J Electr Eng Technol Vol. 9, No. 4: 1217-1228, 2014
http://dx.doi.org/10.5370/JEET.2014.9.4.1217

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Fault Line Detection Methodology for Four Parallel Lines on the Same Tower

Botong Li†, Yongli Li* and Chuang Yao*

Abstract – A method for faulted line detection of four parallel lines on the same tower is presented, based on four-summing and double-differential sequences of one terminal current. Four-summing and double-differential sequences of fault current can be calculated using a certain transformation matrix for parameter decoupling of four parallel transmission lines. According to fault boundary conditions, the amplitude and phase characteristics of four-summing and double-differential sequences of fault current is studied under conditions of different types of fault. Through the analysis of the relationship of terminal current and fault current, a novel methodology for fault line detection of four parallel transmission line on the same tower is put forward, which can pick out the fault lines no matter the fault occurs in single line or cross double lines. Simulation results validate that the methodology is correct and reliable under conditions of different load currents, transient resistances and fault locations.

Keywords: Four parallel lines on the same tower, Fault line detection, Fault in single line, Fault cross double lines, Four-summing sequence, Double-differential sequence

1. Introduction

With the advantage of large transmission capacity within small passageway, the constructions of four parallel transmission lines on the same tower become an inevitable trend for the main network of power system [1-3]. Due to the short distance of the four lines on the same tower, there are not only mutual inductances and capacitances between two phases in single line, but also complex mutual inductances and capacitances between every two phases in different lines [4]. Because faults cross lines probably occur besides faults within one line, there are sum to 8184 types of fault on four parallel lines on the same tower [5-7]. To minimize system insecurity and instability, fault lines must be accurately detected and tripped swiftly to make the sound lines back to normal operation when fault occurs. Therefore, accurate and quick fault line detection is very important for the selective operation of protection on four parallel lines on the same tower [8-9].

Due to the complexity of line parameters of four parallel transmission lines on the same tower, there are few methods for fault line detection have been proposed recently. Based on an transformer matrix for decoupling ideal but not actual parameter of four parallel line, which supposes the mutual impedances and capacitances between every two lines only share the same value respectively, a method for fault line detection of four parallel lines on the same tower was proposed, using the homodromous and circumfluent sequences of fault current [10]. Based on an different transformer matrix for decoupling ideal but not actual parameter of four parallel lines, which supposes the mutual impedances and capacitances between every two lines only share two different values respectively, a method for fault line detection of four parallel lines on the same tower is proposed, using the circumfluent sequences of fault current [11-12]. In fact, the mutual impedances and capacitances between every two lines are different from each other, so there are three different values respectively, which means both methods above cannot be put into implementation [13-14]. Moreover, they can only be used for fault line selection of fault in single line but not for fault cross lines. Indeed, though the probabilities of fault cross lines are on the lower level, it is much more serious of the damage it brings. So research on fault line detection for faults cross lines seems to be more necessary.

Based on the transformer matrix for actual parameter decoupling of four parallel transmission lines, which supposes the mutual impedances and capacitances between every two lines share different values from each other respectively, four-summing and double-differential sequences of fault current are calculated and the characteristics of their amplitudes and phases are studied. Through the analysis of the relationship of terminal current and fault current, an effective method for fault line detection of all fault types in four parallel transmission lines on the same tower is proposed using one terminal current.

† Corresponding Author: Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China. (libotong 2006@gmail.com)
* Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China.
Received: May 7, 2013; Accepted: February 24, 2014

2. Parameter Decoupling Method of Four Parallel Transmission Lines on the Same Tower

The model of four parallel transmission lines on the same tower with system at both terminals is shown in Fig. 1.

There are various tower structures of four parallel transmission lines on the same tower, such as six layers, four layers, three layers, et al. Tower structures which have been put into practical application in China are presanted in [13]. The parameters of four parallel transmission lines change with tower structures.

Due to the short distances, there are mutual impedances and capacitances between every two phases in different lines besides that between two phases in single line. According to Carson formula, the mutual parameters depend on the distance between two conductors. Therefore, taking the different distance between every two lines into account, the mutual impedances and capacitances between every two lines are different from each other, so there are three different values of mutual impedances and capacitances respectively. Based on a reasonable approximation of impedances and capacitances according to actual line construction, Line parameter decoupling matrix M is obtained in [13], which is shown in (1):

$$\mathbf{M}=\frac{1}{12}\begin{bmatrix}\mathbf{S} & \mathbf{S} & \mathbf{S} & \mathbf{S}\\ \mathbf{S} & \mathbf{S} & -\mathbf{S} & -\mathbf{S}\\ \mathbf{S} & -\mathbf{S} & \mathbf{S} & -\mathbf{S}\\ \mathbf{S} & -\mathbf{S} & -\mathbf{S} & \mathbf{S}\end{bmatrix} \tag{1}$$

$$\mathbf{S}=\begin{bmatrix}1 & \alpha & \alpha^2\\ 1 & \alpha^2 & \alpha\\ 1 & 1 & 1\end{bmatrix} \tag{2}$$

Using matrix M to transform the 12 phasors of currents in four lines into four-summing positive, negative and zero sequences and three different double-differential positive, negative and zero sequences, column vector of $\dot{\mathbf{I}}_{\mathrm{TF}}$ is shown as follows.

$$\dot{\mathbf{I}}_{\mathrm{TF}}=\mathbf{M}\times\dot{\mathbf{I}}_{\mathrm{ph}} \tag{3}$$

Where

$$\dot{\mathbf{I}}_{\mathrm{ph}}=[\dot{I}_{\mathrm{Ia}}\dot{I}_{\mathrm{Ib}}\dot{I}_{\mathrm{Ic}}\dot{I}_{\mathrm{IIa}}\dot{I}_{\mathrm{IIb}}\dot{I}_{\mathrm{IIc}}\dot{I}_{\mathrm{IIIa}}\dot{I}_{\mathrm{IIIb}}\dot{I}_{\mathrm{IIIc}}\dot{I}_{\mathrm{IVa}}\dot{I}_{\mathrm{IVb}}\dot{I}_{\mathrm{IVc}}]^{\mathrm{T}}$$

$$\dot{\mathbf{I}}_{\mathrm{TF}}=[\dot{I}_{\mathrm{T1}}\dot{I}_{\mathrm{T2}}\dot{I}_{\mathrm{T0}}\dot{I}_{\mathrm{F1}}\dot{I}_{\mathrm{F2}}\dot{I}_{\mathrm{F0}}\dot{I}'_{\mathrm{F1}}\dot{I}'_{\mathrm{F2}}\dot{I}'_{\mathrm{F0}}\dot{I}''_{\mathrm{F1}}\dot{I}''_{\mathrm{F2}}\dot{I}''_{\mathrm{F0}}]^{\mathrm{T}}$$

$\dot{I}_{\mathrm{T}i}$ is four-summing positive, negative or zero sequences of currents, $\dot{I}_{\mathrm{F}i}$, $\dot{I}'_{\mathrm{F}i}$ and $\dot{I}''_{\mathrm{F}i}$ are three different double-differential positive, negative or zero sequences of currents. i is 1, 2 or 0.

