages and currents at Bus *M* (considering the distributed capacitance by lumped parameters), as shown in Eq. (2).

$$\dot{I}_{Fi}=\frac{(\Delta\dot{I}_{Mi}-DY_i\Delta\dot{U}_{Mi})\left[\left(Z_{NSi}//\frac{1}{(L-D)Y_i}\right)+(L-D)Z_i\right]}{\left(Z_{NSi}//\frac{1}{(L-D)Y_i}\right)+LZ_i+\left(Z_{MSi}//\frac{1}{DY_i}\right)} \tag{2}$$

where "//" means the parallel impedance of two impedances.

The sequence currents flowing in the fault resistance can be solved from the sudden-change sequence voltages and currents at Bus *N* (considering the distributed capacitance by lumped parameters), as shown in Eq. (3).

$$\dot{I}'_{Fi}=\frac{(\Delta\dot{I}_{Ni}-DY_i\Delta\dot{U}_{Ni})\left[\left(Z_{MSi}//\frac{1}{DY_i}\right)+DZ_i\right]}{\left(Z_{NSi}//\frac{1}{(L-D)Y_i}\right)+LZ_i+\left(Z_{MSi}//\frac{1}{Y_iD}\right)} \tag{3}$$

where Z_i is the corresponding sequence impedance per km of the line, Y_i is the corresponding sequence admittance per km of the line (all the parameters can be seen in Tables 1, 2, and 3), and *D* is the distance from the fault point to the Bus *M*. If the data of two terminals are completely synchronous, the current flowing in the fault resistance calculated from Bus *M* and Bus *N* must be equal. In fact, the data of two terminals are not completely synchronous, so we assume that the phase difference is δ, and then Eq. (4) exists.

$$\dot{I}'_{Fi}=\dot{I}_{Fi}\mathrm{e}^{\mathrm{j}\delta} \tag{4}$$

The modulus value of the two items of Eq. (4) is equal, namely,

$$\left|\frac{(\Delta\dot{I}_{Mi}-DY_i\Delta\dot{U}_{Mi})\left[\left(Z_{NSi}//\frac{1}{(L-D)Y_i}\right)+(L-D)Z_i\right]}{\left(Z_{NSi}//\frac{1}{(L-D)Y_i}\right)+LZ_i+\left(Z_{MSi}//\frac{1}{DY_i}\right)}\right|=\left|\frac{(\Delta\dot{I}_{Ni}-DY_i\Delta\dot{U}_{Ni})\left[\left(Z_{MSi}//\frac{1}{DY_i}\right)+DZ_i\right]}{\left(Z_{NSi}//\frac{1}{(L-D)Y_i}\right)+LZ_i+\left(Z_{MSi}//\frac{1}{Y_iD}\right)}\right| \tag{5}$$

Equation (5) is a high ordered equation about D[13], and this equation is redundant because it is a complex equation that can be separated into two equations. Obviously, the modulus value of $\dot{I}_{Fi}$ decreases as *D* increases; the modulus value of $\dot{I}'_{Fi}$ increases as *D* increases. Therefore, the solution of Eq. (5) must be unique. When the step length is Δd, *D* can be searched in the range of 0-*L* to get the least differential value of the modulus value of two terminals of Eq. (5).

3 EMTP Simulation

3.1 EMTP simulation model

The fault location method is verified by electromagnetic transient program simulation. The simulation model of the parallel line is shown in Fig. 4.

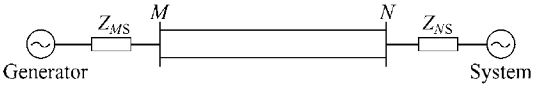


Fig. 4 Simulation system of joint parallel lines

3.2 Parameters of simulation model

The system frequency is 50 Hz. The impedance of transmission line is π equivalent circuit. The resistance, reactance, and capacitance of each π circuit are shown in Tables 1, 2, and 3. System's impedance is shown in Table 4.

