

A New Principle of Fault Identification of on the Same Tower Based on Traveling Wave Reactive Powers

Hao Wu^{1*}, Ruikai Ye¹, Xingxing Dong¹, Kunjian Yu¹, Zhengwei Chang²

¹School of Electrical Automation and Information Engineering, Sichuan University of Science and Engineering, Zigong, China

²Electric Power Research Institute, Sichuan Electric Power Company of China Power Grid, Chengdu, China

Email: *wuhao801212@163.com

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Abstract

In order to improve the reliability of fault identification of the double-circuit transmission lines on the same tower, a new algorithm for fast protection of double-circuit transmission lines on the same tower based on the reactive powers of traveling wave is proposed. With the implementation of S-transform, the initial traveling wave reactive powers are calculated and the change characteristics of reactive power under different fault conditions are studied. The protection criterion is constructed by analyzing the ratio of the reactive powers of the same end on double-circuit transmission lines and the ratio of the reactive powers at both ends on the same line. According to the ratio of reactive power on the same side of the line and both ends of the same line, it is possible to identify whether the faults of the double-circuit line of the same tower occurred in or out of the protection zone. A large number of simulation results show that the protection performance is sensitive and reliable, and quick to respond. The criterion is simple and is basically not affected by fault initial angles, fault types, and transitional resistances.

Keywords

Double-Circuit Transmission Line on the Same Tower, Traveling Wave Reactive Power, S-Transform, Fault Identification

1. Introduction

With the advantages of saving investment cost and effectively improving power transmission capacity, the double circuit transmission lines on the same tower have been widely used in China's high-voltage power grid in [1]. However, the distance between the double circuit transmission lines is short due to the sharing

of the same tower, which leads to more complex inter-phase coupling and inter-line coupling compared with what happened to single circuit transmission line. The transmission line protection scheme on single circuit transmission line is not applicable to double circuit transmission lines on the same tower, so many scholars have made a lot of research on the protection scheme of the double circuit line on the same tower.

The literature [2]-[8] mainly studies the protection and the fault phase selection of the double circuit transmission lines on the same tower based on power frequency, which has a slight deficiency in the response time. In [9], a fault locating method using single-ended impedance is proposed, which has high robustness, however, when a cross-line fault of the same name occurs, the fault location accuracy rate was not high. The literature [10] uses the circuit line protection scheme of the single-ended transient main frequency to satisfy the requirement of rapidity, but its reliability depends on too many factors. The literature [11] proposed the concept of the modal differential transverse current, and quoted the concept of constructing the line fault diagnosis criterion, which can accurately identify the internal and external faults, but the ability to identify the complex faults is still insufficient. In [12], the fault current traveling wave characteristics on the double-circuit line on the same tower are analyzed, but no specific circuit protection scheme is proposed. The literature [13] used the characteristics of inconsistent traveling wave speeds when a metallic fault on the same tower occurred and proposed a differential protection scheme for traveling wave on the same tower double circuit line. The sensitivity and rapidity of the scheme are relatively high.

Based on the research ideas of literature [14] [15] [16], this paper proposes a new fault identification principle based on reactive power of the traveling wave on double-circuit lines on the same tower. The S-transform is used to extract the single-frequency initial voltage and current traveling wave after the fault occurs. The initial traveling wave reactive power is calculated using initial voltage and current traveling wave. The fault identification principle identifies the internal and external faults according to the ratio of the reactive power of the same ends of the line and both the ends of the same line. The experimental simulation results show that the program provides a quick response, high identification accuracy and sensitivity.

2. Analysis of Fault Current Traveling Wave of Double Circuit Line on The same Tower

Figure 1 is the model of double-circuit lines on the same tower, busbar M and N are connected to the transmission lines, MN is the double-circuit line protection zone, PM section and NO section are outside the protection zone and $R_1 \sim R_6$ are corresponding traveling wave protection units.

The forward direction of the traveling wave is defined as the direction from the bus to the double circuit. Taking the traveling wave protection unit R_1 as an example, suppose that u and i are respectively the voltage and current traveling

waves detected by R_1 . If t_0 is the traveling wave arrives at bus M from the fault point for the first time, t_1 is the second time the traveling wave arrives at M after the wave reflection occurs, then the fault traveling wave acquired by R_1 is called the initial voltage and current traveling wave in time-slot $t_0 \sim t_1$ in [14].

2.1. Fault of Single-Circuit Transmission Line in the Area

A fault occurs at point K_1 on the double-circuit line on the same tower, according to Peterson principle in [14], the fault feature can be simplified as shown in Figure 2, and Figure 2(a) & Figure 2(b) are respectively models of traveling wave propagating to bus M and to bus N. $\Delta \dot{I}_k$ ($k=1,2,3,4,5,6$) in the figure shows the fault current traveling wave detected by the corresponding traveling wave protection unit on the double-circuit line of the same tower; $\Delta \dot{U}_M$ and $\Delta \dot{U}_N$ are the initial voltage traveling wave on busbar M and busbar N; $Z_{c1} \sim Z_{c4}$ are respectively the corresponding wave impedance of line $L_1 \sim L_4$, and Z_{cM} and Z_{cN} are the ground stray capacitance equivalent impedance of busbar M and busbar N respectively.

According to [14], in Peterson equivalent circuit, when the traveling wave frequency $f = 50 - 100$ kHz, the wave impedance of the extra (ultra) high-voltage transmission line approximates to a real constant and can be equivalent to resistance R . Therefore, the impedance in Figure 2 approximates to $Z_{c1} = Z_{c2} = Z_{c3} = Z_{c4} \approx R$. $Z_{cM} = 1/j\omega C_M = 1/j2\pi C_M$ is the ground equivalent capacitance wave impedance of the busbar. Take the direction in which the traveling wave propagates to the bus M as an example result at the equation of:

$$\Delta \dot{I}_1 = -\frac{\Delta \dot{U}_M}{Z_{c2} \parallel Z_{c3} \parallel Z_{cM}} \approx -\Delta \dot{U}_M \cdot \frac{2 + j\omega C_M R}{R} \tag{1}$$

$$\Delta \dot{I}_2 = \frac{\Delta \dot{U}_M}{Z_{c2}} \approx \frac{\Delta \dot{U}_M}{R} \tag{2}$$

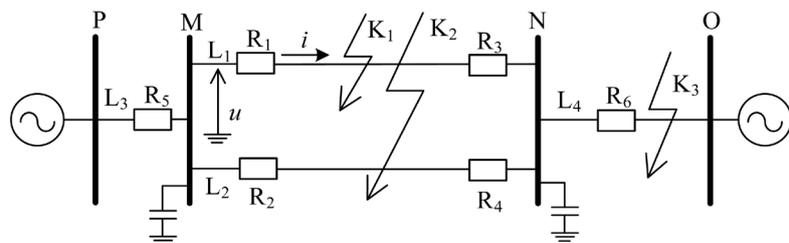


Figure 1. Simplified model of double-circuit transmission lines on the same tower.

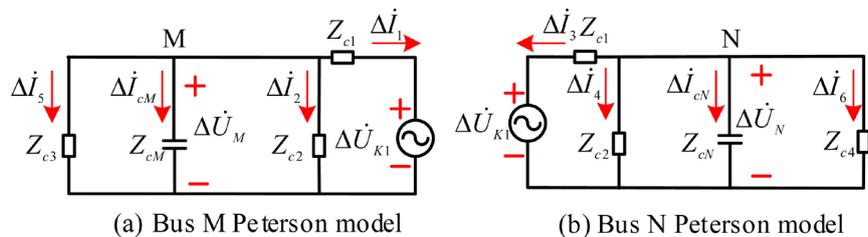


Figure 2. Peterson model of single-line fault in the zone.

