Study of Secondary Arc Suppression at Double-Circuit Transmission Line

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Abstract

Due to the coupling of double-circuit transmission line, the values of the secondary arc current and the recovery voltage on the double-circuit line are higher than that on the single-circuit line. These will affect the possibility of successful auto-reclosing. In order to ensure the successful single-pole auto-reclosing, the values of the secondary arc current and the recovery voltage must be limited below to a certain values. In this paper, two schemes to limit the secondary arc current and the recovery voltage were proposed respectively. Firstly, for the EHV double-circuit transmission line which has shunt reactor compensation, the fourth reactor compensation scheme was proposed to extinguish the secondary arc. The paper discussed the effect of the different connection styles and the values of the fourth reactor on the secondary arc current and the recovery voltage of a double-circuit transmission line. The calculation results showed that the secondary arc current and the recovery voltage could be limited to desired values by choosing appropriate value and different connection styles of the fourth reactor. Then, for the double-circuit transmission line which has no shunt reactor compensation, the scheme using the high speed grounding switches (HSGS) to extinguish the secondary arc on the double-circuit line was proposed. The simulation results showed that the magnitude of the secondary arc current and the recovery voltage was reduced by HSGS notably. The calculation results satisfied with the theoretical analysis. The proposed schemes in this paper are good approaches to extinguish the secondary arc on the double-circuit transmission lines.

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Keywords: double-circuit transmission lines; single pole auto-reclosing; secondary arc current; recovery voltage; high speed grounding switches (HSGS)

1. Introduction

Single phase auto-reclosing which is widely used in EHV transmission lines is an important measure to improve the reliability and stability of power system operation [1]. Successful single phase reclosing of a faulted EHV transmission line depends on rapid secondary arc extinction. Two factors which govern the probability of secondary arc extinction are the effective value of the steady-state secondary arc current and the rate of rise of the recovery voltage. Successful application of single phase reclosing requires that the magnitude of the secondary arc current should be kept below a certain level [2]. Methods currently used to limit the secondary arc current and the recovery voltage are the fourth reactor compensation scheme [3] and the High Speed Grounding Switch (HSGS) scheme[4]. The fourth reactor compensation scheme was used at the shunt compensated EHV transmission lines. But the Neutral reactor requires higher insulation levels, and which have poor operational flexibility. In addition, at the UHV transmission system which have fixed shunt reactor compensation, the reactive power balance and voltage regulator are difficult[5], and the values of the secondary arc current is difficult to restrict below to the required value by the fourth reactor compensation scheme [6]. The HSGS compensation scheme was used at the no shunt compensated transmission lines, which the fourth reactor compensation scheme can not be used to extinguish the secondary arc.

With the development of the power system, the double-circuit transmission lines which have more advantages are widely used in the EHV transmission system. Due to the electrostatic coupling and the electromagnetic coupling strengthened because of the closer distance of the double circuit lines, the values of the secondary arc current and the recovery voltage will become larger than that on the single-circuit transmission line when the single-phase ground fault occurs. The secondary arc became more difficult to extinguish and lower the successful rate of single-phase auto-reclosing. The current proposed methods of secondary arc suppression were mainly used for the single-circuit transmission line. The arc extinction effects of these methods are not satisfied. Appropriate measures must be taken to promote the arc extinction, and ensure the success of the single-phase reclosing [7]. But the study for the secondary arc extinction of the double-circuit transmission lines is less and imperfect presently. There is very less published paper about arc suppression of double-circuit transmission lines. Reference [8] proposed a non-optimal compensation, but the impact of the grounding resistance at the fault point on the secondary arc current did not be considered. Although the HSGS can be used at the transmission lines with no shunt reactor compensation to extinguish the arc, but its protection and control means are more complex. The special design was needed when HSGS used for the double circuit transmission line.

In this paper, two kinds of connection styles of the fourth reactor compensation schemes for the shunt compensated double-circuit transmission line were analyzed firstly. The appropriate compensation scheme to limit the secondary arc current and the recovery voltage was proposed for double-circuit transmission line. Then, the HSGS compensation scheme for the no shunt compensated double-circuit transmission line was proposed to extinguish the secondary arc. The principle and the effect of HSGS applied to the double-circuit transmission line was analyzed and calculated respectively. Simulation results satisfied with theoretical analysis.