Table 1 Resistance of each π circuit of the joint parallel transmission line

Phase	Resistance (Ω)					
	1A	1B	1C	2A	2B	2C
1A	0.3545					
1B	0.2599	0.349				
1C	0.2624	0.2599	0.3545			
2A	0.2619	0.2595	0.2622	0.3657		
2B	0.2615	0.2593	0.2619	0.2624	0.3656	
2C	0.2610	0.2588	0.2616	0.2623	0.2624	0.2656

Since this fault location method is based on the lumped parameter, the distributed model is used in the simulation model to examine the adaptability of the

Table 2 Reactance of each π circuit of the joint parallel transmission line

Phase	Reactance(Ω)					
	1A	1B	1C	2A	2B	2C
1A	3.2009					
1B	1.5430	3.2067				
1C	1.4840	1.5430	3.2009			
2A	1.1280	1.1848	1.2824	3.6724		
2B	1.0374	1.0834	1.1492	1.5455	3.6724	
2C	0.9663	1.0050	1.0540	1.3076	1.5510	3.6724

Table 3 Capacitance of each π circuit of the joint parallel transmission line

Phase	Capacitance (μF)					
	1A	1B	1C	2A	2B	2C
1A	0.0476					
1B	−0.0088	0.0449				
1C	−0.0060	−0.0087	0.0479			
2A	−0.0008	-0.0018	−0.0025	0.0363		
2B	−0.0004	−0.0020	−0.0011	−0.0052	0.0361	
2C	−0.0003	−0.0007	−0.0006	−0.0020	−0.0053	0.0360

Table 4 System's impedance (Max load: 600 MW)

	Z_{MS}/Ω	Z_{NS}/Ω
Positive	0.54+j18.25	j90
Zero	1.85+j54	j133

method to long transmission line. In the model, the studied line is composed by 20 π circuit sections, the length of each π circuit is 6 km, and the total length of the line is 120 km. In addition, in order to examine the influence of asymmetry of the parameters on the fault location accuracy, asymmetrical parameters of transmission line model are employed.

3.3 Simulation result

Various types of faults in the joint parallel line have been simulated, including all the single line faults (single phase grounded fault, phase to phase fault, phase to phase grounded fault, and three-phase fault), overline fault between different phases, overline fault between same phases, etc. Fault type classification and relative representation are shown in Table 5.

Fault points near the bus and in the middle of the line for all types of the line are simulated by EMTP. To examine the influence of fault resistance on fault location accuracy, the fault resistance is set at 10 Ω to 200 Ω for the grounded fault and 5 Ω for the phase-to-phase fault.

Table 5 Fault type classification and relative representation

Fault type				Representation
Single line fault	Ground fault	Single phase		1AG
		Two phases		1ABG
		Three phases		1ABCG
	Non-ground fault	Two phases		1BC
		Three phases		1ABC
Over line fault	Non-ground fault	One phase of line 1 to other phase of line 2		1A2B
		One phase of line 1 to other two phases of line 2		1A2BC
		One phase of line 1 to other three phases of line 2		1A2ABC
		Two phases of line 1 to other two phases of line 2		1AB2BC
		Two phases of line 1 to other three phases of line 2		1AB2ABC
		Same phase to phase	One phase	1A2A
			Two phases	1BC2BC
			Three phases	1ABC2ABC
	Ground fault	Fault type is same as above		Add “G” after the representation of the above

3.3.1 Fault location result of single line fault

The single line faults are simulated by EMTP, and the output fault data is applied to find the fault location. The fault location result and the corresponding location error are shown in Table 6.

Table 6 obviously shows that the sudden-changes of the six-sequence-component method is suitable for single line fault and the fault location result is accurate in various types of fault and various fault resistances.

3.3.2 Fault location result of overline fault

The overline faults are simulated by EMTP, and the output fault data is applied to locate the fault point. The fault location result and the corresponding location error is shown in Table 7. Table 7 shows that the six-sequence-component method is suitable for overline fault and the fault location result is accurate in various types of fault and various fault resistances.