According to circuit theory, the complex power $\tilde{S} = U \cdot I^* = P + jQ$, where P is the active power and Q is the reactive power, the traveling wave complex power obtained at the Bus M is:

$$\begin{cases} \tilde{S}_1 = \Delta \dot{U}_M \cdot \Delta \dot{I}_M^* \approx -\frac{2\Delta U_M^2}{R} + j \cdot \Delta U_M^2 \cdot \omega C_M = P_1 + jQ_1 \\ \tilde{S}_2 = \Delta \dot{U}_M \cdot \Delta \dot{I}_N^* \approx \frac{\Delta U_M^2}{R} = P_2 + jQ_2 \end{cases} \quad (3)$$

The corresponding initial traveling wave reactive power can be obtained as follows:

$$\begin{cases} Q_1 \approx \Delta U_M^2 \cdot \omega C_M \\ Q_2 \approx 0 \end{cases} \quad (4)$$

According to the calculation, the ratio of reactive power of the initial traveling wave on the M side of the double-circuit transmission line of the same tower is:

$$\lambda = \frac{\max(|Q_1|, |Q_2|)}{\min(|Q_1|, |Q_2|)} = \frac{\Delta U_M^2 \cdot \omega C_M}{0} \rightarrow \infty \quad (5)$$

In other words, the reactive power ratio λ of the double circuit transmission line on the same side is a large number when the single circuit fault occurs in the fault area, and the fault can be clearly identified by utilizing this feature.

2.2. Same Name Phase Cross Line Ground Faults in the Area

A same-name phase cross line ground fault occurs at point K_2 on the same-tower double-circuit line. The Peterson model of the transmission line is shown in **Figure 3**.

The traveling wave of each current can be obtained as follows:

$$\begin{cases} \Delta \dot{I}_k = -\frac{1}{2} \cdot \frac{\Delta \dot{U}_{K_2}}{(Z_{c3} // Z_{cM} + Z_{c1} // Z_{c2})} = -\frac{\Delta \dot{U}_{K_2} (1 + j\omega C_M R)}{3R + j\omega C_M R^2} (k = 1, 2) \\ \Delta \dot{I}_k = -\frac{1}{2} \cdot \frac{\Delta \dot{U}_{K_2}}{(Z_{c4} // Z_{cN} + Z_{c1} // Z_{c2})} = -\frac{\Delta \dot{U}_{K_2} (1 + j\omega C_N R)}{3R + j\omega C_N R^2} (k = 3, 4) \end{cases} \quad (6)$$

The complex power of the transmission line is:

$$\begin{cases} \tilde{S}_k = \Delta \dot{U}_{K_2} \cdot \Delta \dot{I}_k^* = P_k + jQ_k (k = 1, 2) \\ = -\frac{\Delta U_{K_2}^2 \cdot (3R + \omega^2 C_M^2 R^3)}{9R^2 + \omega^2 C_M^2 R^4} + j \cdot \frac{2\Delta U_{K_2}^2 \omega C_M R^2}{9R^2 + \omega^2 C_M^2 R^4} \\ \tilde{S}_k = \Delta \dot{U}_{K_2} \cdot \Delta \dot{I}_k^* = P_k + jQ_k (k = 3, 4) \\ = -\frac{\Delta U_{K_2}^2 \cdot (3R + \omega^2 C_N^2 R^3)}{9R^2 + \omega^2 C_N^2 R^4} + j \cdot \frac{2\Delta U_{K_2}^2 \omega C_N R^2}{9R^2 + \omega^2 C_N^2 R^4} \end{cases} \quad (7)$$

The reactive power of the same end of the double circuit line is:

$$\begin{cases} \text{BusM} \begin{cases} Q_1 = Q_2 \approx \frac{2\Delta U_{K_2}^2 \omega C_M R^2}{9R^2 + \omega^2 C_M^2 R^4} \end{cases} \\ \text{BusN} \begin{cases} Q_3 = Q_4 \approx \frac{2\Delta U_{K_2}^2 \omega C_N R^2}{9R^2 + \omega^2 C_N^2 R^4} \end{cases} \end{cases} \quad (8)$$

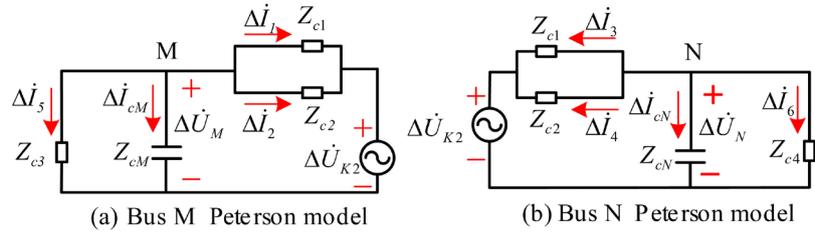


Figure 3. Peterson model of Same-name phase cross line ground fault in protection zone

The reactive powers on the same side of the line are approximately equal. And the ratio of the reactive powers is approximately one.

Take line L_1 as an example, the reactive power ratio at both ends of the same line can be derived as:

$$\lambda = \frac{\max(|Q_1|, |Q_3|)}{\min(|Q_1|, |Q_3|)} = \frac{2\Delta U_{K_2}^2 \omega C_M R^2}{9R^2 + \omega^2 C_M^2 R^4} \cdot \frac{9R^2 + \omega^2 C_N^2 R^4}{2\Delta U_{K_2}^2 \omega C_N R^2} \tag{9}$$

$$= \frac{C_M (9 + \omega^2 C_N^2 R^2)}{C_N (9 + \omega^2 C_M^2 R^2)}$$

In formula (9), the value of λ is determined by the ground capacitance of busbar. Ideally, the ground capacitance of busbar at both ends of the double circuit transmission line are about the same size, so $\lambda \approx 1$.

2.3. Fault out the Area

When a fault occurs at point K_3 outside the protection zone, the line fault feature can be simplified to the Peterson model of Figure 4.

Each current traveling wave can be expressed as:

$$\begin{cases} \Delta i_k = -\frac{1}{2} \cdot \frac{\Delta \dot{U}_N}{(Z_{c3} \parallel Z_{cM} + Z_{c1} \parallel Z_{c2})} \approx -\frac{\Delta \dot{U}_N (1 + j\omega C_M R)}{3R + j\omega C_M R^2} (k = 1, 2) \\ \Delta i_k = \frac{\Delta \dot{U}_N}{Z_{ck}} \approx \frac{\Delta \dot{U}_N}{R} (k = 3, 4) \end{cases} \tag{10}$$

The complex power on the line can be expressed as:

$$\begin{cases} \tilde{S}_k = \Delta \dot{U}_N \cdot \Delta i_k^* = P_k + jQ_k (k = 1, 2) \\ = -\frac{\Delta U_N^2 \cdot (3R + \omega^2 C_M^2 R^3)}{9R^2 + \omega^2 C_M^2 R^4} + j \cdot \frac{2\Delta U_N^2 \omega C_M R^2}{9R^2 + \omega^2 C_M^2 R^4} \\ \tilde{S}_k = \Delta \dot{U}_N \cdot \Delta i_k^* = \frac{\Delta U_N^2}{R} = P_k + jQ_k (k = 3, 4) \end{cases} \tag{11}$$

When a fault occurs outside the protection zone, the reactive power of the

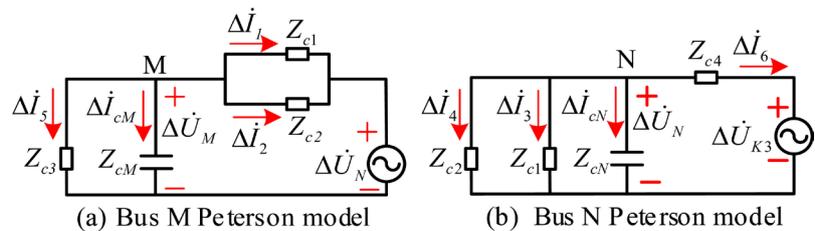


Figure 4. Peterson model of a fault occurred outside the zone.

