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Research on Current Interruption by Grounding switch Used in 750kV Double-circuit Transmission Lines

***Abstract**. In order to interrupt electromagnetically and electro-statically inductive current with high amplitude, grounding switches are applied in double-circuit transmission lines. In this paper, the formula of the induced voltage and current are drawn under different condition of grounding switch installed on the maintenance line. In order to clarify the characteristics of every electrical parameter, after calculating the capacitance and inductance matrix of 750kV double circuit transmission lines, simulation research is conducted using EMTP-ATP. Inductive voltage and current of 750kV double-circuit transmission line are calculated and analyzed. Furthermore, in order to classify the worst switching parameter of grounding switches, the steady-state currents and the transient recovery voltage (TRV) are also calculated and analyzed. And then, the tests of capacitive and inductive current interruption for a 800kV grounding switch are also carried out in the laboratory. The results of the simulation and experiment in this paper provide guiding opinions for selecting grounding switches used in the 750kV double-circuit transmission lines.*

***Streszczenie.** W pracy określano zależności prądu i napięcia indukowanego w uziemionym przełączniku przy różnych warunkach pracy. Obliczono pojemność i indukcyjność linii transmisyjnej 750 kV a następnie symulowano przebiegi prądów. (**Badania prądu przerwania w uziemionym przełączniku używanym w podwójnej linii transmisyjnej 750 kV**)*

Keywords: 750kV double-circuit line, Grounding switch, Simulation, Experimental
Słowa kluczowe: przełącznik wysokonapięciowy, prady przerwania

Introduction

With the development of the electric power system, the 750kV transmission system will become the backbone of northwest China electric power system [1]. To adopt the double-circuit transmission line is an effective technology to decrease the transmission corridor and improve the capability of the power transmission. Therefore, it has become the main development trend of the large-scale transmission systems.

Due to the extensive utilization of the double-circuit transmission line, the electrostatic and electromagnetic coupling effects become remarkable. When one transmission line is disconnected and grounded at both ends, and the other one continues to carry the normal loading current, a high current will be inducted into the grounded transmission line, obviously, this current will flow through the closed grounding switches [2-6]. Therefore, if the grounded line is put into running again, the grounding switches have to open two different current depending on the operating sequence of the switches. The grounding switch opened firstly has to interrupt a relatively high induced inductive current. While, the second grounding switch has to interrupt a much smaller capacitive current [7]. In both cases, there is a transient recovery voltage (TRV) with high value in operation grounding switch. Therefore, the grounding switches of the double-circuit must be able to interrupt the two kinds of current [8-12].

Several equivalent electrical models have been developed and used to help study the electrostatic and electromagnetic coupling effects of double circuit transmission lines. The following case was dealt with as an example in [4]: A 500 kV line carries a current of 4 kA. If this line is 450 km long, it induces a maximum current of 255 A rms (361 A peak value) in the grounded line running in parallel. When the grounding switches are opened, a TRV with a rate-of-rise of up to 38 V/ps and a peak value of up to 108 kV will show up across the open contacts. In [3], both the electrostatic and the electromagnetic induction levels are given for the different voltage class combinations between the energized and the de-energized circuits in the range 69 kV to 1150 kV. However, there are yet few reports about the electrical models characterizing the inductive voltage and current of 750kV double circuit transmission lines. Moreover, the range of inductive parameter is still not known yet, which limits the choice of appropriate switch for the 750kV lines. In addition, we have not seen any reports about the test on the 750kV grounding switch.

Based on the calculation model of the double circuit transmission lines, this paper presented the calculation equation for the induced voltage and current along the maintenance line. And then various factors that affect the induced voltage and current were studied. Combining with the calculation equation, the induced voltage and current under different operation states are calculated by ATP-EMTP [13]. Finally, in order to test the switching capability of the 800kV grounding switches, which are used in the 750kV double-circuit, tests for switching capacitive and inductive currents of the grounding switch are conducted in the test lab.

Induced voltage and current

(A) Calculation Methods of induced voltage and current

The calculation model of the coupling effects between the double circuits transmission line is shown in Fig.1.

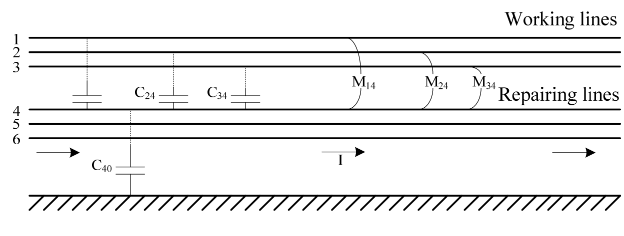


Fig. 1. The calculation model of the coupling effects between the double circuits transmission line

In Fig.1, line 1、2、3 represent the three phase of the working lines, and line 4、5、6 are the three phase of the maintenance lines. $\dot{U}_1$ and $\dot{U}_2$, $\dot{I}_1$ and $\dot{I}_2$ are the induced voltage and current of sending and receiving end of the maintenance lines respectively. C_{14}、C_{24}、C_{34} and M_{14}、M_{24}、M_{34} are mutual capacitance and mutual inductance between two circuits. C_{40} is inductance to the ground per unit length of the line 4.