Assuming that the sequences of currents in each line are shown as follow:

$$\dot{\mathbf{I}}_{\mathrm{se}}=[\dot{I}_{\mathrm{I1}}\dot{I}_{\mathrm{I2}}\dot{I}_{\mathrm{I0}}\dot{I}_{\mathrm{II1}}\dot{I}_{\mathrm{II2}}\dot{I}_{\mathrm{II0}}\dot{I}_{\mathrm{III1}}\dot{I}_{\mathrm{III2}}\dot{I}_{\mathrm{III0}}\dot{I}_{\mathrm{IV1}}\dot{I}_{\mathrm{IV2}}\dot{I}_{\mathrm{IV0}}]^{\mathrm{T}}$$

The relationships between components in $\dot{\mathbf{I}}_{\mathrm{TF}}$ and $\dot{\mathbf{I}}_{\mathrm{se}}$ are shown in (4):

$$\begin{cases}\dot{I}_{\mathrm{T}i}=(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{II}i}+\dot{I}_{\mathrm{III}i}+\dot{I}_{\mathrm{IV}i})/4\\ \dot{I}_{\mathrm{F}i}=(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{II}i}-\dot{I}_{\mathrm{III}i}-\dot{I}_{\mathrm{IV}i})/4\\ \dot{I}'_{\mathrm{F}i}=(\dot{I}_{\mathrm{I}i}-\dot{I}_{\mathrm{II}i}+\dot{I}_{\mathrm{III}i}-\dot{I}_{\mathrm{IV}i})/4\\ \dot{I}''_{\mathrm{F}i}=(\dot{I}_{\mathrm{I}i}-\dot{I}_{\mathrm{II}i}-\dot{I}_{\mathrm{III}i}+\dot{I}_{\mathrm{IV}i})/4\end{cases} \tag{4}$$

Where i=1, 2, 0.

$\dot{\mathbf{I}}_{\mathrm{se}}$ can be obtained through transformation matrix P, which is used for mutual parameter decoupling between phases in single line.

$$\dot{\mathbf{I}}_{\mathrm{se}}=\mathbf{P}\times\dot{\mathbf{I}}_{\mathrm{ph}} \tag{5}$$

Where $\mathbf{P}=(1/3)\mathrm{diag}[\mathbf{S}\quad\mathbf{S}\quad\mathbf{S}\quad\mathbf{S}]$.

It can be seen that four-summing sequence is the sum of a certain sequence of current in each line, and three double-differential sequences are the difference between a certain sequence of currents in double lines and other double lines.

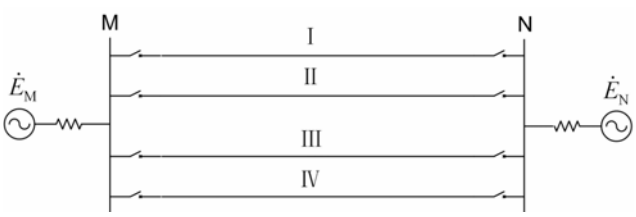


Fig. 1. Model of four parallel transmission lines on the same tower

3. Characteristics of Fault Current in the Case of Fault in Single Line

Taking faults in line I as an example, four-summing and double-differential sequences of fault current are deduced as follows in the case of single phase to ground fault, interphase fault, double phase to ground fault and three-phase fault.

When ground fault occurs on phase A in line I, boundary conditions of fault current are shown in (6):

$$\begin{aligned}\dot{I}_{\mathrm{IB}}=\dot{I}_{\mathrm{IC}}=\dot{I}_{\mathrm{IIA}}=\dot{I}_{\mathrm{IIB}}=\dot{I}_{\mathrm{IIC}}=\dot{I}_{\mathrm{IIIA}}\\ =\dot{I}_{\mathrm{IIIB}}=\dot{I}_{\mathrm{IIIC}}=\dot{I}_{\mathrm{IVA}}=\dot{I}_{\mathrm{IVB}}=\dot{I}_{\mathrm{IVC}}=0\end{aligned} \tag{6}$$

Through (3), the relationship between four-summing and double-differential sequences of fault current can be obtained as follows:

$$\dot{I}_{\mathrm{T}i}=\dot{I}_{\mathrm{F}i}=\dot{I}'_{\mathrm{F}i}=\dot{I}''_{\mathrm{F}i} \tag{7}$$

Where i=1, 2, 0.

When ground fault occurs on phase B and C in line I, boundary conditions of fault currents are shown in (8):

$$\begin{aligned}\dot{I}_{\text{IA}} &= \dot{I}_{\text{IIA}} = \dot{I}_{\text{IIB}} = \dot{I}_{\text{IIC}} = \dot{I}_{\text{IIIA}} = \dot{I}_{\text{IIIB}} \\ &= \dot{I}_{\text{IIIC}} = \dot{I}_{\text{IVA}} = \dot{I}_{\text{IVB}} = \dot{I}_{\text{IVC}} = 0\end{aligned} \tag{8}$$

The relationship between four-summing and double-differential sequences of fault current is the same as (7).

When interphase fault occurs on phase B and C in line I, boundary conditions of fault currents are shown in (9):

$$\begin{cases}\dot{I}_{\text{IB}} + \dot{I}_{\text{IC}} = 0 \\ \dot{I}_{\text{IA}} = \dot{I}_{\text{IIA}} = \dot{I}_{\text{IIB}} = \dot{I}_{\text{IIC}} = \dot{I}_{\text{IIIA}} = \dot{I}_{\text{IIIB}} \\ \quad = \dot{I}_{\text{IIIC}} = \dot{I}_{\text{IVA}} = \dot{I}_{\text{IVB}} = \dot{I}_{\text{IVC}} = 0\end{cases} \tag{9}$$

The relationship between four-summing and double-differential sequences of fault current is the same as (7). Because it is an interphase but not ground fault, there is no four-summing and double-differential zero sequences of fault current, which means i can be 1 or 2 but not 0.

When three-phase fault occurs in line Ⅰ, boundary conditions of fault currents are shown in (10).

$$\begin{cases}\dot{I}_{\text{IA}} + \dot{I}_{\text{IB}} + \dot{I}_{\text{IC}} = 0 \\ \dot{I}_{\text{IIA}} = \dot{I}_{\text{IIB}} = \dot{I}_{\text{IIC}} = \dot{I}_{\text{IIIA}} = \dot{I}_{\text{IIIB}} = \dot{I}_{\text{IIIC}} = \dot{I}_{\text{IVA}} = \dot{I}_{\text{IVB}} = \dot{I}_{\text{IVC}} = 0\end{cases} \tag{10}$$

The relationship between four-summing and double-differential sequences of fault current is the same as (7). Because it is a symmetrical fault, there is no four-summing and double-differential positive and zero sequences of fault current, which means i can be 1 but not 2 or 0.

When different types of fault occur in line Ⅱ, based on boundary conditions, the relationship between four-summing and double-differential sequences of fault current are shown in (11):

$$\dot{I}_{\text{T}i} = \dot{I}_{\text{F}i} = -\dot{I}'_{\text{F}i} = -\dot{I}''_{\text{F}i} \tag{11}$$

When different types of fault occur in line Ⅲ, based on boundary conditions, the relationship between four-summing and double-differential sequences of fault current are shown in (12):

$$\dot{I}_{\text{T}i} = -\dot{I}_{\text{F}i} = \dot{I}'_{\text{F}i} = -\dot{I}''_{\text{F}i} \tag{12}$$

When different types of fault occur in line Ⅳ, based on boundary conditions, the relationship between four-summing and double-differential sequences of fault current are shown in (13):

$$\dot{I}_{\text{T}i} = -\dot{I}_{\text{F}i} = -\dot{I}'_{\text{F}i} = \dot{I}''_{\text{F}i} \tag{13}$$

Table 1. Relationships of three double-differential sequences of fault current in the case of fault in single line.

Fault Line	$\dot{I}'_{\text{F}i}/\dot{I}_{\text{F}i}$	$\dot{I}''_{\text{F}i}/\dot{I}_{\text{F}i}$
line Ⅰ	$1\angle 0^\circ$	$1\angle 0^\circ$
line Ⅱ	$1\angle 180^\circ$	$1\angle 180^\circ$
line Ⅲ	$1\angle 180^\circ$	$1\angle 0^\circ$
line Ⅳ	$1\angle 0^\circ$	$1\angle 180^\circ$

The same as fault in line I, i depends on the type of fault.

It can be concluded that when a fault occurs in single line, three double-differential sequences of fault current have the same amplitude and 0° or 180° phase difference, which can be seen in Table 1.

It can be seen from Table 1 that double-differential sequences of fault current have different characteristics when fault occurs in different line, so it is an effective method for fault line detection in the case of fault in single line. Both double-differential positive and negative sequences of fault current can be used for asymmetric faults, but only double-differential positive sequences can be used for three-phase faults.