2. The principle and theconnection styles of the fourth reactor compensation scheme

The secondary arc current and the recovery voltage consist of electrostatic induction component and electromagnetic induction component. Electrostatic induction component arising from the capacitive coupling between phases and lines can be partly or totally eliminated by appropriate shunt reactor. Electromagnetic induction component arising from the inductive coupling between phases and lines is affected by phases current and fault location, and is difficult to be eliminated by appropriate shunt reactor. Electrostatic induction component accounts a large proportion of the secondary arc current.

2.1 Connection styles and compensation principle on the single-circuit line

For the single-circuit transmission line, the fourth reactor compensation scheme is showed in Figure 1. The equivalent circuit of Figure 1 is showed in Figure 2. It can be concluded that,

$$X_1 = \frac{X_P}{X_N}(X_P + 3X_N) \tag{1}$$

$$X_0 = X_P + 3X_N \tag{2}$$

Where, X_P is the shunt compensation reactor at sending and receiving end of the line, X_N is the fourth reactor, X_1 and X_0 is equivalent reactance used for compensating capacitance of phase to phase and phase to ground.

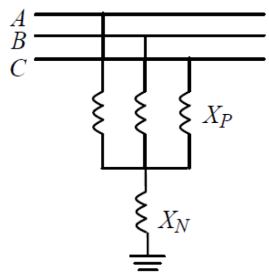


Figure 1. the fourth reactor compensation scheme

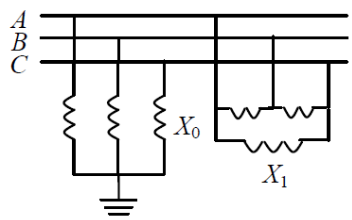


Figure 2. the equivalent of circuit of Figure 1

2. 2 Connection styles and compensation principle on the double-circuit transmission line

For the double-circuit transmission line, the connection style of the fourth reactor is the same with that on the single circuit line showed in Figure 1, here named method 1. The phase-to-phase and phase-to-ground capacitance can be compensated by the appropriate reactance X_1 and X_0. In addition, when the single-phase ground fault occurs, after tripping the fault phase, due to electrostatic coupling and electromagnetic coupling between the fault phase and the non-fault phase, power frequency component of the recovery voltage on fault phase will be generated as following,

$$U_m = U_y + U_{XL}/2 \tag{3}$$

Where, U_y is capacitance coupling component of recovery voltage. U_{XL} is inductance coupling component of recovery voltage.

Equation (3) can be written as following,

$$u_1(t) = U_1 \cos(\omega t + \theta_1) \tag{4}$$

Due to the existence of shunt complement reactance and the phase-to-phase and phase-to-ground capacitance, the resonance component will be generated on the inductance and capacitance elements of the circuit. The resonance component of recovery voltage can be written as following,

$$u_2(t) = U_0 \cos(\omega_0 t + \theta_0) \tag{5}$$

The recovery voltage on the fault phase is the superposition of these two components,

$$u(t) = u_1(t) - u_2(t) = \sqrt{U_1^2 + U_0^2 - 2U_1U_0\cos(\omega_2 t + \theta_2)}\cos(\omega t + \theta_1 + \delta) \tag{6}$$

Where,

$$\theta_2 = \theta_1 - \theta_0,\quad \omega_2 = \omega_1 - \omega_0,\quad \delta = tg^{-1}\frac{U_0\sin(\omega_0 t + \theta_2)}{U_1 - U_0\cos(\omega_0 t + \theta_2)}$$

Let

$$f(\omega_2 t) = \sqrt{U_1^2 + U_0^2 - 2U_1U_0\cos(\omega_2 t + \theta_2)} \tag{7}$$

