Xing DENG, Xianggen YIN, Zhe ZHANG, Yi LIU

State Key Laboratory of Advanced Electromagnetic Engineering and Technology，Huazhong University of Science and Technology

A Novel Single-Phase Adaptive Reclosure Scheme for Double-Circuit Transmission Lines

***Abstract**. In this study, a new single-phase adaptive reclosure scheme to distinguish between transient fault and permanent fault for double-circuit transmission lines is proposed. Based on the recovery voltage characteristics, this scheme is composed of voltage phase criterion, voltage amplitude criterion and reclosing phase by phase. The simulation results show that the proposed scheme can identify the fault nature of single-phase-to-ground fault or single-phase inter-circuit fault correctly and it is helpful to improve the success rate of automatic reclosure for double-circuit lines.*

***Streszczenie.** W artykule przedstawiono jednofazowy adaptacyjny schemat ponownego załączania, na potrzeby rozróżnienia przypadków awarii chwilowej i trwałej w dwutorowych liniach przesyłowych. Struktura składa się z następujących elementów: kryterium fazy i amplitudy napięcia oraz bloku ponownego załączania kolejnych faz. Badania symulacyjne wykazały skuteczność metody w wykrywaniu awarii fazowych doziemnych i wewnątrz-torowych i ponownym załączaniu linii dwutorowych. (**Adaptacyjna struktura ponownego zamknięcia dla dwutorowych linii przesyłowych**).*

Keywords: double-circuit transmission lines; adaptive reclosure; voltage phase criterion; voltage amplitude criterion; reclosing phase by phase

Słowa kluczowe: dwutorowa linia przesyłowa, adaptacyjne ponowne załączenie, kryterium fazowe, kryterium amplitudowe, ponowne załączanie faz.

Introduction

The long-term power system operation statistics show that most of faults on double-circuit transmission lines are transient; of those are mainly single-phase-to-ground fault and single-phase inter-circuit fault. Conventional automatic reclosure cannot identify whether the fault is transient or permanent, and it may close on permanent fault or transient fault before arc extinguishing. Peculiarly, the reclosure of double-circuit lines close on permanent fault will have a great impact on power system and close on inter-circuit fault before arc extinguishing will lead to the simultaneous tripping of double-circuit lines [1,2,3,4]. Therefore, researching on adaptive reclosure for double-circuit lines has great significance for power system stability and power transmission efficiency.

At present, there are two main methods to distinguish between transient fault and permanent fault: 1) the criterion based on transient characteristics of fault arc [5,6]; 2) the criterion based on recovery voltage characteristics after arc extinguishing [7]. The method based on transient characteristics of fault arc tends to be affected by many factors, such as arc extinguishing process, sampling precision of transient signals and fault conditions, these factors will lead to inaccuracy of the results, thus this method is hard to be applied in engineering practice. Among the methods that based on recovery voltage characteristics, voltage amplitude criterion and voltage phase criterion are very simple and wide application. But the sensitivity of voltage amplitude criterion is influenced by line length and transition resistance; Voltage phase criterion may lead to incorrect judgment in the case of line at no-load or light-load conditions. Furthermore, a method to identify permanent fault based on fault location is proposed in [8], which can't be used when location failure. Wang [9] present a criterion based on correlation algorithm to distinguish transient fault from permanent fault, but this algorithm is influenced by load current and the changes of operation conditions. In Aggarwal [10] and Fitton [11], the neural network is used to identify permanent fault, which required sufficient training samples to achieve complexity. Lin [12] proposed a discriminator based on fuzzy logic, but the identification of the fuzzy decision table needs to obtain data under various operation modes, thus it is difficulty to realize. These research results mainly concentrate in single-circuit lines, the adaptive reclosure for double-circuit lines need further study.

For double-circuit lines, as the distance between two circuit lines is close, inter-circuit faults tend to occur. In order to improve the success rate of reclosure, transmission systems in Japan mainly adopt the multi pole reclosure. This reclosure strategy may be reclosed on multi-phase permanent fault, which is not allowed in China [1].