4. Characteristics of Fault Current in the Case of Fault Cross Double Lines

There are thousands of cross line fault types in four parallel transmission lines on the same tower, but the possibility of fault cross more than two lines is extremely small, so only faults cross double lines are considered in the paper.

When fault occurs cross line Ⅰ and Ⅱ, phasors of fault current in non-fault lines are 0 no matter which fault type it is, so boundary conditions are shown in (14).

$$\dot{I}_{\text{IIIA}} = \dot{I}_{\text{IIIB}} = \dot{I}_{\text{IIIC}} = \dot{I}_{\text{IVA}} = \dot{I}_{\text{IVB}} = \dot{I}_{\text{IVC}} = 0 \tag{14}$$

Fault current sequences of each line are shown in (15):

$$\begin{cases}\dot{I}_{\text{I}i} = \dot{I}_{\text{II}i} \neq 0 \\ \dot{I}_{\text{III}i} = \dot{I}_{\text{IV}i} = 0\end{cases} \tag{15}$$

where i can be 1, 2 or 0, which depends on the type of fault.

The four-summing sequences and three double-differential sequences of fault current can be calculated by (4), shown in (16):

$$\begin{cases}\dot{I}_{\text{T}i} = (\dot{I}_{\text{I}i} + \dot{I}_{\text{II}i})/4 \\ \dot{I}_{\text{F}i} = (\dot{I}_{\text{I}i} + \dot{I}_{\text{II}i})/4 \\ \dot{I}'_{\text{F}i} = (\dot{I}_{\text{I}i} - \dot{I}_{\text{II}i})/4 \\ \dot{I}''_{\text{F}i} = (\dot{I}_{\text{I}i} - \dot{I}_{\text{II}i})/4\end{cases} \tag{16}$$

When fault occurs cross line Ⅰ and Ⅲ, four-summing sequences and three double-differential sequences of fault current are shown in (17).

$$\begin{cases} \dot{I}_{Ti} = (\dot{I}_{\mathrm{I}i} + \dot{I}_{\mathrm{III}i})/4 \\ \dot{I}_{Fi} = (\dot{I}_{\mathrm{I}i} - \dot{I}_{\mathrm{III}i})/4 \\ \dot{I}'_{Fi} = (\dot{I}_{\mathrm{I}i} + \dot{I}_{\mathrm{III}i})/4 \\ \dot{I}''_{Fi} = (\dot{I}_{\mathrm{I}i} - \dot{I}_{\mathrm{III}i})/4 \end{cases} \tag{17}$$

When fault occurs cross line Ⅰ and Ⅳ, four-summing sequences and three double-differential sequences of fault current are shown in (18).

$$\begin{cases} \dot{I}_{Ti} = (\dot{I}_{\mathrm{I}i} + \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}_{Fi} = (\dot{I}_{\mathrm{I}i} - \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}'_{Fi} = (\dot{I}_{\mathrm{I}i} - \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}''_{Fi} = (\dot{I}_{\mathrm{I}i} + \dot{I}_{\mathrm{IV}i})/4 \end{cases} \tag{18}$$

When fault occurs cross line Ⅱ and Ⅲ, four-summing sequences and three double-differential sequences of fault current are shown in (19).

$$\begin{cases} \dot{I}_{Ti} = (\dot{I}_{\mathrm{II}i} + \dot{I}_{\mathrm{III}i})/4 \\ \dot{I}_{Fi} = (\dot{I}_{\mathrm{II}i} - \dot{I}_{\mathrm{III}i})/4 \\ \dot{I}'_{Fi} = (\dot{I}_{\mathrm{II}i} + \dot{I}_{\mathrm{III}i})/4 \\ \dot{I}''_{Fi} = (\dot{I}_{\mathrm{II}i} - \dot{I}_{\mathrm{III}i})/4 \end{cases} \tag{19}$$

When fault occurs cross line II and IV, four-summing sequences and three double-differential sequences of fault current are shown in (20).

$$\begin{cases} \dot{I}_{Ti} = (\dot{I}_{\mathrm{II}i} + \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}_{Fi} = (\dot{I}_{\mathrm{II}i} - \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}'_{Fi} = (\dot{I}_{\mathrm{II}i} - \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}''_{Fi} = (\dot{I}_{\mathrm{II}i} + \dot{I}_{\mathrm{IV}i})/4 \end{cases} \tag{20}$$

When fault occurs cross line Ⅲ and Ⅳ, four-summing sequences and three double-differential sequences of fault current are shown in (21).

$$\begin{cases} \dot{I}_{Ti} = (\dot{I}_{\mathrm{III}i} + \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}_{Fi} = (-\dot{I}_{\mathrm{III}i} - \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}'_{Fi} = (\dot{I}_{\mathrm{III}i} - \dot{I}_{\mathrm{IV}i})/4 \\ \dot{I}''_{Fi} = (-\dot{I}_{\mathrm{III}i} + \dot{I}_{\mathrm{IV}i})/4 \end{cases} \tag{21}$$

it can be concluded that when a fault cross double lines occurs, the relationships of three double-differential sequences of fault current is complex, which are summarized in Table 2.

Table 2. Relationship of three double-differential sequences of fault current in case of fault cross double lines

Fault Line	$\dot{I}'_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i}$	$\dot{I}''_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i}$
Ⅰ&Ⅱ	$(\dot{I}_{\mathrm{I}i}-\dot{I}_{\mathrm{II}i})/(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{II}i})$	$(\dot{I}_{\mathrm{I}i}-\dot{I}_{\mathrm{II}i})/(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{II}i})$
Ⅰ&Ⅲ	$(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{III}i})/(\dot{I}_{\mathrm{I}i}-\dot{I}_{\mathrm{III}i})$	$1\angle 0^\circ$
Ⅰ&Ⅳ	$1\angle 0^\circ$	$(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{IV}i})/(\dot{I}_{\mathrm{I}i}-\dot{I}_{\mathrm{IV}i})$
Ⅱ&Ⅲ	$1\angle 180^\circ$	$-(\dot{I}_{\mathrm{II}i}+\dot{I}_{\mathrm{III}i})/(\dot{I}_{\mathrm{II}i}-\dot{I}_{\mathrm{III}i})$
Ⅱ&Ⅳ	$-(\dot{I}_{\mathrm{II}i}+\dot{I}_{\mathrm{IV}i})/(\dot{I}_{\mathrm{II}i}-\dot{I}_{\mathrm{IV}i})$	$1\angle 180^\circ$
Ⅲ&Ⅳ	$-(\dot{I}_{\mathrm{III}i}-\dot{I}_{\mathrm{IV}i})/(\dot{I}_{\mathrm{III}i}+\dot{I}_{\mathrm{IV}i})$	$(\dot{I}_{\mathrm{III}i}-\dot{I}_{\mathrm{IV}i})/(\dot{I}_{\mathrm{III}i}+\dot{I}_{\mathrm{IV}i})$

It can be seen from Table 2 that double-differential sequences of fault current have different characteristics when fault occurs cross different lines, so it is an effective method for fault line detection in the case of fault cross double lines.

In Table 2, at least one magnitude ratio of two double-differential sequences of fault current is not 1, because the sum of current sequence of two fault lines is not equal to the difference of these two. However, in Table 1, both magnitude ratios of two double-differential sequences of fault current are 1. Based on the difference of these two magnitude radios, it is an effective way to identify whether a fault in single line or cross double lines.

In exceptional cases, when phase difference of current sequences of two fault lines are 90°or 270°, the sum of these two current sequences has the same magnitude as the difference of these two current sequences, so both magnitude ratios of two double-differential sequences of fault current are 1. However, According to Table 1, both phase differences of two double-differential sequences of fault current are 0°or 180°, not 90°or 270°, when fault in single line occurs. In order to identify whether a fault in single line or cross double lines in these exceptional cases, phase differences of two double-differential sequences are used besides magnitude radios.