traveling wave can be derived as:

$$\begin{cases} Q_1 = Q_2 \approx \frac{2\Delta U_N^2 \omega C_M R^2}{9R^2 + \omega^2 C_M^2 R^4} \\ Q_3 = Q_4 \approx 0 \end{cases} \quad (12)$$

The traveling wave reactive powers on the same end of the double-circuit transmission line on the same tower are approximately equal. Taking line L1 as an example, the reactive power ratio of initial travelling wave at both ends of the line is:

$$\lambda = \frac{\max(|Q_1|, |Q_3|)}{\min(|Q_1|, |Q_3|)} = \frac{\frac{2\Delta U_N^2 \omega C_M R^2}{9R^2 + \omega^2 C_M^2 R^4}}{0} \rightarrow \infty \quad (13)$$

When a fault occurs out of the protection zone, the reactive power on the bus near the fault location is approximately zero, and the reactive power of the busbar on the far side of fault location is non-zero. The reactive power ratio at both ends of the same line is a large number.

Based on the above analysis, it can be seen that when a fault occurs out of the protection zone, 1) the reactive power of traveling wave on the same side is approximately equal; 2) the ratio of reactive power of traveling wave on both ends of the same line is relatively large.

3. Algorithm Implementation

3.1. Phase Mode Transformation

There is a more complicated coupling in the double-circuit transmission line of the same tower than that of a single-circuit transmission line. There is coupling between the phases and between the lines, so the phase-mode transformation must be implemented to decouple before calculating the fault components. This paper chooses the decoupling transformation matrix resembling Clarke transformation matrix M in [2].

$$M = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & -\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 & 0 \\ 1 & 1 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 & 0 \\ 1 & -1 & 0 & 0 & 1 & 0 \\ 1 & -1 & 0 & 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 1 & -1 & 0 & 0 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (14)$$

The relationship between the six-phase current I and the modulus current I_m on the double-circuit transmission line on the same tower is:

$$I_m = M^{-1}I \quad (15)$$

In the formula, the components represented by I and I_m are:

$$I_m = [I_{I0} \quad I_{II0} \quad I_{I\alpha} \quad I_{II\alpha} \quad I_{I\beta} \quad I_{II\beta}] \tag{16}$$

$$I = [I_{IA} \quad I_{IB} \quad I_{IC} \quad I_{IIA} \quad I_{IIB} \quad I_{IIC}] \tag{17}$$

Similarly, relationship between the corresponding six-phase voltage U and the modulus voltage U_m is:

$$U_m = M^{-1}U \tag{18}$$

In the formula, the components represented by U and U_m are:

$$U_m = [U_{I0} \quad U_{II0} \quad U_{I\alpha} \quad U_{I\beta} \quad U_{II\alpha} \quad U_{II\beta}] \tag{19}$$

$$U = [U_{IA} \quad U_{IB} \quad U_{IC} \quad U_{IIA} \quad U_{IIB} \quad U_{IIC}] \tag{20}$$

In the formula, 0, α , β respectively represent the zero-modulus, α -modulus, and β -modulus components after the phase-mode transformation is implemented; subscripts I and II denote the I-circuit and the II-circuit transmission line of the double-circuit line on the same tower respectively.

3.2. S-Transform

S-transform is a method of signal time-frequency joint analysis, and it is the development of continuous wavelet transform and short-time Fourier transform. Assume the discrete time sequence of the signal $h(t)$ is $h[kT]$ ($k = 0, 1, 2, \dots, N-1$), where T is the time interval, and the discrete Fourier transform of $h[kT]$ is

$$H\left[\frac{n}{NT}\right] = \frac{1}{N} \sum_{k=0}^{N-1} h[kT] e^{-j\frac{2\pi nk}{N}} \tag{21}$$

where $n = 0, 1, \dots, N-1$.

When $n \neq 0$, the discrete S transform of time sequence $h[kT]$ can be derived as:

$$S\left[kT, \frac{n}{NT}\right] = \sum_{r=0}^{N-1} H\left[\frac{r+n}{NT}\right] e^{-\frac{2\pi^2 r^2}{n^2}} e^{j\frac{2\pi rk}{N}} \tag{22}$$

When $n = 0$, the discrete transformation of time series $h[kT]$ is a constant, which can be derived as:

$$S[kT, 0] = \frac{1}{N} \sum_{r=0}^{N-1} h\left(\frac{r}{NT}\right) \tag{23}$$

In formula (23), $k, n = 0, 1, \dots, N-1$. A two-dimensional time-frequency matrix of the signal $h[kT]$ is obtained with the implementation of S-transform. The rows in this matrix correspond to the sampling time of the signal and the columns correspond to discrete frequencies.

Because S-transform has good signal extraction characteristics in time-frequency analysis, this paper uses S-transform to extract fault current traveling wave and voltage traveling wave. Based on this, the corresponding complex power and reactive power are calculated.

3.3. Calculation of Initial Traveling Wave Reactive Power

Take the three-phase grounding fault occurred at point K_1 on line L_1 in **Figure 1** as an example. The fault current component is detected on protection unit R_1 , and Δi_1 is the combined-modulus current obtained using phase-mode transformation. Discrete S-transform is performed on the current modulus Δi_1 according to Equations (22) and (23). One-dimensional complex phasor is obtained at selected frequency f_z [14], which can be derived as:

$$\Delta \dot{I}_1(t, f_z) = \Delta I_1 \exp[j\theta_{\Delta I_1}] \quad (24)$$

where ΔI_1 , $\theta_{\Delta I_1}$ are the amplitude and phasor of the $\Delta \dot{I}_1(t, f_z)$ respectively. If at the time t_1 , the amplitude of the traveling wave head reaches a maximum value $\Delta I_{\max,1}$, the modulus current $\Delta \dot{I}_1(t_1, f_z)$ at this moment is the initial current traveling wave peak phasor at the selected frequency f_z in [16]. Similarly, the initial voltage traveling wave peak phasor $\Delta \dot{U}_M(t_1, f_z)$ of busbar M can be determined. According to the calculation formula of complex frequency, the faulted initial traveling wave complex frequency on line L_1 near M terminal can be obtained as:

$$\tilde{S}_1 = \Delta \dot{U}_M \cdot \Delta \dot{I}_1^* = P_1 + jQ_1 = \Delta U_M \cdot \Delta I_1 \exp[j(\theta_{\Delta U_M} - \theta_{\Delta I_1})] \quad (25)$$

Q_1 is the fault initial traveling wave reactive power on line L_1 on Busbar M. Similarly, the initial traveling wave reactive power Q_2 , Q_3 , Q_4 on other protection units can be calculated in the double-circuit line on the same-tower.

Based on the derivation above, the initial traveling wave reactive power detected by each protection unit of the double-circuit line on the same tower under different fault types can be calculated by using the initial traveling wave peak phasor obtained at the selected single frequency with the supplementation of S-transform.

PSCAD software was used to simulate the faults of $K_1 - K_3$. The fault data was imported into MATLAB for decoupling and S-transform. The corresponding waveform of the initial voltage and current traveling wave and initial traveling wave reactive power of protection units $R_1 - R_4$ were obtained.

For the single-circuit L_1 fault in double-circuit line on the same tower, the waveform of the initial voltage and current traveling wave and the waveform of the initial traveling wave reactive powers are shown in **Figure 5** and **Figure 6** respectively.

Analysis of **Figure 5** shows that when a single circuit transmission line fault occurs in the protection zone, the reactive power of fault line L_1 detected at bus M of the double-circuit line on the same tower is much greater than that of the non-fault transmission line L_2 . Similarly, the reactive power of the fault line L_1 detected at the bus N is also greater than that of the non-fault line L_2 .