In this paper, characteristics of traditional voltage amplitude criterion and voltage phase criterion are firstly analyzed, as well as the problems of those methods in double-circuit lines. On this basis, an adaptive reclosure scheme based on voltage phase criterion, voltage amplitude criterion and reclosing phase by phase is proposed. The simulation results demonstrate that the scheme is simple, reliably and has high sensitive.

Adaptive reclosure criterion for single-circuit transmission lines

A. Voltage amplitude criterion

Voltage amplitude criterion identifies the fault nature according to voltage amplitude of the open phase [7,13]. When a permanent fault occurs (especially metallic grounding fault), the capacitive coupling voltage from sound phase is almost zero, the voltage of open phase is approximate equal to the inductive coupling voltage. As for the transient fault, after arc extinguishing, the voltage of the open phase includes capacitive coupling voltage inductive coupling voltage.

For easy to analyze, it is assumed that phase B has transient grounding fault, the inter-phase mutual capacitance is C_m, and the shunt capacitance is C_0. The inter-phase mutual impedance per unit length is z_m. Hence, the capacitive coupling voltage $\dot{U}_y$ of phase B can be written as

$$\dot{U}_y = \frac{C_m}{C_0 + 2C_m}(\dot{U}_A + \dot{U}_C) \tag{1}$$

In (1), both C_m and C_0 are proportional to the line length so that capacitive coupling voltage of transmission lines is independent of the length of transmission lines. The inductive coupling voltage $\dot{U}_{xl}$ of phase B can be expressed as

(2) $$\dot{U}_{\text{xl}} = (\dot{I}_{\text{A}} + \dot{I}_{\text{C}}) z_{\text{m}} L$$

where *L* is the line length.

It can be seen from (2) that inductive coupling voltage is related to the load current and the line length. The larger the load current is and the longer the line length is, the larger the inductive coupling voltage will be.

According to analysis of Kang [3] and Fan [13], voltage amplitude criterion can reliably identify the fault nature when the line length satisfies

(3) $$L \le \frac{\dot{U}_{\text{y}}}{k(\dot{I}_{\text{AH}} + \dot{I}_{\text{CH}}) z_{\text{m}}}$$

Where *k*=1.1~1.2; $\dot{I}_{\text{AH}}$ and $\dot{I}_{\text{CH}}$ are load currents of phase A and phase C.

(3) shows that the effective line length is in inverse proportion to the load current. When the line length exceeds the effective line length, the voltage amplitude criterion cannot accurately identify the fault nature. It is recommended to quit running.

B. Voltage phase criterion

Voltage phase criterion applies the compensation voltage and inductive coupling voltage of the open phase to distinguish transient fault from permanent fault [14].

It is also assumed that phase B occurs a transient fault, and phase B has been separated from system. The pre-fault current of sound phase A and C keeps unchanged. From (1) and (2), set the power factor angle of the system as θ , the phasor diagram of electric quantities can be drawn as Fig. 1.

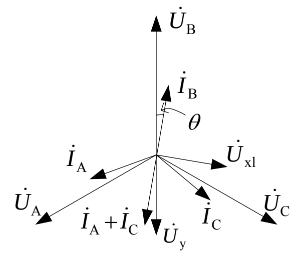

Fig.1. Phasor diagram when phase B occurs a transient fault

From T-type equivalent circuit, compensation voltage at middle point of the line is $\dot{U} - 0.5\dot{U}_{\text{xl}}$, where $\dot{U}$ is measuring voltage of the line. When a transient fault occurs, compensation voltage is $\dot{U}_{\text{y}}$, and the angel of compensation voltage delayed $\dot{U}_{\text{xl}}$ is $90° - \theta$. When a permanent fault occurs, measuring voltage $\dot{U}$ does not contain capacitive coupling voltage. It changes from 0 to $\dot{U}_{\text{xl}}$ with different fault positions. Thus, compensation voltage $\dot{U} - 0.5\dot{U}_{\text{xl}}$ varies from $-0.5\dot{U}_{\text{xl}}$ to $0.5\dot{U}_{\text{xl}}$, and the phase difference between compensation voltage and capacitive coupling voltage of permanent fault is 0 or 180° . Therefore, according to the different phase relationship between compensation voltage and inductive coupling voltage during transient fault and permanent fault, the voltage phase criterion can be formed as