According to the above analysis, criterion for distinguishing faults in single line from fault cross double lines is shown in (22).

$$\begin{cases} \left| |\dot{I}'_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i}| - 1 \right| < l \ \& \\ (|\arg(\dot{I}'_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i})| < \varphi \ || \ \left| |\arg(\dot{I}'_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i})| - 180^\circ \right| < \varphi) \ \& \\ \left| |\dot{I}''_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i}| - 1 \right| < l \ \& \\ (|\arg(\dot{I}''_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i})| < \varphi \ || \ \left| |\arg(\dot{I}''_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i})| - 180^\circ \right| < \varphi) \end{cases} \tag{22}$$

Where l is setting value of amplitude ratio for identifying 0, φ is setting value of phase difference for identifying 0°, and i depends on the type of fault.

If fault phase(s) in double lines is(are) the same, for example, fault types of ⅠABCⅡABC(G), ⅠABⅡAB(G), ⅠAⅡAG, et al, current sequences of two fault lines will be equal to each other, so the double-differential sequence

Table 3. Double-differential sequences of fault currents in the case of fault with same fault phase(s) cross double lines

Fault Line	$\dot{I}_{\mathrm{T}i}$	$\dot{I}_{\mathrm{F}i}/\dot{I}_{\mathrm{T}i}$	$\dot{I}'_{\mathrm{F}i}/\dot{I}_{\mathrm{T}i}$	$\dot{I}''_{\mathrm{F}i}/\dot{I}_{\mathrm{T}i}$
Ⅰ&Ⅱ	$(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{II}i})$	1	0	0
Ⅰ&Ⅲ	$(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{III}i})$	0	1	0
Ⅰ&Ⅳ	$(\dot{I}_{\mathrm{I}i}+\dot{I}_{\mathrm{IV}i})$	0	0	1
Ⅱ&Ⅲ	$(\dot{I}_{\mathrm{II}i}+\dot{I}_{\mathrm{III}i})$	0	0	-1
Ⅱ&Ⅳ	$(\dot{I}_{\mathrm{II}i}+\dot{I}_{\mathrm{IV}i})$	0	-1	0
Ⅲ&Ⅳ	$(\dot{I}_{\mathrm{III}i}+\dot{I}_{\mathrm{IV}i})$	-1	0	0

of fault current, which correspond to the difference of current sequences of the two fault lines, is 0, as shown in Table 3.

These fault types must be considered separately for fault line selection. Criterion for identifying these fault types from others is shown in (23).

$$\left|\dot{I}_{\mathrm{F}i}/\dot{I}_{\mathrm{T}i}\right|<l \,||\, \left|\dot{I}'_{\mathrm{F}i}/\dot{I}_{\mathrm{T}i}\right|<l \,||\, \left|\dot{I}''_{\mathrm{F}i}/\dot{I}_{\mathrm{T}i}\right|<l \tag{23}$$

Where i can be 1 or 2.

5. Line Detection Methodology for Four Parallel Transmission Line on the Same Tower

Based on the characteristics of $\dot{I}_{\mathrm{T}i}$, $\dot{I}_{\mathrm{F}i}$, $\dot{I}'_{\mathrm{F}i}$ and $\dot{I}''_{\mathrm{F}i}$, fault lines can be detected effectively no matter what type of fault it is. Types of fault are classified by (22) and (23), and then different methods of fault line detection are used for different types of fault. The basic flowchart is shown in Fig. 2.

Four-summing and double-differential negative sequence of terminal current are used for asymmetric fault; Four-summing and double-differential positive sequences of terminal current are used for three-phase fault which negative sequences of current are 0.

5.1 Fault line detection method for fault in single line

According to Table 1, phase differences of $\dot{I}'_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i}$ and $\dot{I}''_{\mathrm{F}i}/\dot{I}_{\mathrm{F}i}$ are used for fault line detection when fault in single line occurs. Specific method is shown in Fig. 3.

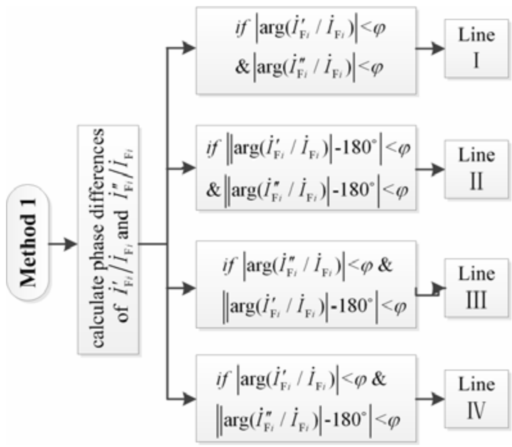


Fig. 3. Fault line selection method for fault in single line

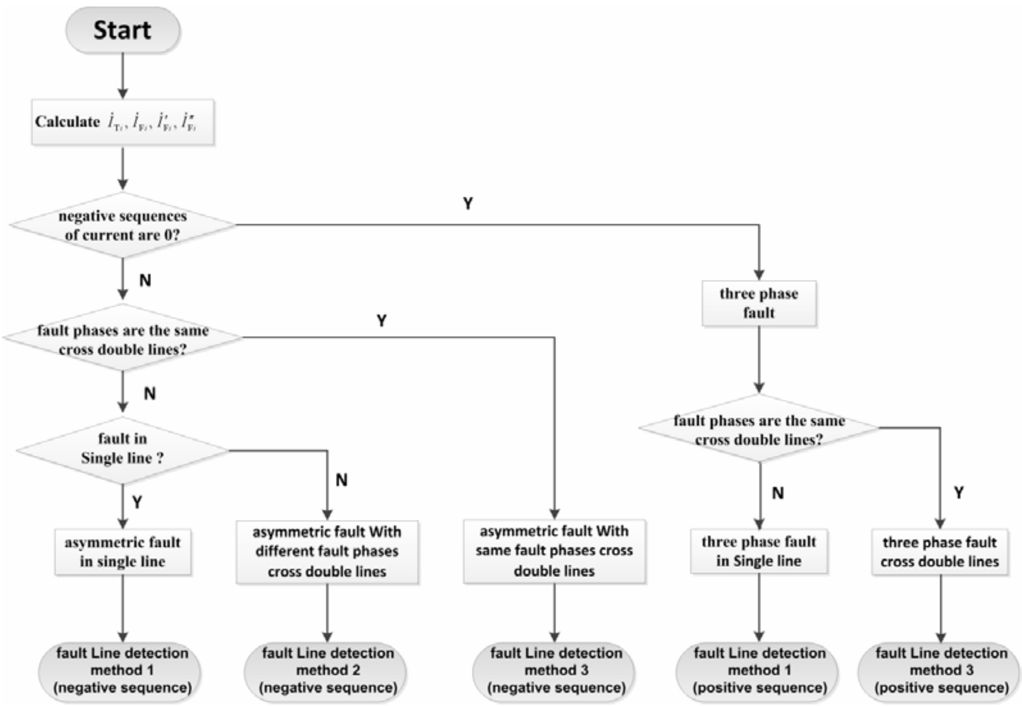


Fig. 2. The caption for a figure must follow the figure

5.2 Fault line detection method for fault cross double lines

Faults cross double lines are classified into two categories according to the characteristics of fault currents. Two methods for fault line selection are proposed respectively.

5.2.1 Fault line detection method for asymmetric fault with different fault phases cross double lines:

Not a double-differential sequence of current is 0 when these types of fault occur. According to Table 2, characteristics of $\dot{I}'_{Fi}/\dot{I}_{Fi}$ and $\dot{I}''_{Fi}/\dot{I}_{Fi}$, which used for fault line detection, are illustrated as follows: when fault occurs cross line Ⅰ&Ⅱ, amplitude of $\dot{I}'_{Fi}/\dot{I}_{Fi}$ and $\dot{I}''_{Fi}/\dot{I}_{Fi}$ are the same and both phases are identical; when a fault occurs cross line Ⅲ & Ⅳ, amplitudes of $\dot{I}'_{Fi}/\dot{I}_{Fi}$ and $\dot{I}''_{Fi}/\dot{I}_{Fi}$ are the same, but their phase difference is 180°; when a fault occurs cross line Ⅰ& Ⅲ, Ⅰ& Ⅳ, Ⅱ& Ⅲ and Ⅱ& Ⅳ, at least one amplitude of $\dot{I}'_{Fi}/\dot{I}_{Fi}$ and $\dot{I}''_{Fi}/\dot{I}_{Fi}$ is 1, and their phases is 0°or 180°. The specific method is shown in Fig. 4.