In the case of the same-name phase cross line ground fault within double-circuit transmission line on the same tower, the waveform of the initial travelling wave reactive powers are shown in **Figure 7** and **Figure 8** respectively. The analysis

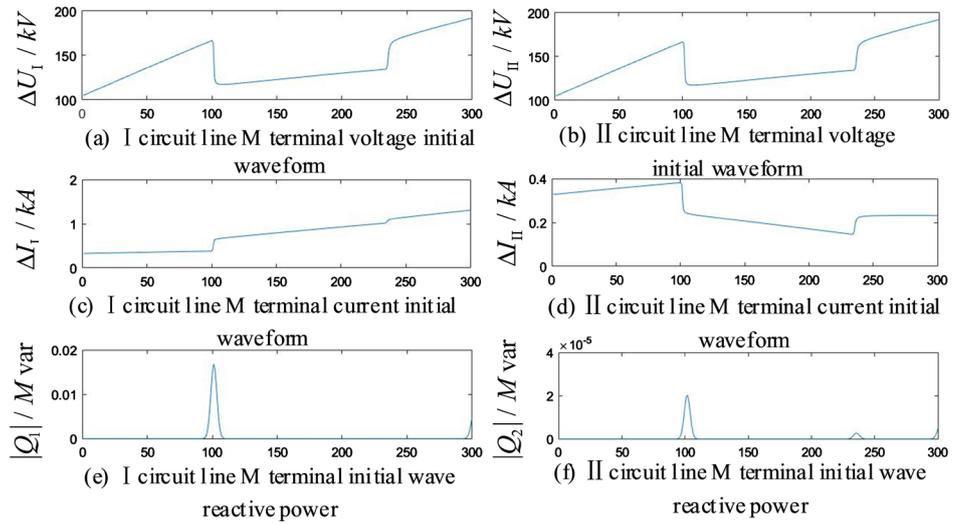


Figure 5. Waveform of single-circuit L_1 fault in the protection zone at Bus M.

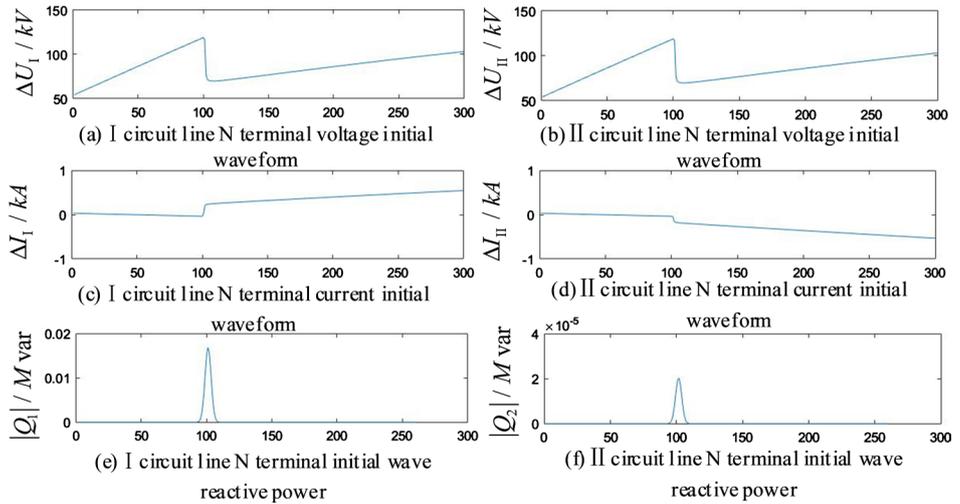


Figure 6. Waveform of single-circuit L_1 fault in the protection zone at Bus N.

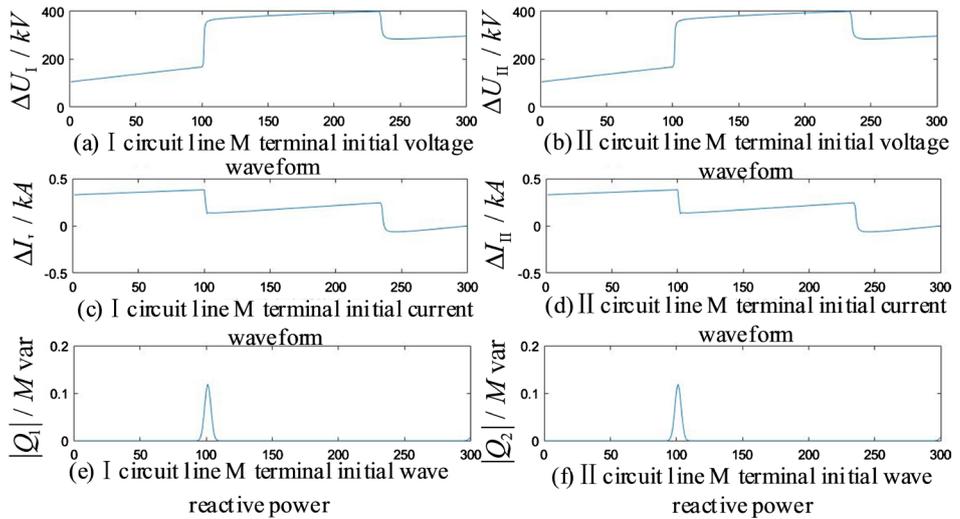


Figure 7. Waveform of same-name phase cross line ground fault in protection zone at Bus M.

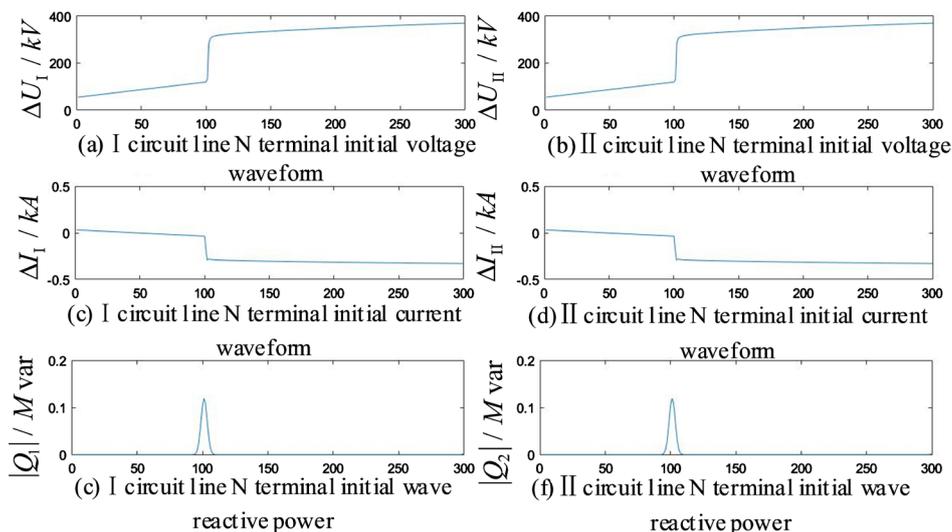


Figure 8. Waveform of same-name phase cross line ground fault in protection zone at Bus N.