(4) $$\left\| \arg \frac{\dot{U} - 0.5\dot{U}_{\text{xl}}}{\dot{U}_{\text{xl}}} \right| - 90° \right| \le \varphi_{\text{set}}$$

Where φ_{set} is the setting value, it is decided by the power factor of system. In this paper, $\varphi_{\text{set}} = \theta + 15°$.

When (4) is satisfied, it is judged as transient fault. Otherwise, it is judged as permanent fault.

With the consideration of the relationship between sound phase current and zero-sequence current after single-phase-to-ground fault, and as the relationship between sequence impedance and mutual impedance of lines, (4) can be equivalent to:

(5) $$\left\| \arg \frac{\dot{U} - 0.5\dot{I}_0 (Z_0 - Z_1)}{\dot{I}_0 (Z_0 - Z_1)} \right| - 90° \right| \le \varphi_{\text{set}}$$

Guo [15] pointed out that the transition resistance has little influence on voltage phase criterion, and this criterion can distinguish permanent fault from transient fault reliably. But this criterion can not work well when the fault occurred at or near the middle point of the line. Because compensation voltage is very small or even to zero in this case that can not meet the calculation accuracy of phase comparison. Simultaneously, when the line at light-load or no-load, the inductive coupling voltage $\dot{U}_{\text{xl}}$ is very small or even to 0, which can not be used to calculation either.

Analysis on fault features of double-circuit lines

Like single-circuit line, during permanent fault of double-circuit lines, the voltage of open phase is mainly the inductive coupling voltage. During transient fault, after the fault disappeared, the voltage of open phase includes inductive coupling voltage and capacitive coupling voltage. But the fault type and mutual coupling of double-circuit lines are more complex, therefore, it is necessary to analyze whether the adaptive reclosure criteria of single-circuit line suit for double-circuit lines.

A. Single-phase-to-ground fault

It is assumed that the inter-circuit mutual capacitance is C'_{m} , the inter-phase mutual capacitance is C_{m} and the shunt capacitance is C_0 .when phase B of circuit I (IB for short) occurs a transient fault, after the fault disappeared, the capacitive coupling voltage of open phase IB is shown in Fig. 2.

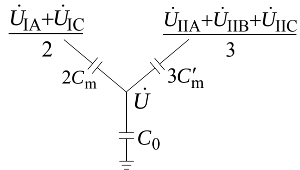

Fig.2. Capacitive coupling voltage of IB during a transient fault

As three phases of system are symmetrical, the sum of three-phase voltage is zero. Thus, the equivalent circuit in Fig. 2 can be simplified as Fig. 3.

It can be seen from Fig. 3 that the capacitive coupling voltage of open phase IB is:

(6) $$\dot{U} = \frac{(\dot{U}_{\text{IA}} + \dot{U}_{\text{IC}}) C_{\text{m}}}{C_0 + 3C'_{\text{m}} + 2C_{\text{m}}}$$

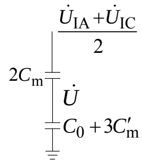

Fig.3. Simplified circuit of the capacitive coupling voltage of IB during a transient fault

For double-circuit lines, the inductive coupling voltage of open phase IB is not only affected by mutual inductance of circuit I but also by the mutual inductance of another circuit.