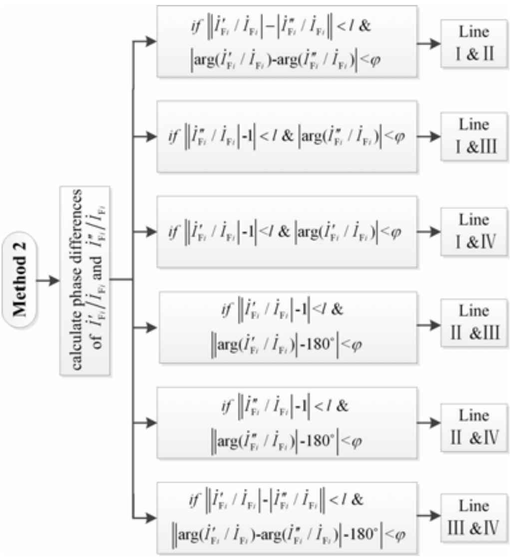


Fig. 4. Fault line selection method for asymmetric fault with different fault phases cross double lines

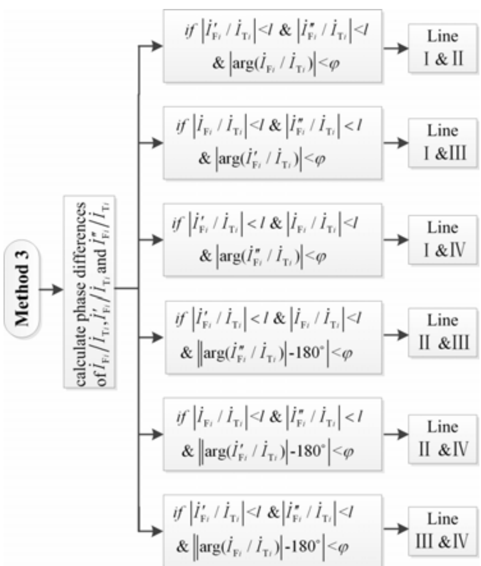


Fig. 5. Fault line selection method for fault with same fault phase(s) cross double lines

5.2.2 Fault line detection method for fault with same fault phase(s) cross double lines:

According to Table 3, only one of the three double-differential sequences of fault currents is not 0 when these types of fault occur, so the four-summing sequence of current needs to be used as an reference. The amplitude ratio of this double-differential sequence and four-summing sequence of fault currents is 1 and phase difference is 0°or 180°. The specific method is shown in Fig. 5.

For asymmetric fault, four-summing and double-differential negative sequences of terminal currents are used in the method, and for three-phase fault, four-summing and double-differential positive sequence of terminal current are used in the method which negative sequences of currents are 0.

5.3 Analysis for the effect of branch coefficient

The above theoretical analysis and methods are based on fault current, but in practical application, fault line detection methods shown in Figs. 2-5 can only use terminal currents of M or N. therefore, the effect of branch coefficient of fault current must be taken into account.

For fault in single line and asymmetric fault with different fault phases cross double lines, only double-differential negative or positive sequence currents are used for fault line detection. Through the analysis of network of double-differential sequences, it is known that $\dot{I}_{Fi}$, $\dot{I}'_{Fi}$ and $\dot{I}''_{Fi}$ are current sequences circulating from two lines into the other two lines but not to systems on both sides. Branch coefficients of double-differential sequences of fault currents only depend on fault point location and have the same real number for each sequence, as $C_{Fi}=C'_{Fi}=C''_{Fi}$, so ratios of every two double-differential sequences of terminal current are equal to that of fault current, which means branch coefficients have no influence on fault line detection method when terminal current is used instead of fault current in method 1 and 2. The errors of unbalanced currents, CT measurement and other factors should be considered for setting values. l can be set as about 0.3 for identification of 0, and φ can be set as 90°at most for non-overlapping area of fault line detection.

For fault with same fault phase(s) cross double lines, not only double-differential negative or positive sequences of fault current but also four-summing negative or positive sequences of fault current are used for fault line detection. Through the analysis of network of four-summing sequence, it is known that $\dot{I}_{Ti}$ is the sum of sequences of currents in four lines, which circulate from four lines into systems on both sides. So, branch coefficients of four-summing sequences of fault current, which are not only depend on fault location but also on system resistances, are different from that of double-differential sequence of fault currents. Angle errors, as four-summing sequences of terminal currents are used instead of that of fault current, must be considered as an important factor for setting of φ.

6. Simulation Studies

The simulation studies were carried out with PSCAD/ EMTDC software. The model of d four parallel transmission lines on the same tower with system at both terminals is shown in Fig. 1. The line parameters are based on a practical four parallel transmission lines in Shanghai city in China. The conductor type of line I and II is LGJ-400/35 and that of line III and IV is LGJ-630/45 with 4 bundle of each phase. The line is 100 km long. Frequency dependent (phase) model is used and geometric parameter with ideal transposition in each line is set for simulation.

System parameters of M side are as follows:

Z_{M1}=3.93+i49.34 Ω, Z_{M0}=2.52+i46.03 Ω;

System parameters of N side are as follows:

Z_{N1}=2.76+i41.34 Ω, Z_{N0}=1.57+i134.09 Ω.

Typical fault types in single line or cross double lines are simulated to verify the effectiveness of the fault line detection methodology. Transition resistance is set as 0 Ω for metal fault, 300 Ω for non-metal grounding L-G fault and 30 Ω for non-metal interphase or interline L-L fault.

6.1 Simulation results of fault in single line

Double-differential positive sequence currents are used for three-phase fault in single line. Simulation results of this type of fault with 0 Ω and 30 Ω transition resistances are shown in Table 4 to validate fault line detection method 1. Double-differential negative sequence currents are used for asymmetric faults in single line. Simulation results of these types fault with 0 Ω and 30 Ω L-L and 300 Ω L-G transition resistances are shown in Table 5. It is shown that phase differences of $\dot{I}'_{Fi}/\dot{I}_{Fi}$ and $\dot{I}''_{Fi}/\dot{I}_{Fi}$ in simulation are consistent with theoretical analysis and not influenced by transition resistance.

6.2 Line simulation results of fault cross double lines

Double-differential negative sequence currents are used for asymmetric fault with different fault phases cross double lines. Simulation results of these types of fault with 0 Ω and 30 Ω L-L and 300 Ω L-G transition resistances is presented in Tables 6 and 7. It is can be known that the simulation results are consistent with theoretical analysis and not influenced by transition resistance.

Four-summing negative sequence current is used as a reference current for asymmetric fault with the same fault phases cross double lines. Simulation results of these types of fault with 0 Ω and 30 Ω L-L and 300 Ω L-G transition resistances is presented in Tables 8 and 9. Because the influence of its branch coefficients, errors of simulation results are larger than fault line detection method 1 but still small because the angle of system resistance are close to that of the line.

Four-summing positive sequence current is used as a reference current for three-phase fault cross double lines. Simulation results of these fault type with 0 Ω and 30 Ω L-L and 300 Ω L-G transition resistances are shown in Tables 10 and 11. Because of the influence of its branch coefficients and load currents, errors of simulation results are up to 18.3°, which are much larger than fault line detection method 1 and 2.