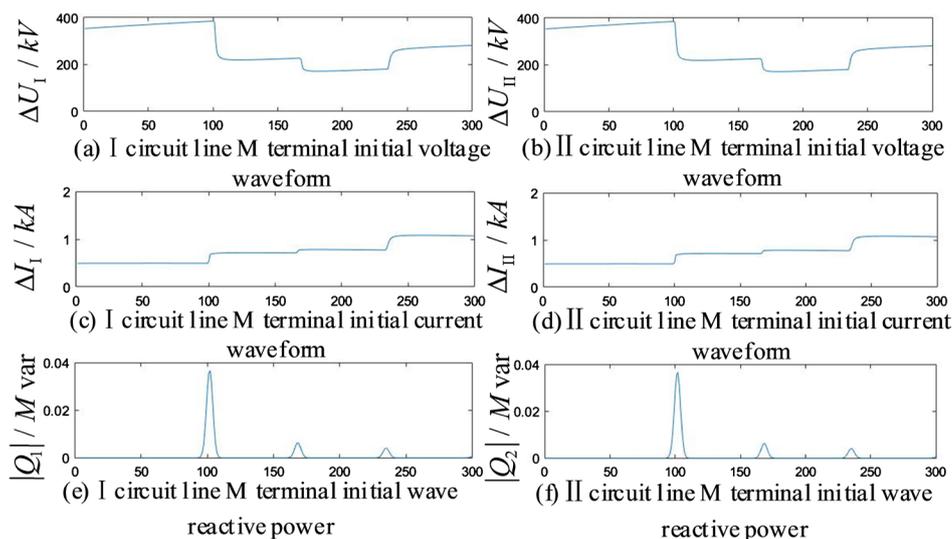


Figure 9. Waveform of the fault out of the protection zone at Bus M.

shows that the reactive power detected on the same end of the double circuit line is approximately equal, and the reactive power detected on both the ends of the same line is approximately equal.

When a fault occurs at point K_3 of the double-circuit line on the same tower, the waveform of the initial travelling wave reactive powers are shown in **Figure 9** and **Figure 10** respectively. Analysis of **Figure 9** and **Figure 10** shows that when a fault occurs out of the protection zone, the traveling wave reactive power on the same side of the double circuit line is approximately equal, and the reactive powers of the traveling wave at both ends of the same line vary significantly, and the reactive power of the traveling wave of the busbar near the fault is much greater than that of the traveling wave of the busbar far from the fault.

Based on the analysis above, when a fault occurs on the single-circuit transmission line in the protection zone, the ratio of the reactive power at the same

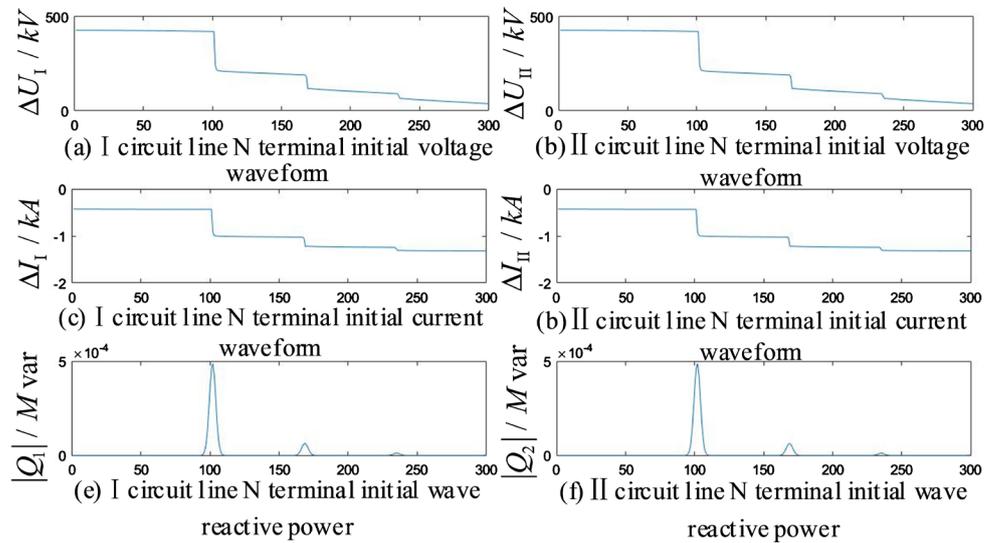


Figure 10. Waveform of the fault out of the protection zone at Bus N.

end of the two lines is big. When the same-name phase cross-line ground fault occurs in the protection zone, the reactive powers of the traveling wave of the same end of the two lines and both the ends of the same line are similar. When a fault occurs out of the protection zone, the reactive power of the same end of the two lines is approximately equal and the ratio is approximately 1; and the reactive power of the initial traveling wave at both the ends of the same line varies greatly, the ratio of the reactive powers is a large value. These changing characteristics of the reactive powers can be used to identify faults which occurred in or out the protection zone.

4. Establishment of Criterion

In order to accurately identify the faults occurred double circuit transmission line on the same tower, the reactive power ratios of the traveling wave on the same side of the two lines and the traveling wave reactive power ratios of the two ends of the same line on the double-circuit line on the same tower are calculated to construct the primary criterion and secondary criterion for fault identification.

4.1. Primary Criterion for Fault Identification

Take the system of **Figure 1** as an example. The initial traveling wave reactive power measured by the four traveling wave protection units $R_1 \sim R_4$ on the same-tower double-circuit transmission line is $Q_1 \sim Q_4$, and the ratio of the initial traveling wave reactive power on the same side of double-circuit line on the same tower is:

$$\begin{cases} \lambda_M = \frac{\max\{|Q_1|, |Q_2|\}}{\min\{|Q_1|, |Q_2|\}} \\ \lambda_N = \frac{\max\{|Q_3|, |Q_4|\}}{\min\{|Q_3|, |Q_4|\}} \end{cases} \quad (26)$$

The primary criterion established for the ratio of the initial traveling wave reactive power on the same side of double-circuit line on the same-tower is:

$$\begin{cases} \lambda_M > \lambda_{SET-S} \\ \lambda_N > \lambda_{SET-S} \end{cases} \quad (27)$$

In the equation, λ_{SET-S} is the threshold value, and $\lambda_{SET-S} = 50$ tentatively. When the initial traveling wave reactive power ratio λ_k ($k = M, N$) at the same end of the double-circuit line satisfies the primary criterion (27), it can be concluded that an internal fault occurs.

According to statistical data, when a fault occurs, the probability that a fault would occur on a single-circuit transmission line is much greater than that of a cross-line fault. The frequency of cross-line faults is only 2% - 3% of the total number of faults on the same-tower double-circuit transmission line in [17]. Therefore, with the primary criterion, most faults occurred on double-circuit line on the same-tower in the protection zone can be identified.

4.2. Secondary Criterion for Fault Identification

If the ratio of the initial traveling wave reactive powers on the same end of the double-circuit line on the same-tower cannot satisfy the primary criterion, the secondary criterion is invoked. The ratio is calculated using the initial traveling wave reactive powers at both ends of the same line according to the secondary criterion:

$$\begin{cases} \rho_I = \frac{\max\{|Q_1|, |Q_3|\}}{\min\{|Q_1|, |Q_3|\}} \\ \rho_{II} = \frac{\max\{|Q_2|, |Q_4|\}}{\min\{|Q_2|, |Q_4|\}} \end{cases} \quad (28)$$

In the formula, ρ_I and ρ_{II} represent the initial reactive wave reactive power ratios at both ends of the I circuit line and both ends of the II circuit line of the double-circuit line on the same tower. The comparison criterion of the initial traveling wave reactive power ratio of the two ends of the same line on the double-circuit line on the same-tower is:

$$\begin{cases} \rho_I < \rho_{SET-D} \\ \rho_{II} < \rho_{SET-D} \end{cases} \quad (29)$$

In the criterion, ρ_{SET-D} is the threshold value, and $\rho_{SET-D} = 100$ tentatively. Therefore, when the reactive power ratio of the traveling wave at both ends of the same line ρ_k ($k = I, II$) satisfies the secondary criterion (29), it can be concluded that a fault occurs in the protection zone, otherwise, a fault occurs out of the zone.