Thus, its inductive coupling voltage $\dot{U}_{\mathrm{xl}}$ can be expressed as

(7) $\dot{U}_{\mathrm{xl}} = (\dot{I}_{\mathrm{IA}} + \dot{I}_{\mathrm{IC}})Z_{\mathrm{m}} + \dot{I}_{\mathrm{IIA}}Z_{\mathrm{mIIA}} + \dot{I}_{\mathrm{IIB}}Z_{\mathrm{mIIB}} + \dot{I}_{\mathrm{IIC}}Z_{\mathrm{mIIC}}$

Where Z_{m} is the inter-phase mutual impedance, Z_{mIIA}, Z_{mIIB} and Z_{mIIC} are mutual inductances respectively between three phases of circuit II and phase IB.

With the symmetry of line parameters, Z_{mIIA}, Z_{mIIB} and Z_{mIIC} are equal, and can expressed as Z'_{m}. During normal operation of circuit II, its current is also symmetrical. Thus, (7) can be simplified to

(8) $$\dot{U}_{\mathrm{xl}} = (\dot{I}_{\mathrm{IA}} + \dot{I}_{\mathrm{IC}})Z_{\mathrm{m}}$$

It can be seen that compared with single-circuit line, the amplitude and phase of the capacitive coupling voltage and the inductive coupling voltage of double-circuit line are changed little. Therefore, voltage amplitude criterion and voltage phase criterion can be applied to identify the nature of single-phase-to-ground fault of double-circuit lines.

B. Phase-to-phase-to-ground inter-circuit fault between two same phases

It is assumed that a transient phase-to-phase-to-ground inter-circuit fault occurs between phase IB and phase IIB. After the fault disappeared, the capacitive coupling voltage of open phase IB and IIB are shown in Fig. 4.

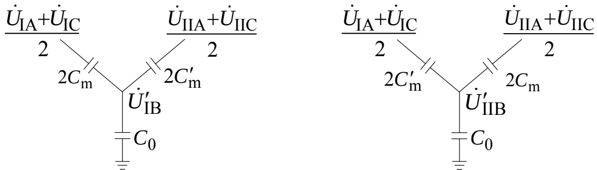

Fig.4. Capacitive coupling voltage of IB and IIB during a transient fault

When two circuit lines are parallel running, there are $\dot{U}_{\mathrm{IA}} = \dot{U}_{\mathrm{IIA}}$, $\dot{U}_{\mathrm{IB}} = \dot{U}_{\mathrm{IIB}}$, $\dot{U}_{\mathrm{IC}} = \dot{U}_{\mathrm{IIC}}$. From Fig. 4, the capacitive coupling voltage of open phase IB and IIB are equal as

(9) $$\dot{U} = \frac{(\dot{U}_{\mathrm{IA}} + \dot{U}_{\mathrm{IC}})(C_{\mathrm{m}} + C'_{\mathrm{m}})}{C_0 + 2C'_{\mathrm{m}} + 2C_{\mathrm{m}}}$$

Compare with (1) and (9), the capacitive coupling voltage phase in (9) is equal to that in (1), the capacitive coupling voltage amplitude in (9) and (1) are different.

The inductive coupling voltage $\dot{U}_{\mathrm{xl}}$ of open phase IB is not only decided by the mutual inductance of circuit I but also influenced by the mutual inductance between two circuits. It can be expressed as

(10) $$\dot{U}_{\mathrm{xl}} = (\dot{I}_{\mathrm{IA}} + \dot{I}_{\mathrm{IC}})Z_{\mathrm{m}} + \dot{I}_{\mathrm{IIA}}Z'_{\mathrm{m}} + \dot{I}_{\mathrm{IIC}}Z'_{\mathrm{m}}$$

When two circuit lines are parallel running, the corresponding phase current of two circuits are equivalent. Thus (10) can be simplified as

(11) $$\dot{U}_{\mathrm{xl}} = (\dot{I}_{\mathrm{IA}} + \dot{I}_{\mathrm{IC}})(Z_{\mathrm{m}} + Z'_{\mathrm{m}})$$

In (11), the inductive coupling voltage is larger than the single-circuit line, and the voltage is relevant to the load current of system. The larger the load current is, the larger the inductive coupling voltage is. But phase of the inductive coupling voltage is the same with the single-circuit line.