The above simulation results shown in Tables 4 - Table 11 are all under the following scenarios: the angle between system source M and N is set as 30°for simulating a certain load current; the fault locations are all at the middle of the line。For the full verification of the fault line detection methodology, lots of simulations were carried out while

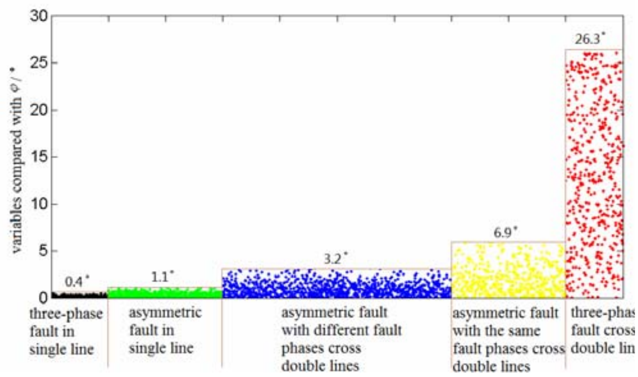


Fig. 6. Variables compared with φ in different fault types and conditions

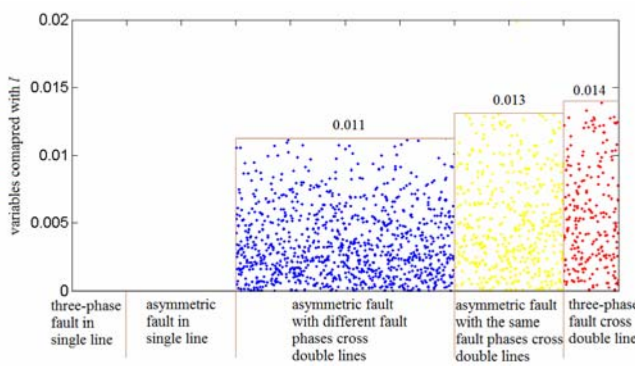


Fig. 7. The Variables compared with l in different fault types and conditions

angle between system source M and N is set as 0°, 15°, 30°and 45°, fault location is set as 0 km, 20 km, 40 km, 60 km and 100 km, and transition resistance is set as 0 Ω, 15 Ω, and 30 Ω for L-L fault and 0 Ω, 100 Ω, 200 Ω, 300 Ω for L-G fault. For different typical fault types mentioned in Fig. 2, simulations were carried out through multiple-run-model in PSCAD. The variables used to compare with the setting φ and l in Figs. 2-5 are calculated and recorded in order to identify the fault line(s). The summary of simulation result is shown in Fig. 6.

All the points shown in Figs. 6 and 7 are the calculated variables compared with *the* setting φ or *l*. the maximum value is shown for these variables in different fault types in Fig. 2. It can be known from Fig. 6 that the maximum value compared with φ is among the variables used for three-phase fault cross double lines, because it is affected by branch coefficients and load currents. However, the methodology can work well with that error, for φ can be set as 90°at most for non-overlapping area of fault line detection. Variables compared with *l* are very small in different fault types because they are not affected by branch coefficients, load currents and fault locations. Therefore, *l* can be set as a small value such as 0.1 to identify if the calculated variables are 0.

6.3 Simulation results of fault in unbalanced four parallel transmission lines on the same tower

Conductors of four parallel transmission lines on the same tower may not be transposed because of short length in actual situation, so lots of simulations are carried out on four parallel transmission lines without uniform transposition. From the simulation results, it is known that a certain error exists between results of simulation and theoretical analysis, but the three methods can operate accurately with reasonable setting values.

7. Conclusion

Based on the characteristics of four-summing and double-differential sequence components of fault currents, fault line detection methodology of parallel transmission lines on the same tower is proposed. Types of fault are identified first and then different methods are presented respectively for asymmetric or three-phase fault in single line, asymmetric fault with different fault phases cross double lines and asymmetric or three-phase fault with same fault phase(s) cross double lines. Because terminal currents are used for the raised methodology, the effect of branch coefficient is analyzed for each different method according to fault types. Lots of Simulation is done in EMTDC and it is shown that the method can operate correctly and reliably for all the fault types in single line or cross double lines under conditions of different load current, transient resistance and fault location.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC) (No. 51207102, No. 51277130)

References

[1] Jianguo Xu, "Investigation and analysis on transmission line technique of EHV multiple-circuit on the same tower abroad," *Electric Power Construction*, vol. 22, no. 7, pp. 15-18, Jul. 2001.

[2] Aihua. Huang, Xu Zheng, and Guangzhong Qian, "Application of technology of constructing multiple circuits on the same tower," *East China Electric Power*, vol. 34, no. 8, pp. 60-63, Aug. 2006.

[3] J. M. Zhang and R. L. Ge, "Features and application of power transmission technology of multi-circuit lines on the same tower," *East China Electric Power*, vol. 33, no. 7, pp. 23-26, Jul. 2005.

[4] Bingyi Zhang, Xiaohui Wang, Min Zhao, et al "Analysis of Ecological Environment for 500kV Four Circuits Power Transmission Lines on Same Tower," *in International Conference on Power System Technology* , Chongqing, China, 2006.

[5] Yu. Tian, Chunju Fan, and Zhendong Gong, "Twelve-sequence component method of four-parallel lines on same towers," *Automation of Electric Power Systems*, vol.31, no.21, pp.35-39, 105, Nov. 2007.

[6] Menghua Deng, Chunju Fan, Ling Liu, Qiaojun Shu, Zhengdong Gong and Qi Tu, "Calculation of short circuit fault of four jointed parallel lines on the same tower based on twelve-sequence components," *Automation of electric power system*, vol. 32, no. 14, pp. 64-67, Jul. 2008.

[7] Peng Xu, Gang Wang, Haifeng Li, Yuansheng Liang and Pu Zhang, "A short-circuit fault calculation scheme for four-parallel transmission lines," *Power and Energy Engineering Conference,* Chengdu, China, 2010.

[8] Qiaojun Shu, Songshi Chen, Chunju Fan, and, Hengyuan Bai "A new method of fault line selection for incomplete-journey four-jointed parallel line on the same tower," *Power System Protection and Control*, vol.38, no.19, pp.131-136, Oct. 2010.

[9] Bhalja Bhavesh, R P Maheshwari, "Trends in adaptive distance protection of multi-terminal and double-circuit lines," *Electric Power Components and Systems*, vol. 34, no. 7, pp. 603-617, Jun. 2006.

[10] Menghua Deng, Chunju Fan, Qiaojun Shu, Ling Liu, Zhengdong Gong, and Qi Tu, "Method for fault line selection of four jointed parallel lines on the same tower," *Automation of Electric Power Systems*, vol. 32, no. 15, pp. 57-60, Aug. 2008.

[11] Menghua Deng, Chunju Fan, Ming Zong, Chun HuaNi,

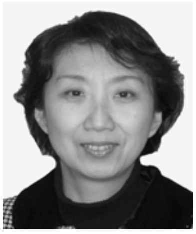
Zhenping Yan and Jiaqing Zong, "New faulted phase selecting method for four transmission lines on the same tower based on loop flow com-ponent," Power System Protection and Control, vol. 40, no.1, pp.138-144, Jan. 2012.

[12] Peng Xu, Gang Wang, Haifeng Li, Yuansheng Liang and Pu Zhang, "A new method for fault line selection of four-parallel transmission lines," *Power and Energy Engineering Conference*, Chengdu, China, 2010.

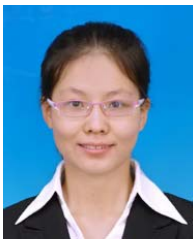
[13] Bongtong Li, Yongli Li, and Li Chen, "Method for parameter decoupling and fault analysis of four-circuit transmission lines on the same tower," *Power System Protection and Control*, vol. 38, no. 19, pp. 1-9, Oct. 2010.

[14] Zhipeng Su, Pingping Wang, Zheng Yang and Zhenyu Xu, "Method for parameter decoupling for four-circuit transmission lines on the same tower," *Power and Energy Engineering Conference*, Shanghai, China, 2010.

Bong-Tong Li He received PH.D. degree in electrical engineering and automation from Tianjin university, Tianjin China. He is a lecturer in School of electrical and automation, Tianjin University, China. His research interests are power system protection and control.