4.3. Algorithm Flow

When a fault traveling wave occurs on the double circuit transmission line on the same tower, the α -modulus and β -modulus of the corresponding voltage and

current are obtained through phase mode transformation. According to the literature [2], when the line protection device detects that the fault is a single-phase fault or two phases, same-name phases cross line grounding fault, α -modulus is selected for S-transform, and β -modulus is selected to identify other faults.

Time-frequency transformation is performed on the selected modulus with the implementation of S-transform. The single-frequency fault initial voltage traveling wave and current traveling wave corresponding to 60 kHz are selected with the implementation of S-transform in [14], and the corresponding initial traveling wave reactive power is calculated.

Primary and secondary criteria are used to achieve fault recognition of double-circuit line on the same tower, and the fault identification algorithm flow is shown in Figure 11.

5. Simulation Verification

In this paper, PSCAD software is used to establish the simulation model of double-circuit transmission lines on the same tower. The total length of the line

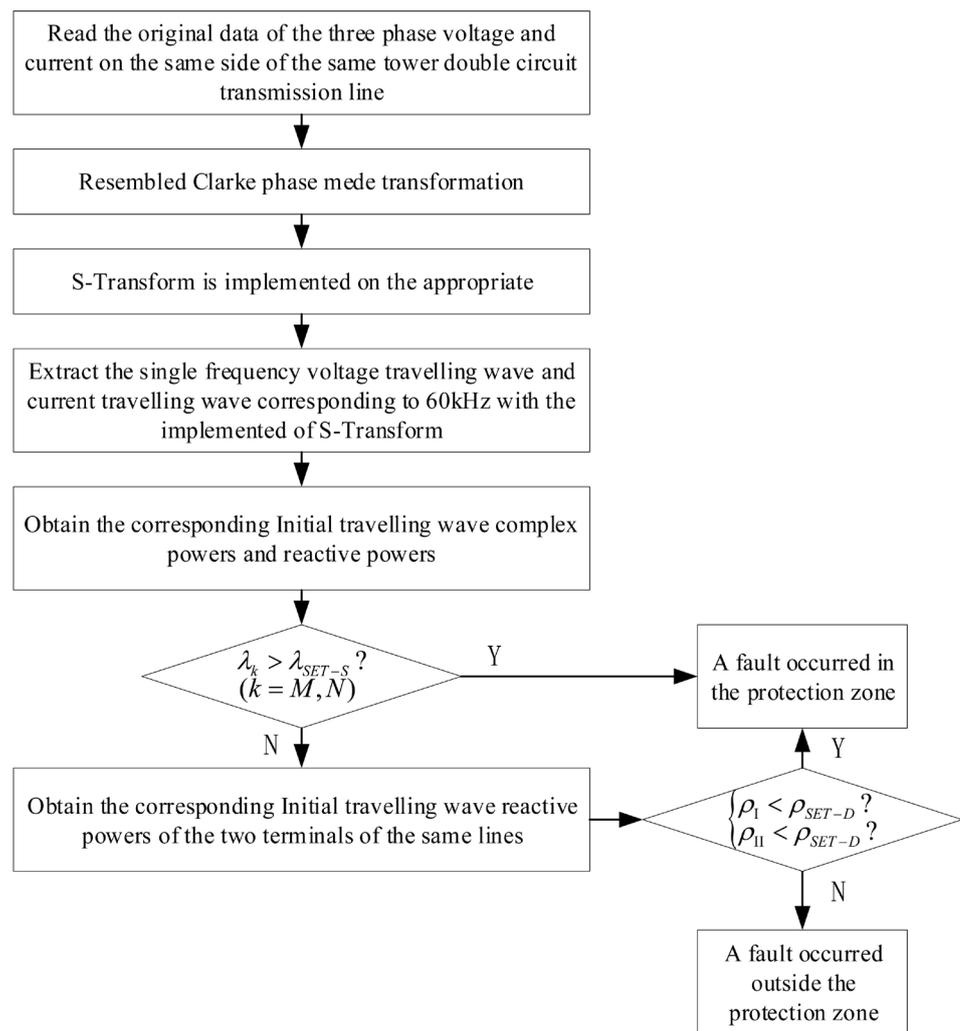


Figure 11. Flow of fault recognition algorithm for double-circuit lines on the same tower.

is 300 km. Both of the voltages at bus M and bus N are 500 kV and the frequency 50 Hz. The location of the protection unit is as shown in **Figure 1**. The line parameters of the double-circuit lines on the same tower is Tower:3L12. The line parameter used for the single-circuit line is Tower:3H5, and the sampling frequency is set as 200 kHz.

5.1. Faults Occurred in the Protection Zone

A single-phase ground fault occurred on the double-circuit transmission line on the same tower. Take AB phase grounded fault occurred on the I circuit transmission line as an example. The fault location is 100 km away from bus N, the transitional resistance is 500 Ω , the fault initial angle is 45°, and the diagrammatic map of the current traveling wave on the transmission line is shown in Fig 2. According to the criteria of this paper, after calculating the initial traveling wave reactive power with the implementation of S-transform, the ratio of the traveling wave reactive power at bus M is $\lambda_M \approx 8.5593 \times 10^2$, and the ratio of the traveling wave reactive power at bus N is $\lambda_N \approx 8.5590 \times 10^2$, and both reactive power ratios satisfy the primary criterion (27), thus it can be judged as a fault occurred in the protection zone. In order to verify the effectiveness of the algorithm in the protection zone of fault identification, a lot of simulation tests are carried out in this paper.

Table 1 shows the fault simulation of the double-circuit line on the same tower in the protection zone under different fault types. From the analysis in **Table 1**, it can be seen that a secondary criterion (29) is needed for the same-name

Table 1. Identification result of protection algorithm under different fault types when an internal fault occurs on double-circuit transmission line on the same tower.

Fault location	Fault type	circuit	The data of reactive power				Identification result
			Q_1 (kvar)	λ_M	Q_3 (kvar)	λ_N	
			Q_2 (kvar)		Q_4 (kvar)		
A fault occurs at a distance of 100 km from bus N; fault initial angel is 90°; transitional resistance is 200 Ω	IIAG	I circuit	1.2481e-03	8.9816e+02	1.2489e-03	8.9752e+02	Internal fault
		II circuit	1.1210		1.1210		Internal fault
	IBC	I circuit	1.6898e+01	8.5339e+02	1.6898e+01	8.5333e+02	Internal fault
		II circuit	1.9801e-02		1.9802e-02		Internal fault
	IBCIIA	I circuit	1.6898e+01	8.5339e+02	1.6898e+01	8.5333e+02	Internal fault
		II circuit	1.9801e-02		1.9802e-02		Internal fault
	ICIICG	I circuit	3.5440	1.0000	3.5440	1.0000	1.0000 Internal fault
		II circuit	3.5440		3.5440		1.0000 Internal fault
	IABIIAB	I circuit	1.1951e+02	1.0000	1.1951e+02	1.0000	1.0000 Internal fault
		II circuit	1.1951e+02		1.1951e+02		1.0000 Internal fault
	IABCG	I circuit	3.3745e+01	1.0000	3.3745e+01	1.0000	1.0000 Internal fault
		II circuit	3.3745e+01		3.3745e+01		1.0000 Internal fault

phases cross-line fault, while other cross-line faults and single-circuit faults only need to use the primary criterion (27) to identify the fault in the protection zone. Using these two criteria, the algorithm will not misjudge under different types of faults.

From **Table 2**, we can see that the ratio of the traveling wave reactive powers of the same side of the line is high with small fault initial angle, and it satisfies the primary criterion (27). When a complex cross-line fault occurs, the reactive powers of the same side of the line are not affected by the fault initial angle, but the ratio is approximately 1, and the primary criterion (27) cannot be satisfied. The secondary criterion (29) is needed to calculate the ratio of the traveling wave reactive power of both ends of the same-tower double-circuit line. The calculation result satisfies the secondary criterion, which shows that the protection algorithm can accurately identify the faults occurred in the protection zone with different fault initial angles.