Therefore，during a transient phase-to-phase-to-ground inter-circuit between two same phases, phase of the capacitive coupling voltage and the inductive coupling voltage of double-circuit lines are identical with the single-circuit line. Hence, the voltage phase criterion can also be used in double-circuit lines.

C. Phase-to-phase-to-ground inter-circuit fault between two different phases

Assume that a transient phase-to-phase-to-ground inter-circuit fault occurs between phase IB and phase IIA. After the fault disappeared, the capacitive coupling voltage of open phase IB and IIA are shown in Fig. 5. (As the voltage of open phase IB and IIA are approximately equal, to simplify the analysis, the capacitive coupling voltage between two open phases is ignored).

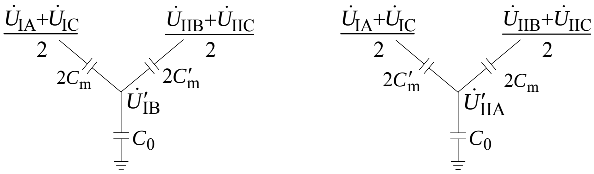

Fig.5. Capacitive coupling voltage of IB and IIA during a transient fault

It is also assumed that the double-circuit line is parallel running. It can be seen from Fig. 5 that the capacitive coupling voltage $\dot{U}'_{\mathrm{IB}}$ of open phase IB and $\dot{U}'_{\mathrm{IIA}}$ of open phase IIA are respectively

(12) $$\dot{U}'_{\mathrm{IB}} = -\frac{\dot{U}_{\mathrm{IB}}C_{\mathrm{m}} + \dot{U}_{\mathrm{IA}}C'_{\mathrm{m}}}{C_0 + 2C'_{\mathrm{m}} + 2C_{\mathrm{m}}}$$

(13) $$\dot{U}'_{\mathrm{IIA}} = -\frac{\dot{U}_{\mathrm{IA}}C_{\mathrm{m}} + \dot{U}_{\mathrm{IB}}C'_{\mathrm{m}}}{C_0 + 2C'_{\mathrm{m}} + 2C_{\mathrm{m}}}$$

As the distance of conductors of double-circuit lines are close, we can assume that the inter-phase capacity C_{m} in (12) and (13) is equivalent to the inter-circuit capacity C'_{m}, thus (12) is equivalent to (13).

When a transient phase-to-phase-to-ground inter-circuit fault occurs between two different phases, the inductive coupling voltage $\dot{U}_{\mathrm{xl}}$ of open phase IB is affected by the mutual inductance of two circuits. The expression is

(14) $$\dot{U}_{\mathrm{xl}} = (\dot{I}_{\mathrm{IA}} + \dot{I}_{\mathrm{IC}})Z_{\mathrm{m}} + \dot{I}_{\mathrm{IIB}}Z'_{\mathrm{m}} + \dot{I}_{\mathrm{IIC}}Z'_{\mathrm{m}}$$

Similarly, when the double-circuit line is parallel running, the corresponding phase current of two circuit lines are equal, and the sound phase current keeps unchanged. Thus (14) can be simplified as

(15) $$\dot{U}_{\mathrm{xl}} = -\dot{I}_{\mathrm{IB}}Z_{\mathrm{m}} - \dot{I}_{\mathrm{IA}}Z'_{\mathrm{m}}$$

It can be inferred from the analysis that in open phase IB, the angle between $-\frac{\dot{U}_{\mathrm{IB}}C_{\mathrm{m}}}{C_0 + 2C'_{\mathrm{m}} + 2C_{\mathrm{m}}}$ and $-\dot{I}_{\mathrm{IB}}Z_{\mathrm{m}}$ is $90° - \theta$, and the angle between $-\frac{\dot{U}_{\mathrm{IA}}C'_{\mathrm{m}}}{C_0 + 2C'_{\mathrm{m}} + 2C_{\mathrm{m}}}$ and $-\dot{I}_{\mathrm{IA}}Z'_{\mathrm{m}}$ is also $90° - \theta$. Thus, the phasor diagram of the capacitive coupling voltage and the inductive coupling voltage is shown in Fig. 6.