Yongli Li was born in Hebei, China, in 1963. She received the B.S. degree and M.S. degree in Electrical Engineering from Tianjin University, China, in 1984 and 1987, respectively. In1993, she received the Ph.D degree in Electrical Engineering from Universite Libre de Bruxelles, Belgium. Dr. Li is currently a Professor in the Department of Electrical Engineering and Automation, Tianjin University, and also a member of CIGRE SC-B5. Her research interests include fault analysis of power system and fault diagnosis of electrical equipment, protection and adaptive reclosing of EHV/UHV transmission system, protection and control of the microgrid and distribution network.



Chuang Yao was born in Shanxi China, in January 1989. She received her master degree in electrical engineering and automation at Tianjin University in 2013, and her research interests are power system protection and control.

APPENDIX

Table 4. Simulation results of three-phase fault in single line

Fault types		$\arg(\dot{I}'_{F1}/\dot{I}_{F1})$		$\arg(\dot{I}''_{F1}/\dot{I}_{F1})$	
		Fault with 0 Ω transition resistance	Fault with 30 Ω L-L and 300 Ω L-G transition resistance	Fault with 0 Ω transition resistance	Fault with 30 Ω L-L and 300 Ω L-G transition resistances
line Ⅰ	Ⅰ ABCG	0.345°	0.168°	0.345°	0.168°
line Ⅱ	Ⅱ ABCG	180.345°	180.168°	180.345°	180.168°
line Ⅲ	ⅢABCG	-180.342°	-180.165°	-0.342°	-0.165°
line Ⅳ	ⅣABCG	-0.342°	-0.165°	-180.342°	-180.165°

Table 5. Simulation results of asymmetric fault in single line

Fault types		$\arg(\dot{I}'_{F2}/\dot{I}_{F2})$		$\arg(\dot{I}''_{F2}/\dot{I}_{F2})$	
		fault with 0 Ω transition resistance	Fault with 30 Ω L-L and 300 Ω L-G transition resistances	Fault with 0 Ω transition resistance	Fault with 30 Ω L-L and 300 Ω L-G transition resistances
line Ⅰ	Ⅰ AG	0.067°	0.068°	0.067°	0.068°
	Ⅰ BCG	0.068°	0.067°	0.068°	0.067°
	Ⅰ BC	0.067°	0.067°	0.067°	0.067°
line Ⅱ	Ⅱ AG	180.068°	180.067°	180.068°	180.067°
	Ⅱ BCG	-179.935°	-179.933°	-179.935°	-179.933°
	Ⅱ BC	-179.933°	-179.933°	-179.933°	-179.933°
line Ⅲ	ⅢAG	180.067°	-180.067°	-0.067°	-0.067°
	ⅢBCG	179.932°	179.933°	-0.068°	-0.067°
	ⅢBC	179.933°	179.933°	-0.067°	-0.067°
line Ⅳ	ⅣAG	-0.067°	-0.067°	-180.067°	-180.067°
	ⅣBCG	-0.067°	-0.067°	179.933°	179.933°
	ⅣBC	-0.067°	-0.067°	179.933°	179.933°

Table 6. Simulation results of asymmetric fault with different fault phases cross double lines with 0 Ω transition resistances

Fault types		$\lvert \dot{I}'_{F2}/\dot{I}_{F2} \rvert$	$\lvert \dot{I}''_{F2}/\dot{I}_{F2} \rvert$	$\arg(\dot{I}'_{F2}/\dot{I}_{F2})$	$\arg(\dot{I}''_{F2}/\dot{I}_{F2})$
Ⅰ & Ⅱ	Ⅰ A-Ⅱ BG	1.413	1.413	270.419°	270.419°
	Ⅰ A-Ⅱ BCG	26.793	26.793	-184.248°°	-184.248°
	Ⅰ A-Ⅱ ABCG	8.202	8.202	-0.039°	-0.039°
	Ⅰ BC-Ⅱ ABCG	8.202	8.202	-0.039°	-0.039°
Ⅰ &Ⅲ	Ⅰ A-ⅢBG	0.729	0.999	-270.072°	-0.024°
	Ⅰ A-ⅢBCG	0.023	1	176.765°	-0.002°
	Ⅰ A-ⅢABCG	0.119	1	1.479°	0.008°
	Ⅰ BC-ⅢABCG	0.119	1	1.479°	0.008°
Ⅰ &Ⅳ	Ⅰ A-ⅣBG	0.999	0.702	-0.023°	270.057°
	Ⅰ A-ⅣBCG	1	0.049	-0.003°	180.598°
	Ⅰ A-ⅣABCG	1	0.119	0.008°	1.479°
	Ⅰ BC-ⅣABCG	1	0.119	0.008°	1.479°
Ⅱ &Ⅲ	Ⅱ A-ⅢBG	0.999	0.702	-180.023°	-90.259°
	Ⅱ A-ⅢBCG	1	0.049	179.997°	0.598°
	Ⅱ A-ⅢABCG	1	0.119	180.008°	181.479°
	Ⅱ BC-ⅢABCG	1	0.119	-179.992°	-178.521°
Ⅱ &Ⅳ	Ⅱ A-ⅣBG	0.729	0.999	-90.073°	-180.024°
	Ⅱ A-ⅣBCG	0.023	1	-3.233°	179.998°
	Ⅱ A-ⅣABCG	0.119	1	181.479°	180.008°
	Ⅱ BC-ⅣABCG	0.119	1	-178.520°	-179.993°
Ⅲ&Ⅳ	ⅢA-ⅣBG	1.403	1.403	90.414°	-89.586°
	ⅢA-ⅣBCG	29.213	29.213	-4.127°	175.873°
	ⅢA-ⅣABCG	8.427	8.427	-181.534°	-1.538°
	ⅢBC-ⅣABCG	8.426	8.426	178.461°	-1.538°

Table 7. Simulation results of asymmetric fault with different fault phases cross double lines with 30 Ω L-L and 300 Ω L-G transition resistances

Fault types		$\lvert \dot{I}'_{F2}/\dot{I}_{F2} \rvert$	$\lvert \dot{I}''_{F2}/\dot{I}_{F2} \rvert$	$\arg(\dot{I}'_{F2}/\dot{I}_{F2})$	$\arg(\dot{I}''_{F2}/\dot{I}_{F2})$
Ⅰ & Ⅱ	Ⅰ A-Ⅱ BG	0.620	0.620	-86.534°	-86.534°
	Ⅰ A-Ⅱ BCG	38.147	38.147	-226.044°	-226.044°
	Ⅰ A-Ⅱ ABCG	2.033	2.033	45.496°	45.496°
	Ⅰ BC-Ⅱ ABCG	2.033	2.033	45.496°	45.496°
Ⅰ &Ⅲ	Ⅰ A-ⅢBG	1.609	0.998	86.649°	-0.046°
	Ⅰ A-ⅢBCG	0.016	1	219.235°	-0.001°
	Ⅰ A-ⅢABCG	0.490	1	-45.705°	-0.034°
	Ⅰ BC-ⅢABCG	0.490	1	-45.705°	0.034°
Ⅰ &Ⅳ	Ⅰ A-ⅣBG	0.998	1.609	-0.046°	86.545°
	Ⅰ A-ⅣBCG	1	0.035	-0.001°	222.465°
	Ⅰ A-ⅣABCG	1	0.490	-0.034°	-45.705°
	Ⅰ BC-ⅣABCG	1	0.490	0.034°	-45.705°
Ⅱ &Ⅲ	Ⅱ A-ⅢBG	0.998	1.609	179.954°	266.545°
	Ⅱ A-ⅢBCG	1	0.035	179.999°	42.465°
	Ⅱ A-ⅢABCG	1	0.490	180.034°	134.295°
	Ⅱ BC-ⅢABCG	1	0.490	-179.966°	-225.705°
Ⅱ &Ⅳ	Ⅱ A-ⅣBG	1.609	0.998	266.649°	179.954°
	Ⅱ A-ⅣBCG	0.016	1	39.235°	180.000°
	Ⅱ A-ⅣABCG	0.490	1	134.295°	180.034°
	Ⅱ BC-ⅣABCG	0.490	1	-225.705°	-179.966°
Ⅲ&Ⅳ	ⅢA-ⅣBG	0.620	0.620	-266.698°	-86.698°
	ⅢA-ⅣBCG	41.520	41.520	-46.325°	133.676°
	ⅢA-ⅣABCG	2.042	2.042	-134.328°	45.672°
	ⅢBC-ⅣABCG	2.041	2.041	225.672°	45.672°