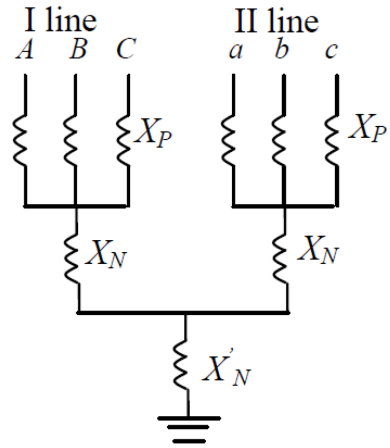


Figure 3. the compensation scheme on double-circuit lines

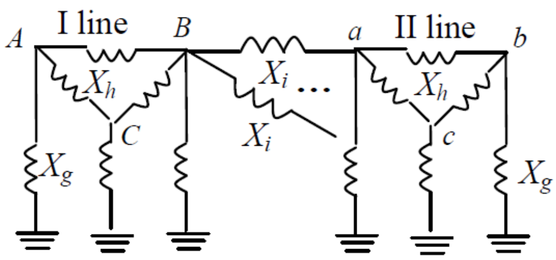


Figure 4. the equivalent circuit of Fig.3

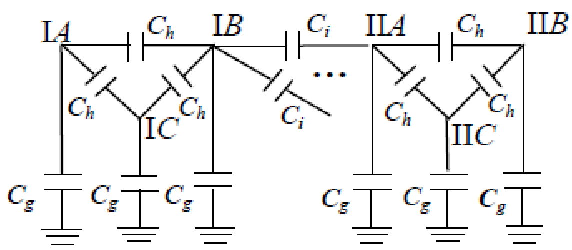


Figure 5. the coupling capacitance of double-circuit lines

From Figure 3 and Figure 4, it can be obtained that,

$$X_g = X_P + 3X_N + 6X_N' \tag{10}$$

$$X_h = \frac{X_P(X_P + 3X_N + 6X_N')}{X_N + 2X_N' - \dfrac{X_P X_N'}{X_P + 3X_N}} \tag{11}$$

$$X_i = \frac{X_P + 3X_N}{X'_N}(X_P + 3X_N + 6X'_N) \quad (12)$$

Setting the compensation degree is k. The B_g 、B_h and B_i is susceptance of the phase -to-ground, phase -to-phase, and line-to-line respectively. $B_g = \omega C_g$, $B_h = \omega C_h$, $B_i = \omega C_i$. So $X_g B_g = k$, $X_h B_h = k$, $X_i B_i = k$. Then according to the requirement of compensation degree, choose the appropriate X_g 、X_h and X_i , the values of X_P 、X_N and X'_N can be obtained accordingly.

$$X_P = \frac{1}{k(B_g + 3B_h + 3B_i)} \quad (13)$$

$$X_N = \frac{X_P}{\frac{1}{X_P(B_h - B_i)} - 3} \quad (14)$$

$$X'_N = \frac{B_i}{\left[\frac{1}{X_P} - 3(B_h + B_i)\right]\left[\frac{1}{X_P} - 3(B_h - B_i)\right]} \quad (15)$$

The secondary arc current and the recovery voltage can be limited to below the required value.

3. The Principle of the High Speed Grounding Switch

For the no shunt compensated double-circuit transmission line, HSGS scheme was used to improve the successful rate of auto-reclosing. HSGS was installed at the sending and receiving end of the line. Using HSGS to extinguish secondary arc is a cost-effective way. The principle of this method is to make the open arc at point of failure converted into compression arc within the switch. The secondary arc current and the recovery voltage are greatly reduced so that the arc is easy to extinguish. And only a few hundred amperes of current through the HSGS, the switch could break easily as well. The action process of HSGS is as following,

a) single-phase ground fault occurs, the primary arc generated;

b) the circuit breaker at the both ends of the fault phase is tripped, the primary arc is extinguished, the secondary arc generated;

c) the HSGS installed at the both ends of the fault phase is grounded quickly, the secondary arc extinguished;

d) the HSGS opened quickly;

e) The circuit breaker is closed again,

the transmission lines to resume normal operation.

The Installation of HSGS on transmission lines is showed in Figure 6 (only single line was showed).

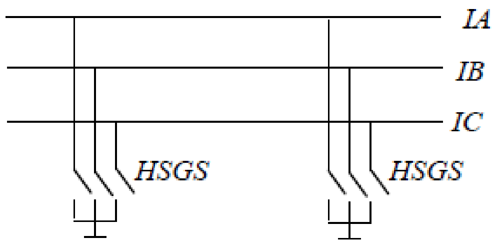


Figure 6. a transmission line with HSGS scheme

Because of the HSGS grounded, the voltage of the fault phase was reduced greatly. The equivalent capacitance at the both ends of fault phase is shunted by the HSGS, so the secondary arc current was reduced and conducive to the extinguishing of the arc. The HSGS shunt effect is affected by the ratio of frequency grounding resistance of the HSGS to that of fault point.