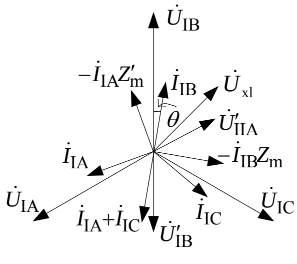

Fig.6. Phasor Diagram of the capacitive coupling voltage and the inductive coupling voltage during a IBIIAG transient fault

It can be seen from Fig. 6 that the angle between the capacitive coupling voltage and the inductive coupling voltage of open phase IB is $90° - \theta$, thus, voltage phase criterion is feasible in this case. Similarly, voltage phase criterion can be applied to another open phase IIA.

Adaptive reclosure combination criteria for double-circuit lines

A. Combination criteria

According to the analysis results of fault characteristics of double-circuit lines, the voltage amplitude criterion and the voltage phase criterion can be applied to double-circuit line. On one hand, voltage amplitude criterion presents perfect accuracy under no-load or light load status, and it is also not affected by the line length, but the sensitivity of this criterion will be reduced or mistakenly identified under heavy power flow. On the other hand, the voltage phase criterion is reliable and sensitive under heavy power flow, but it will be ineffective under no-load or light-load status. Therefore, voltage amplitude criterion is mutually complementary to voltage phase criterion. In this paper, voltage amplitude criterion and voltage phase criterion are integrated in combination criteria for double-circuit line. The combination criteria are formed as follows

(16) $$\left| \left| \arg \frac{\dot{U} - 0.5\dot{U}_{\mathrm{xl}}}{\dot{U}_{\mathrm{xl}}} \right| - 90° \right| \le \varphi_{\mathrm{set}}$$

(17) $$\left| \left| \arg \frac{\dot{U} - 0.25\dot{U}_{\mathrm{xl}}}{\dot{U}_{\mathrm{xl}}} \right| - 90° \right| \le \varphi_{\mathrm{set}}$$

(18) $$\begin{cases} \left|\dot{U}\right| \ge U_{\mathrm{set}} \\ \left|\dot{I}\right| < I_{\mathrm{set}} \end{cases}$$

If any criterion from (16) to (18) can be valid, it is transient fault; otherwise, it is permanent fault. (16) is conventional voltage phase criterion, in order to solve the problem that conventional voltage phase criterion is ineffective when the fault occurred at or near the middle point of the line, the assistant criterion (17) is added. The physical significance of (17) is to divide the line into two segments of equal length. For the first half, its phase criterion can be obtained from (17). When faults occur at or near the middle point of the original line, (16) is ineffective. But for (17), it is equivalent to the faults occur at the end of the line, in this case, (17) can accurately distinguish transient fault from permanent fault. (18) is voltage amplitude criterion, it is mainly used to make up for the deficiency of (16) under no-load and light-load status. The inductive coupling voltage $\dot{U}_{\mathrm{xl}}$ is small or even to zero, thus the U_{set} can set as $k\left|\dot{U}_C\right|$, where k=0.90~0.95, $\dot{U}_C$ is the capacitive coupling voltage of open phase. In Eq.(18), $\left|\dot{I}\right| < I_{\mathrm{set}}$ ensures that voltage amplitude criterion functions only under no-load or light-load status. Where $\dot{I}$ is sound phase current, $I_{\mathrm{set}} = 0.1I_{\mathrm{n}} \sim 0.5I_{\mathrm{n}}$, I_{n} is rated current.