Table 8. Simulation results of asymmetric fault with the same fault phases cross double lines with 0 Ω transition resistances

Fault types		$\lvert\dot{I}_{F2}/\dot{I}_{T2}\rvert$	$\lvert\dot{I}'_{F2}/\dot{I}_{T2}\rvert$	$\lvert\dot{I}''_{F1}/\dot{I}_{T2}\rvert$	$\arg(\dot{I}_{F2}/\dot{I}_{T2})$	$\arg(\dot{I}'_{F2}/\dot{I}_{T2})$	$\arg(\dot{I}''_{F2}/\dot{I}_{T2})$
Ⅰ&Ⅱ	ⅠA-ⅡAG	1.048	0	0	-0.246	--	--
	ⅠBC-ⅡBCG	1.048	0	0	-0.246	--	--
	ⅠBC-ⅡBC	1.048	0	0	-0.246	--	--
Ⅰ&Ⅲ	ⅠA-ⅢAG	0.014	1.048	0.015	--	-0.179	--
	ⅠBC-ⅢBCG	0.023	1.049	0.025	--	-0.180	--
	ⅠBC-ⅢBC	0.020	1.048	0.021	--	-0.179	--
Ⅰ&Ⅳ	ⅠA-ⅣAG	0.012	0.013	1.048	--	--	-0.179
	ⅠBC-ⅣBCG	0.024	0.025	1.049	--	--	-0.180
	ⅠBC-ⅣBC	0.020	0.021	1.048	--	--	-0.180
Ⅱ&Ⅲ	ⅡA-ⅢAG	0.012	0.013	1.047	--	--	179.821
	ⅡBC-ⅢBCG	0.024	0.025	1.049	--	--	-180.180
	ⅡBC-ⅢBC	0.020	0.021	1.048	--	--	-180.180
Ⅱ&Ⅳ	ⅡA-ⅣAG	0.014	1.047	0.015	--	179.821	--
	ⅡBC-ⅣBCG	0.023	1.049	0.025	--	-180.179	--
	ⅡBC-ⅣBC	0.020	1.048	0.021	--	-180.180	--
Ⅲ&Ⅳ	ⅢA-ⅣAG	1.047	0	0	179.887	--	--
	ⅢBC-ⅣBCG	1.048	0	0	-180.113	--	--
	ⅢBC-ⅣBC	1.048	0	0	-180.113	--	--

Table 9. Simulation results of asymmetric fault with the same fault phases cross double lines with 30 Ω L-L and 300 Ω L-G transition resistances

Fault types		$\lvert\dot{I}_{F2}/\dot{I}_{T2}\rvert$	$\lvert\dot{I}'_{F2}/\dot{I}_{T2}\rvert$	$\lvert\dot{I}''_{F2}/\dot{I}_{T2}\rvert$	$\arg(\dot{I}_{F2}/\dot{I}_{T2})$	$\arg(\dot{I}'_{F2}/\dot{I}_{T2})$	$\arg(\dot{I}''_{F2}/\dot{I}_{T2})$
Ⅰ&Ⅱ	ⅠA-ⅡAG	1.051	0	0	-0.246	--	--
	ⅠBC-ⅡBCG	1.048	0	0	-0.245	--	--
	ⅠBC-ⅡBC	1.048	0	0	-0.246	--	--
Ⅰ&Ⅲ	ⅠA-ⅢAG	0.005	1.046	0.005	--	-0.180	--
	ⅠBC-ⅢBCG	0.005	1.048	0.004	--	-0.180	--
	ⅠBC-ⅢBC	0.005	1.048	0.005	--	-0.180	--
Ⅰ&Ⅳ	ⅠA-ⅣAG	0.005	0.005	1.046	--	--	-0.180
	ⅠBC-ⅣBCG	0.005	0.004	1.048	--	--	-0.179
	ⅠBC-ⅣBC	0.005	0.004	1.048	--	--	-0.180
Ⅱ&Ⅲ	ⅡA-ⅢAG	0.005	0.005	1.046	--	--	179.821
	ⅡBC-ⅢBCG	0.005	0.004	1.048	--	--	-180.179
	ⅡBC-ⅢBC	0.005	0.004	1.048	--	--	-180.180
Ⅱ&Ⅳ	ⅡA-ⅣAG	0.005	1.046	0.005	--	179.821	--
	ⅡBC-ⅣBCG	0.005	1.048	0.004	--	-180.180	--
	ⅡBC-ⅣBC	0.005	1.048	0.004	--	-180.180	--
Ⅲ&Ⅳ	ⅢA-ⅣAG	1.045	0	0	179.887	--	--
	ⅢBC-ⅣBCG	1.047	0	0	-180.113	--	--
	ⅢBC-ⅣBC	1.047	0	0	-180.113	--	--

Table 10. Simulation results of three-phase fault cross double lines with 0 Ω transition resistances

Fault types		$\lvert\dot{I}_{F1}/\dot{I}_{T1}\rvert$	$\lvert\dot{I}'_{F1}/\dot{I}_{T1}\rvert$	$\lvert\dot{I}''_{F1}/\dot{I}_{T1}\rvert$	$\arg(\dot{I}_{F1}/\dot{I}_{T1})$	$\arg(\dot{I}'_{F1}/\dot{I}_{T1})$	$\arg(\dot{I}''_{F1}/\dot{I}_{T1})$
Ⅰ&Ⅱ	ⅠABC-ⅡABCG	1.054	0	0	18.049	--	--
Ⅰ&Ⅲ	ⅠABC-ⅢABCG	0.020	1.052	0.021	--	-17.707	--
Ⅰ&Ⅳ	ⅠABC-ⅣABCG	0.020	0.021	1.052	--	--	-17.707
Ⅱ&Ⅲ	ⅡABC-ⅢABCG	0.020	0.021	1.052	--	--	162.293
Ⅱ&Ⅳ	ⅡABC-ⅣABCG	0.020	1.052	0.021	--	162.293	--
Ⅲ&Ⅳ	ⅢABC-ⅣABCG	1.056	0	0	162.633	--	--

Table 11. Simulation results of three-phase fault cross double lines with 30 Ω L-L and 300 Ω L-G transition resistances

Fault types		$\lvert \dot{I}_{F1} / \dot{I}_{T1} \rvert$	$\lvert \dot{I}'_{F1} / \dot{I}_{T1} \rvert$	$\lvert \dot{I}''_{F1} / \dot{I}_{T1} \rvert$	$\arg(\dot{I}_{F1} / \dot{I}_{T1})$	$\arg(\dot{I}'_{F1} / \dot{I}_{T1})$	$\arg(\dot{I}''_{F1} / \dot{I}_{T1})$
Ⅰ&Ⅱ	ⅠABC-ⅡABCG	0.894	0	0	-17.425	--	--
Ⅰ&Ⅲ	ⅠABC-ⅢABCG	0.010	0.899	0.004	--	-17.174	--
Ⅰ&Ⅳ	ⅠABC-ⅣABCG	0.010	0.004	0.899	--	--	-17.174
Ⅱ&Ⅲ	ⅡABC-ⅢABCG	0.010	0.004	0.899	--	--	162.826
Ⅱ&Ⅳ	ⅡABC-ⅣABCG	0.010	0.899	0.004	--	162.826	--
Ⅲ&Ⅳ	ⅢABC-ⅣABCG	0.904	0	0	163.073	--	--