4. Simulation of the Double-circuit Lines with Shunt Reactor Compensation

A double-circuit transmission line for simulation study was showed in Figure 7. The parameters of the system are given below,

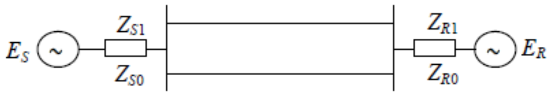


Figure 7. Diagram of simple power system for calculation

Source at sending end: E_S=354.178∠0^0,

Z_{S1}=4.638+j300.947Ω, Z_{S0}=j102.81Ω

Source at receiving end: E_R=286.434∠-20^{0}kV,
Z_{R1}=4.922+j55.3738Ω, Z_{R0}=49.221+j166.121Ω

Z_{S1}, Z_{S0}, Z_{R1}, Z_{R0} are positive and zero sequence impedance at sending and receiving end respectively.

The three phase reactors with the fourth reactor are shunted on each terminal. The apparent power is 120Mvar on the both terminals. The rated voltage is 550kV at one terminal and 525kV at the others. The delivered power on the lines was 245MVA. The fourth reactor on both terminals is 1000Ω. The length of lines is 256km. The impedance of lines is calculated by the EMTP line constants sub-routing program.

4.1 The effect of different connection styles of the fourth reactor on secondary arc current and recovery voltage

Using the two methods described in the previous section 2.2 to limit the arc current and the recovery voltage, respectively. The following two operating conditions were simulated: (1) single grounding fault occurs at phase A of line I. (2) single grounding fault occurs at phase A of line I and phase A of line II simultaneously. The fault point was at x km from the sending end. x=0, 85, 175, 256 respectively. The secondary arc current and the recovery voltage were calculated. Table 1 showed the calculation results of the secondary arc current IS and the recovery voltage VR at IA single phase to ground fault. Where X'_N =400Ω in method 2. Table 2 showed the calculation results of the secondary arc current IS and the recovery voltage VR at IA and IIA simultaneous single phase to ground fault. Where X'_N =700Ω.

From Table 1, we can see that values of the secondary arc current IS and the recovery voltage VR did not exceed allowable values; besides the recovery voltage VR was reduced significantly by using method 2. From Table 2, we can see that the values of the secondary arc current IS and the recovery voltage VR exceed the limit by using method 1, while the value of the secondary arc current IS and the recovery voltage VR can be limited to under demanded values by using method 2.

Table 1. Secondary arc current and recovery voltage at IA single phase to ground fault

x / km		0	85	175	256
V_R /k V	method1	29.65	30.59	30.51	28.87
	method2	11.11	12.22	12.67	12.34
I_S / A	method1	8.01	8.16	8.15	7.87
	method2	9.34	9.31	9.15	8.73

Table 2. Secondary arc current and recovery voltage at IA, IIA simultaneous single phase to ground fault

x / km		0		85		175		256	
		IA	IIA	IA	IIA	IA	IIA	IA	IIA
V_R / kV	method1	102.60	102.3	102.1	101.2	99.33	97.51	94.06	92.08
	method2	28.15	27.33	27.94	23.46	26.93	18.15	24.95	13.14
I_S / A	method1	23.46	23.75	22.89	23.00	22.32	22.14	21.63	21.32
	method2	7.89	8.03	7.76	6.77	7.57	7.37	7.62	3.95

4.2 The effect of the values of the fourth reactor on secondary arc current and recovery voltage

As requirements of reactive power compensation and voltage regulation of EHV transmission system, the shunt compensation reactance X_P has been determined. So in this section different values of the compensation reactance X_N and X'_N was taken to discuss their effects to the secondary arc current and the recovery voltage. Figure 7 and Figure 8 showed curves of the values of the secondary arc current IS and the recovery voltage VR varied with the fourth compensation reactance XN when IA single phase to ground fault and IA IIA simultaneous single phase to ground fault at the scheme 1 respectively.

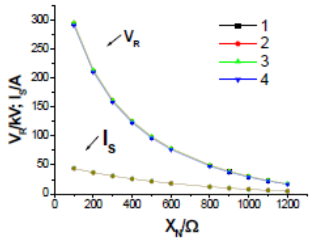


Figure 7. V_R and I_S varied with X_N when IA single phase to ground fault at the scheme 1