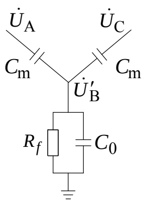

Fig.7. Capacitive coupling voltage of IB during a permanent fault with transition resistance

As voltage amplitude criterion in (18) is the main criterion to judge whether the line under no-load and light-load, the effect of transition resistance on performance of the voltage amplitude criterion requires further analysis. Assume that phase B occurs a permanent single-phase-to-ground fault with transition resistance, the capacitive coupling voltage of open phase B is shown in Fig. 7.

In Fig. 7, $\dot{U}'_{\mathrm{B}}$ represents the capacitive coupling voltage of phase B. It can be obtained from the equivalent circuit that

(19) $$\dot{U}'_{\mathrm{B}} = \frac{\mathrm{j}\omega C_{\mathrm{m}} R_f}{1 + \mathrm{j}\omega C_0 R_f + \mathrm{j}2\omega C_{\mathrm{m}} R_f}(\dot{U}_{\mathrm{A}} + \dot{U}_{\mathrm{C}})$$

Assume voltage amplitude criterion presents mistakes in identification for transition resistance, then

(20) $$\left|\dot{U}'_{\mathrm{B}}\right| = \left| \frac{\mathrm{j}\omega C_{\mathrm{m}} R_f}{1 + \mathrm{j}\omega C_0 R_f + \mathrm{j}2\omega C_{\mathrm{m}} R_f}(\dot{U}_{\mathrm{A}} + \dot{U}_{\mathrm{C}}) \right| \ge k\frac{C_{\mathrm{m}}}{C_0 + 2C_{\mathrm{m}}}(U_{\mathrm{A}} + U_{\mathrm{C}})$$

that is

(21) $$R_f \ge \frac{k}{\sqrt{1-k^2}} \frac{1}{C_0 + 2C_{\mathrm{m}}}$$

Generally, the inter-phase mutual capacitance and the shunt capacitance of transmission lines per unit length are $0.008\mu\mathrm{F/km}$ and $0.015\mu\mathrm{F/km}$. If $k = 0.9$, (18) can identify the fault nature correctly when the transition resistance is less than 2121Ω. Hence, the performance of combination criteria will not be affected by transition resistance.

B. Simulation verification

The rated current of a 500kV transmission line is about 1.25kA and the power factor angle of system is not more than 30°. Hence, the setting value φ_{set}, I_{set} of the combination criteria are 45° and 0.125kA. For different faults of double-circuit line, the capacitive coupling voltage of open phase is different. Therefore, the setting value U_{set} of combination criteria is determined by fault type. U_{set} can set respectively as 22.9kV, 52.5kV, and 25kV for single-phase-to-ground fault, phase-to-phase-to-ground inter-circuit fault between two same lines and phase-to-phase-to-ground inter-circuit fault between two different lines.

Table 1. Performance of the novel adaptive reclosure combination criteria

Fault conditions	Fault nature	Combination criteria		
		Criterion (16)	Criterion (17)	Criterion (18)
90km No-load	Transient	×	×	*1*
	Permanent	×	×	*0*
	Permanent (R_f=400Ω)	×	×	*0*
Middle point Heavy-load	Transient	×	*1*	*0*
	Permanent	×	*0*	*0*
	Permanent (R_f=400Ω)	×	*0*	*0*

Note: × - the criterion is invalid; *1* - the criterion is satisfied; *0* - the criterion is not satisfied.

PSCAD is used to build a typical 100km 500kV double-circuit line model. Positive-sequence impedance of the line is $Z_1 = 27.8\angle 87.9°\ \Omega$, zero-sequence impedance is $Z_0 = 52.5\angle 83.9^\circ \Omega$. Simulating the most unfavorable conditions of combination criteria as: 1) permanent faults and transient faults occur at 90km of the line under no-load statue; 2) permanent faults occur at the middle point of the line under 30° power factor angle. The simulation results of different faults are shown in Table 1.