Table 6 Fault location result for single line fault

Fault type	Practical fault location (%)	Fault resistance (Ω)	Fault location result (%)	Error (%)
Single-phase grounded (1AG)	20	10	21.05	1.05
	20	200	18.95	−1.05
	50	10	50.60	0.60
	50	100	49.10	−0.90
	50	200	49.15	−0.85
Phase-phase fault (1AB)	20	5	20.05	0.05
	50	5	50.10	0.10
Phase-phase grounded (1ABG)	20	5	19.85	−0.15
	20	200	20.10	0.10
	50	5	49.95	−0.05
	50	200	50.10	0.1
Three-phase fault (1ABC)	20	5	20.35	0.35
	50	5	50.20	0.20

Table 7 Fault location result of overline fault

Fault type	Practical fault location (%)	Fault resistance (Ω)	Fault location result (%)	Error(%)
1A2BG	20	10	20.80	0.80
	20	200	20.45	0.45
	50	10	50.10	0.10
	50	200	49.85	−0.15
1A2B	20	5	19.90	−0.1
	50	5	50.00	0.00
1BC2BG	20	10	20.20	0.20
		200	19.75	−0.25
	50	10	50.46	0.46
		200	50.20	0.20
1BC2B	20	5	20.68	0.68
	50	5	50.18	0.18
1AB2BCG	20	10	21.05	1.05
		200	19.97	−0.03
	50	10	49.89	−0.11
		200	50.00	0.00
1AB2BC	20	5	19.95	−0.05
	50	5	49.95	−0.05
1ABC2A (G)	20	10	20.16	0.16
		200	20.46	0.46
	50	10	49.86	−0.14
		200	50.06	0.06
1ABC2A	20	5	20.00	0.00
	50	5	49.80	−0.20
1ABC2BCG	20	10	20.20	0.20
		200	19.76	−0.24
	50	10	50.40	0.40
		200	51.03	1.03
1ABC2BC	20	5	20.49	0.49
	50	5	49.50	−0.50

3.3.3 Fault location result under enhanced length and fault resistance

In order to examine the suitable range of the fault location method, the model is extended to 40 π circuit (a length of 240 km) and the fault resistance is increased to 300 Ω. Parts of the simulation results are shown in Table 8.

Table 8 Fault location result of 240 km and different fault resistances

Fault type	Practical fault location (%)	Fault resistance (Ω)	Fault location result (%)	Error (%)
1AG	20	10	22.75	2.75
		100	17.45	−2.55
		200	17.20	−2.80
		300	17.65	−2.35
	50	10	51.15	1.15
		100	48.15	−1.85
		200	47.95	−2.05
		300	48.20	−1.80
1BC	20	5	20.20	0.20
	50	5	49.60	−0.40
1B2C	20	5	20.10	0.10
	50	5	49.55	−0.45

Table 8 shows that the fault location accuracy is not affected by fault resistance. Although the error of fault location circuit increases as the line lengthenes, the averaged error is about 2%. In fact, as the number of the π sections increases, the simulation error increases, which will influence the fault location accuracy.

4 Conclusions

The six-sequence fault component method was employed to locate the fault location in joint parallel lines, by resolving the mutual induction between the joint parallel lines. In the additional six-sequence fault network, the ratio of the two terminals' root-mean square currents is the function of the line impedance, the system impedance, and the fault distance. Thus, a simplified equation is deduced to obtain the distance of the fault point from the bus.

For various grounded faults, the greatest fault resistance is 300 Ω. The sudden-changing six-sequence fault components are used to solve the system reactance of the two terminals of the transmission line and the fault distance away from the bus. Even if the fault resistance is very large and the fault current direction of the receiving terminal is from the transmission line to the bus, the proposed method still has a high fault location accuracy with an error of about 2%. The simulation results of various types of faults for joint parallel lines indicate that the proposed method can accurately predict fault locations, and is not influenced by factors, such as fault type, the operating mode of the power system the fault resistance at the fault point.

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