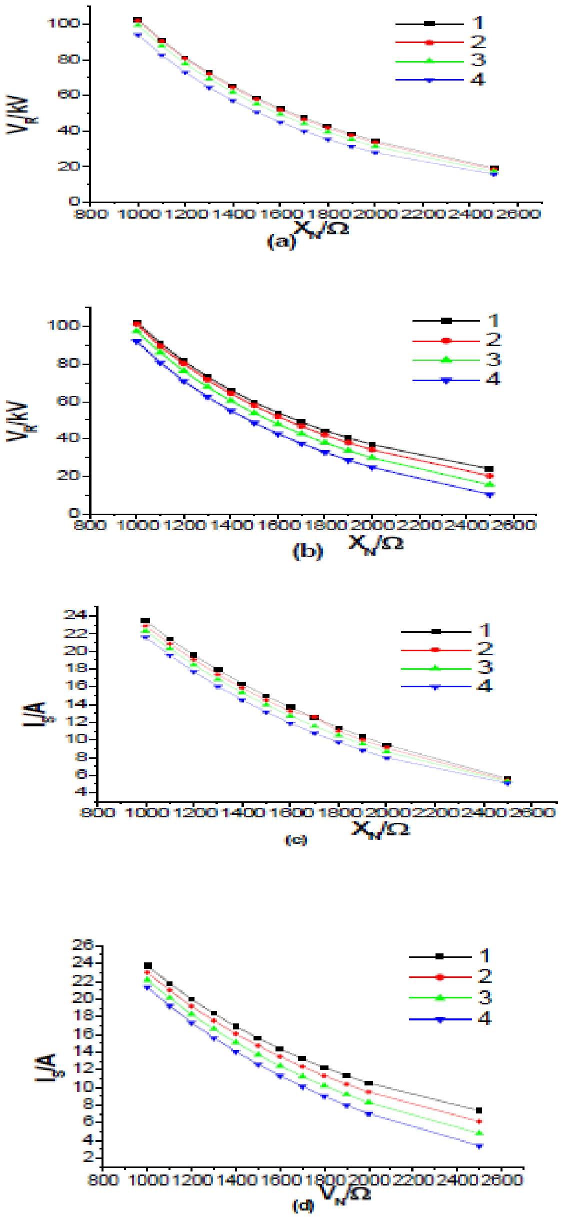


Figure 8. VR and IS varied with XN when IA IIA simultaneous single phase to ground fault at the scheme 1, (a)VR of IA varied with XN, (b) VR of IIA varied with XN, (c)IS of IA varied with XN , (d) IS of IIA varied with XN.

From the Figure 7 and Figure 8, we can see that the values of the secondary arc current I_S and the recovery voltage V_R decreasing with X_N increasing.

Figure 9 and Figure 10 showed the curves of values of the secondary arc current IS and the recovery voltage VR varied with X'_N when IA single phase to ground fault and IA and IIA simultaneous single phase to ground fault at the scheme 2 respectively. We can see from Figure 9, if X'_N =800 ~ 900Ω, the arc current got a minimum value; if X'_N =600Ω，the recovery voltage got a minimum value. With X'_N increasing, the I_S and V_R increasing. When X'_N =1000~1200Ω, I_S and V_R got a minimum value.

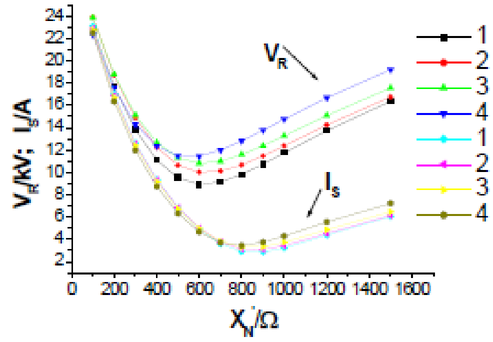
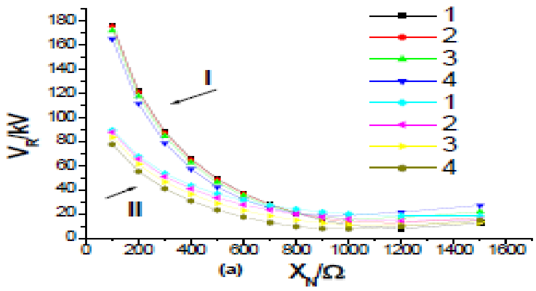
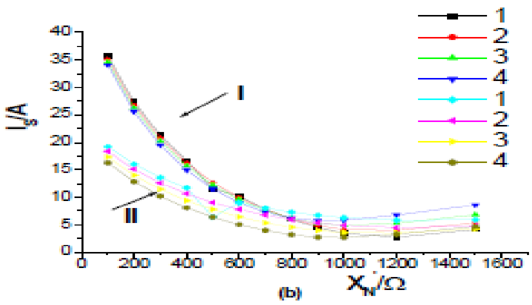


Figure 9. V_R and I_S varied with X'_N when IA single phase to ground fault at the scheme 2



(a)



(b)

Figure 10. V_R and I_S varied with X'_N when IA IIA simultaneous single phase to ground fault at the scheme 2, (a) V_R of IA and IIA varied with X'_N, (b) I_S of IA and IIA varied with X'_N

In addition, the effect of grounding resistance on the secondary arc current and the recovery voltage is very limited by the simulation and calculation.