Adaptive reclosure scheme for double-circuit lines

The combination criteria can identify the fault nature of grounding fault, but it cannot distinguish transient fault from permanent fault of the phase-to-phase inter-circuit fault. Because during a transient phase-to-phase inter-circuit fault, the capacitive coupling voltage of two open phases are almost identical that is the same as the permanent phase-to-phase inter-circuit fault.

To compensate for the disadvantages of the combination criteria, the combination criteria and reclosing phase by phase can be integrated. The concrete steps of this adaptive reclosure scheme are: 1) judge whether the fault is grounding or not; 2) if the fault is grounding, then reclosed the open phase of circuit I; 3) according to the changes of voltage, the fault nature of the open phase of circuit II can be identified. Because during the permanent phase-to-phase inter-circuit fault, the voltage of open phase of circuit II will quickly raise to rated voltage after relcosing of the open phase of circuit I, that is obviously different from the transient fault.

In order to verify the method that reclosing phase by phase, the inter-phase transient fault and permanent fault between phase IA and phase IIC are simulated respectively. From Figure 8 and Figure 9, after phase IA closed, the fault nature of phase IIC can be easily identified by the variation trend of the voltage.

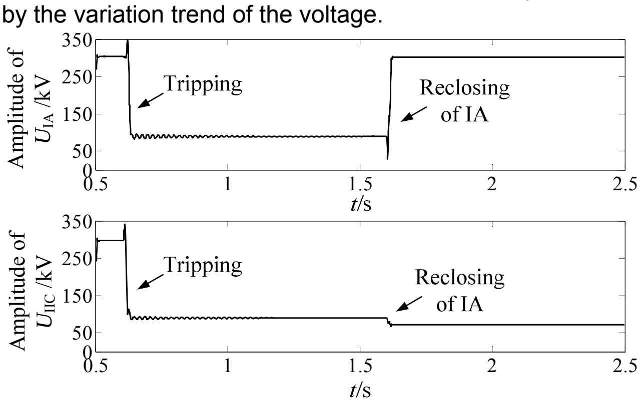

Fig.8. Voltage change trend of IA and IIC during a transient fault

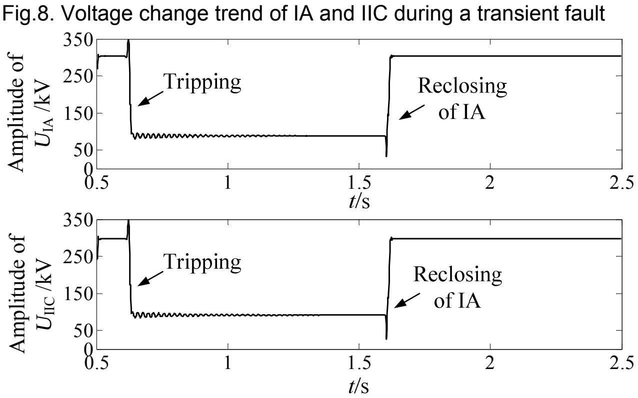

Fig.8. Voltage change trend of IA and IIC during a permanent fault

Conclusion

In this study, principles, advantages and disadvantages of voltage amplitude criterion and voltage phase criterion are analyzed. With the consideration of characteristics of single-phase-to-ground fault and single-phase inter-circuit fault of double-circuit lines, a novel adaptive reclosure scheme based on voltage amplitude criterion and voltage phase criterion and reclosuring phase by phase is proposed. This scheme inherits the advantages of voltage phase criterion and voltage amplitude criterion and overcome their respective shortcomings. The simulation results show that the new adaptive reclosure scheme can effectively distinguish transient fault from permanent fault for double-circuit lines.

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***Authors**: Dr. Candidate Xing DENG, College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China, E-mail: dengxing333@163.com.*