Table 2. Identification result of protection algorithm under different fault initial angles when an internal fault occurs on double-circuit transmission line on the same tower.

Fault location	Fault initial angle (°)	circuit	The data of reactive power					Identification result	
			Q_1 (kvar)	λ_M	Q_3 (kvar)	λ_N	ρ_1		
			Q_2 (kvar)		Q_4 (kvar)		ρ_n		
IB short circuit grounding occurs at a distance of 100 km from bus N; transitional resistance is 100 Ω	5	I circuit	2.3130	6.1383e+03	3.5310	6.8516e+03		Internal fault	
		II circuit	3.7678e-04		5.1538e-04			Internal fault	
	15	I circuit	7.2890	7.1642e+03	1.0309e+01	7.6187e+03		Internal fault	
		II circuit	1.0175e-03		1.3531e-03			Internal fault	
	45	I circuit	3.2971e+01	6.0546e+02	8.1263e+01	9.9396e+02		Internal fault	
		II circuit	5.4455e-02		8.1756e-02			Internal fault	
	90	I circuit	4.8094e+01	6.0523e+02	1.1858e+02	9.9373e+02		Internal fault	
		II circuit	7.9464e-02		1.1933e-01			Internal fault	
	120	I circuit	5.9774e+01	1.3467e+03	4.4028e+01	7.6884e+02		Internal fault	
		II circuit	4.4387e-02		5.7266e-02			Internal fault	
	IABC and IIBC short circuit occurs at a distance of 200 km from bus N	5	I circuit	4.1562e+02	1.0000	7.6294e+02	1.0000	1.8357	Internal fault
			II circuit	4.1562e+02		7.6294e+02		1.8357	Internal fault
15		I circuit	6.8018e+02	1.0000	3.4090e+02	1.0000	1.9953	Internal fault	
		II circuit	6.8018e+02		3.4090e+02		1.9953	Internal fault	
45		I circuit	5.0482e+02	1.0000	2.0542e+02	1.0000	2.4575	Internal fault	
		II circuit	5.0482e+02		2.0542e+02		2.4575	Internal fault	
90		I circuit	7.1952e+01	1.0000	2.9354e+01	1.0000	2.4512	Internal fault	
		II circuit	7.1952e+01		2.9354e+01		2.4512	Internal fault	
120		I circuit	4.5798e+02	1.0000	6.2128e+02	1.0000	1.3566	Internal fault	
		II circuit	4.5798e+02		6.2128e+02		1.3566	Internal fault	

It can be seen from the analysis in **Table 3** that when the transitional resistance and the fault location change, the primary criterion (27) still can be met with the ratio of the traveling wave reactive power, and it hardly changes with the change of transitional resistance, that is, the algorithm is not affected by the change of transitional resistance.

The above analysis shows that with different fault initial angles, transitional resistances, fault types, and fault locations, the simulation data is consistent with the theoretical analysis results, which means the protection can accurately reflect the faults occurred in the protection zone and operate in a reliable way.

5.2. Faults Occurred Out of the Protection Zone

A fault occurred out of the protection zone on the double circuit line on the same tower. Take the BC phase short-circuit fault out of the protection zone as an example. The fault location is 100 km from bus N, and the fault initial angle is 90° . According to the criteria of this paper, after calculating the initial traveling wave reactive power with the implementation of S-transform, the ratio $\lambda_M \approx 1.0000$ of reactive power at the bus M can be obtained, the ratio of reactive power at the bus N is $\lambda_N \approx 1.0000$, and the ratio does not satisfy the primary criterion (27), so the secondary criterion is needed. The criterion uses the ratio of reactive

Table 3. Identification result of protection algorithm under different transitional resistances and fault locations when an internal fault occurs on double-circuit transmission line on the same tower

Fault location	Transitional resistance/ Ω	circuit	The data of reactive power				Identification result		
			Q_1 (kvar)	λ_M	Q_3 (kvar)	λ_N			
			Q_2 (kvar)		Q_4 (kvar)			ρ_i	
IIAC short circuit grounding occurs at a distance of 50 km from bus N; fault initial angle is 45°	0	I circuit	2.7233e-05	8.5505e+02	2.7231e-05	8.5509e+02	Internal fault		
		II circuit	2.3285e-02		2.3285e-02		Internal fault		
	100	I circuit	7.6425e-03	8.4949e+02	7.6416e-03	8.4958E+02	Internal fault		
		II circuit	6.4920		6.4920		Internal fault		
	300	I circuit	1.5208e-02	8.5388e+02	1.5206e-02	8.5395E+02	Internal fault		
		II circuit	1.2985e+01		1.2985e+01		Internal fault		
	600	I circuit	1.9714e-02	8.5468e+02	1.9713e-02	8.5474E+02	Internal fault		
		II circuit	1.6850e+01		1.6850e+01		Internal fault		
	IABIIC short circuit grounding occurs at a distance of 250 km from bus N; fault initial angle is 45°	0	I circuit	8.7770	2.2532	2.2522e+01	2.3305	2.5660	Internal fault
			II circuit	1.9776e+01		5.2487e+01		2.6541	Internal fault
		100	I circuit	8.7770	2.2532	2.2522e+01	2.3305	2.5660	Internal fault
			II circuit	1.9776e+01		5.2487e+01		2.6541	Internal fault
300		I circuit	8.7770	2.2532	2.2522e+01	2.3305	2.5660	Internal fault	
		II circuit	1.9776e+01		5.2487e+01		2.6541	Internal fault	
600		I circuit	8.7770	2.2532	2.2522e+01	2.3305	2.5660	Internal fault	
		II circuit	1.9776e+01		5.2487e+01		2.6541	Internal fault	

power at both ends of the same line, the ratio of reactive power at both ends of the I circuit line is $\rho_1 \approx 2.3013 \times 10^2$, and the ratio of reactive power at both ends of the II circuit line is $\rho_{II} \approx 2.3013 \times 10^2$, which does not meet the secondary criterion (29), so it can be concluded that the fault occurs out of the protection zone.

In order to fully verify the effectiveness of fault identification algorithm out of the protection zone, a lot of simulation experiments have been carried out.

Table 4 shows the fault simulation of double-circuit lines on the same tower out of the protection zone under different fault types. From the analysis of **Table 4**, we can see that in the different fault locations and fault types, and comparing the initial traveling wave reactive power detected by the protection unit of double-circuit line on the same tower, the primary criterion (27) and secondary criterion (29) cannot be met, which shows that the algorithm can accurately identify faults occurred out of the protection zone under different fault types.