The curves 1~4 showed in Figure 7 to Figure 10 indicate the values of V_R and I_S when the fault occurs at 0，85，175，256 km from the sending end respectively.

4.3 The effect of the fourth reactor on the secondary arc at one circuit out of service

When one line operating and another line tripped and grounded of the double-circuit transmission line, the remaining circuit reverts to a single-circuit line. The auto-reclosing performance is good. When the compensation reactor $X_N^{'}$ did not employed, the phase to phase compensation reactance X_1 and the phase to ground compensation reactance X_0 is as following,

$$X_1 = \frac{X_P}{X_N}(X_P + 3X_N) \tag{15}$$

$$X_0 = X_P + 3X_N \tag{16}$$

When the compensation reactor $X_N^{'}$ was employed, the phase to phase compensation reactance X_1 and the phase to ground compensation reactance X_0 is as following,

$$X_h = \frac{X_P(X_P + 3X_N + 6X_N^{'})}{X_N + 2X_N^{'} - \dfrac{X_P X_N^{'}}{X_P + 3X_N}} \tag{17}$$

$$X_g = X_P + 3X_N + 6X_N^{'} \tag{18}$$

Meanwhile, the compensation reactance between the double lines X_i is as following,

$$X_i = \frac{X_P + 3X_N}{X_N^{'}}(X_P + 3X_N + 6X_N^{'}) \tag{19}$$

The reactance compensation degree was increased. The secondary arc extinction does not affected by the employed compensation reactance $X_N^{'}$. The secondary arc does not affected by the tripped line.

5. Simulation of double-circuit line without shunt reactor compensation

Diagram of simulation system is showed in Figure 7，the system parameter is same with the simulation case in section 4. The length of lines is 150km. There is no shunt capacitor compensation on the double-circuit line. The impedance of lines is calculated by the EMTP line constants sub-routing program.

The calculation results of the secondary arc current and the recovery voltage without HSGS compensation scheme were showed in Table 3. The values of the secondary arc current and the recovery voltage exceed the limits when HSGS did not been adopted. The secondary arc can not be extinguished. Using HSGS to extinguish the secondary arc, HSGS power frequency grounding resistance was set to 1.0Ω, short-circuit point power frequency grounding resistance was set to 10Ω. The secondary arc current and the recovery voltage are calculated at single phase grounding fault occurs at phase A of line I by using EMTP. The calculation results were showed in Table 4. The magnitude of the secondary arc current and the recovery voltage were reduced significantly because of the grounding and shunting of the HSGS. This method solved the problem of the secondary arc suppression on the double-circuit lines without shunt reactor compensation.

Table 3. Secondary arc current and recovery voltage without compensation scheme

fault location (x, km)	0	50	100	150
recovery voltage (V)	48.71	48.86	48.68	48.15
Secondary arc current (A)	27.48	27.40	27.31	27.20

Table 4. Secondary arc current and recovery voltage using HSGS scheme

fault location (x, km)	0	50	100	150
recovery voltage (V)	20.04	189.3	177.0	25.65
Secondary arc current (A)	1.82	9.15	8.55	2.33

6. Conclusion

The fast secondary arc extinction is the ensurement of the successful single phase auto-reclosing. The secondary arc current and the recovery voltage must be limited below to the desirable values for the reliable secondary arc extinction. For the shunt compensated double-circuit transmission line, the fourth reactor compensation scheme was proposed to extinguish the secondary arc. The connection style and the value of the compensation reactor was designed and calculated. The secondary arc current and the recovery voltage can be limit to the desirable values by choosing appropriate value of the fourth reactor. Using the method 2 proposed in this paper, a better compensation effect can be got. For the no shunt reactor compensation lines, the HSGS scheme to extinguish the secondary arc on the double-circuit lines was proposed. Because of the effect of grounding and shunting of the HSGS, the magnitude of the secondary arc current and the recovery voltage was reduced by HSGS notably to ensure the successful single-pole auto-reclosing. The theoretical analysis and simulation results showed that the HSGS scheme is a better way to extinguish the secondary arc.

Acknowledgments

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