Table 5 shows that when a fault occurs out of the protection zone, the ratio of the traveling wave reactive power on the same side of the double-circuit line of the same tower is approximately the same when a fault occurs out of the protection zone, and the ratio remains constant at about 1, which does not satisfy the primary criterion (27). Therefore the secondary criterion (29) is needed; on the same transmission line, the reactive powers of the busbar far from the fault point is higher than the reactive power at that of the busbar near the fault point, so the ratios of the reactive powers are relatively high, and all remain at 100 or more. Which not satisfy the secondary criterion (29) and it can be concluded that the

Table 4. Identification result of protection algorithm under different fault types when an external fault occurs on double-circuit transmission line on the same tower

Fault location	Fault type	circuit	The data of reactive power					Identification result
			Q_1 (kvar)	λ_M	Q_3 (kvar)	λ_N	ρ_1	
			Q_2 (kvar)		Q_4 (kvar)		ρ_{II}	
fault occurs on line L_4 at a distance of 50 km from bus N; transitional resistance is 200 Ω ; fault initial angle is 15°	CG	I circuit	1.8190	1.0000	6.1816e-03	1.000	2.9426e+02	External fault
		II circuit	1.8190		6.1816e-03		2.9426e+02	External fault
	BCG	I circuit	1.0422e+02	1.0000	5.6916e-01	1.000	1.8312e+02	External fault
		II circuit	1.0422e+02		5.6916e-01		1.8312e+02	External fault
	ABCG	I circuit	1.0422e+02	1.0000	5.6916e-01	1.000	1.8312e+02	External fault
		II circuit	1.0422e+02		5.6916e-01		1.8312e+02	External fault
fault occurs on line L_4 at a distance of 100 km from bus N; transitional resistance is 500 Ω ; fault initial angle is 120°	CG	I circuit	8.8781e-01	1.0000	3.3912e-03	1.000	2.6180e+02	External fault
		II circuit	8.8781e-01		3.3912e-03		2.6180e+02	External fault
	BCG	I circuit	4.1618e+01	1.0000	1.5589e-01	1.000	2.6697e+02	External fault
		II circuit	4.1618e+01		1.5589e-01		2.6697e+02	External fault
	ABCG	I circuit	4.1619e+01	1.0000	1.5589e-01	1.000	2.6698e+02	External fault
		II circuit	4.1619e+01		1.5589e-01		2.6698e+02	External fault

Table 5. Identification result of protection algorithm under different fault initial angles when an external fault occurs on double-circuit transmission line on the same tower.

Fault location	Fault initial angle/(°)	circuit	The data of reactive power					Identification result	
			Q_1 (kvar)	λ_M	Q_3 (kvar)	λ_N	ρ_1		
			Q_2 (kvar)		Q_4 (kvar)		ρ_{11}		
A phase grounded short circuit occurs on line L_4 at a distance of 50 km from bus N; transitional resistance is 100 Ω	5	I circuit	8.2278e-01	1.0000	3.2481e-03	1.000	2.5331e+05	External fault	
		II circuit	8.2278e-01		3.2481e-03		2.5331e+05	External fault	
	15	I circuit	3.5450e+00	1.0000	1.2243e-02	1.000	2.8955e+05	External fault	
		II circuit	3.5450e+00		1.2243e-02		2.8955e+05	External fault	
	45	I circuit	9.9380e+00	1.0000	5.3274e-02	1.000	1.8654e+05	External fault	
		II circuit	9.9380		5.3274e-02		1.8654e+05	External fault	
	90	I circuit	2.8121e+01	1.0000	1.2000e-01	1.000	2.3433e+05	External fault	
		II circuit	2.8121e+01		1.2000e-01		2.3433e+05	External fault	
	120	I circuit	1.5383e+01	1.0000	9.2246e-02	1.000	1.6676e+05	External fault	
		II circuit	1.5383e+01		9.2246e-02		1.6676e+05	External fault	
	AC phase grounded short circuit occurs on line L_4 at a distance of 100 km from bus N	5	I circuit	5.1890	1.0000	2.0336e-02	1.000	2.5516e+05	External fault
			II circuit	5.1890		9.2246e-02		5.6252e+04	External fault
15		I circuit	1.4780	1.0000	5.0523e-03	1.000	2.9254e+05	External fault	
		II circuit	1.4780		5.0523e-03		2.9254e+05	External fault	
45		I circuit	5.1610	1.0000	2.1929e-02	1.000	2.3535e+05	External fault	
		II circuit	5.1610		2.1929e-02		2.3535e+05	External fault	
90		I circuit	3.6353e+01	1.0000	1.5434e-01	1.000	2.3553e+05	External fault	
		II circuit	3.6353e+01		1.5434e-01		2.3553e+05	External fault	
120		I circuit	3.5642e+01	1.0000	2.1201e-01	1.000	1.6812e+05	External fault	
		II circuit	3.5642e+01		2.1201e-01		1.6812e+05	External fault	

fault occurred out of the protection zone, and the algorithm is not affected by the initial angle of the fault.

Table 6 shows that when faults occur out of the protection zone under different conditions of transitional resistance, the reactive powers of traveling waves detected on the two circuits transmission line on the same side of the double circuit line on the same-tower are approximately equal, and the ratio of the reactive powers of the initial traveling waves detected at both ends of the same line is high, which does not meet the secondary criterion (29). With the increase of the transitional resistance, the ratio of the initial traveling wave reactive power is approximately the same, indicating that this algorithm is not affected by the change of the transitional resistance. When the fault location is different, the reactive power ratio varies with the fault distance, but the secondary fault (29) can still be used to identify the fault occurred out of the protection zone.

In summary, the algorithm can accurately identify faults occurred on the

Table 6. Identification result of protection algorithm under different transitional resistances and fault locations when an external fault occurs on double-circuit transmission line on the same tower.

Fault location	Transitional resistance/ Ω	circuit	The data of reactive power					Identification result
			Q_1 (kvar)	λ_M	Q_3 (kvar)	λ_N	ρ_1	
			Q_2 (kvar)		Q_4 (kvar)		ρ_{II}	
B phase grounded short circuit occurs on the line L_4 at a distance of 50 km from bus N; fault initial angle is 45°	0	I circuit	3.9568e+01	1.0000	1.6714e-01	1.000	2.3673e+02	External fault
		II circuit	3.9568e+01		1.6714e-01		2.3673e+02	External fault
	100	I circuit	1.8789e+01	1.0000	7.9512e-02	1.000	2.3630e+02	External fault
		II circuit	1.8789e+01		7.9512e-02		2.3630e+02	External fault
	300	I circuit	7.1480	1.0000	3.0298e-02	1.000	2.3593e+02	External fault
		II circuit	7.1480		3.0298e-02		2.3593e+02	External fault
	600	I circuit	2.8850	1.0000	1.2242e-02	1.000	2.3566e+02	External fault
		II circuit	2.8850		1.2242e-02		2.3566e+02	External fault
AB phase grounded short circuit occurs on the line L_4 at a distance of 100 km from bus N; fault initial angle is 90°	0	I circuit	1.0578e+01	1.0000	5.6479e-02	1.000	1.8729e+02	External fault
		II circuit	1.0578e+01		5.6479e-02		1.8729e+02	External fault
	100	I circuit	1.4558e+01	1.0000	7.7907e-02	1.000	1.8686e+02	External fault
		II circuit	1.4558e+01		7.7907e-02		1.8686e+02	External fault
	300	I circuit	1.7208e+01	1.0000	9.2136e-02	1.000	1.8677e+02	External fault
		II circuit	1.7208e+01		9.2136e-02		1.8677e+02	External fault
	600	I circuit	1.8520e+01	1.0000	9.9170e-02	1.000	1.8675e+02	External fault
		II circuit	1.8520e+01		9.9170e-02		1.8675e+02	External fault

double-circuit line on the same tower out of the protection zone, and is not affected by initial angles of faults, transitional resistances, and types of faults. The algorithm is accurate and reliable and shows no defect or malfunction. That is to say, the test results are identical with theoretical analysis results.

6. Conclusions

In this paper, the protection principle of the double-circuit transmission line on the same tower based on the ratio of the initial traveling wave reactive power is proposed. The characteristics of the initial traveling wave reactive power of double circuit line on the same tower in and out of the protection zone are analyzed. The phase mode transformation and S-transform are implemented. The ratios of the initial traveling wave reactive power on the same end of double lines and both terminal of single line are collected to identify faults occurred in and out of the protection zone. Simulation results show that:

- 1) The algorithm obtains the single-frequency initial traveling wave reactive powers with the implementation of S-transform. It can accurately identify faults occurred in or out of the protection zone at different initial angles of faults, different transitional resistances and different fault locations, and has strong an-

ti-interference performance.

2) Based on simple criteria, the protection algorithm only uses the initial traveling wave reactive power, needs to collect a small amount of data and is quick in calculation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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