Using the distributed parameter method, the current $\dot{I}$ and voltage $\dot{U}$ of the maintenance line 4 are:

(1) $$-\frac{\partial \dot U}{\partial l} = j\omega L\dot I + j\omega M_{14}\dot I_A + j\omega M_{24}\dot I_B + j\omega M_{34}\dot I_C$$

(2) $$-\frac{\partial \dot I}{\partial l} = j\omega C_{40}\dot U + j\omega C_{14}(\dot U - \dot U_A) + j\omega C_{24}(\dot U - \dot U_B) + j\omega C_{34}(\dot U - \dot U_C)$$

Suppose:

$$\alpha = -\omega^2 L[C_{14} + (-\frac{1}{2} - j\frac{\sqrt{3}}{2})C_{24} + (-\frac{1}{2} + j\frac{\sqrt{3}}{2})C_{34}$$

$$Z_c = \sqrt{L/(C_{40} + C_{41} + C_{42} + C_{43})}$$

$$M = M_{14} + (-\frac{1}{2} - j\frac{\sqrt{3}}{2})M_{24} + (-\frac{1}{2} + j\frac{\sqrt{3}}{2})M_{34}$$

Then:

(3) $$\dot U_2 = \dot U_1 \cos\gamma l - j\dot I_1 Z_c \sin\gamma l + \frac{\alpha}{\gamma^2}\dot U_A(1-\cos\gamma l) - j\frac{M}{L}Z_c\dot I_A \sin\gamma l$$

(4) $$\dot I_2 = -j\frac{\dot U l}{Z_c}\sin\gamma l + \dot I_1\cos\gamma l + j\frac{\alpha}{\gamma^2 Z_c}\dot U_A \sin\gamma l + \frac{M}{L}\dot I_A(\cos\gamma l - 1)$$

where, l is the length of the line, γ is the propagation constant of the transmission line, and $\gamma = j\omega\sqrt{L(C_{40}+C_{41}+C_{42}+C_{43})}$.

(B) Theoretical formula of induced voltage and current for the various switching operations

The induced voltage and current mainly include the electrostatic and electromagnetic induced component. The former is mainly caused by the mutual capacitance between the operating line and maintenance line, and the latter is mainly caused by the mutual inductance between the working line and maintenance line. Due to the various switching operations, the calculation of the induced current and voltage can be divided into the following kinds:

1) Both ends of the line are opened

While the grounding switches of the two ends on the maintenance line are opened, just as shown in Fig.2. Obviously, at this condition, $I_1=I_2=0$. According to equation (1)~(4), the induced voltage $\dot U_1$ and $\dot U_2$ can be drawn,

(5) $$\dot U_1 \approx \dot U_2 \approx \frac{\alpha}{\gamma^2}\dot U_A = \frac{(C_{14} - \frac{1}{2}C_{24} - \frac{1}{2}C_{34}) + j\frac{\sqrt{3}}{2}(C_{24} - C_{34})}{C_{14} + C_{24} + C_{34} + C_{40}}\dot U_A$$

When the grounding switches of the two ends on the maintenance line are unearthed, the induced voltage is up to the electrostatic induced component. The above equation (5) indicates that the electrostatic component is ultimately caused by the imbalance of the mutual capacitance. Moreover, if the line's voltage level is decided, the length of the double-circuits or the transmitted power has no relationship with the induced voltage.

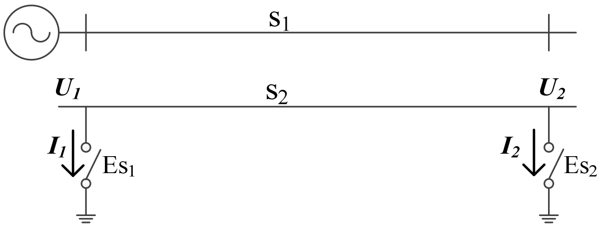


Fig. 2. Both ends of the maintenance lines are opened

2) One of the grounding switches opened and the other one is closed While one of the grounding switches is opened and the other is closed, just as shown in Fig.3. Obviously, at this condition, $I_1=0$, $U_2=0$. According to equation (1)~(4), the induced voltage $\dot U_1$ and current $\dot I_2$ can be drawn respectively,

(6) $$U_1 = j(M/L)Z_c I_A \tan\gamma l = j\omega l(M_{14}I_A + M_{24}I_B + M_{34}I_C)$$

(7) $$I_2 = j(\alpha/\gamma^2 Z_c)U_A \tan\gamma l = j\omega l(C_{14}U_A + C_{24}U_B + C_{34}U_C)$$

The above equations (6) and (7) indicate that when one of the switches is opened while the other one is closed, the induced voltage is up to the electromagnetic induced component, and the induced voltage is decide by the length of the line and the transmitted power. In addition, the induced current is decided by the length of the line and the voltage level.

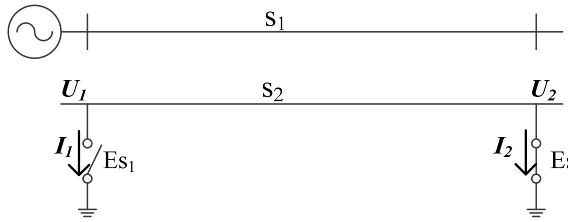


Fig. 3. The sending end is opened and the receiving end is closed

3) Both ends of the line are closed While the grounding switches of the two ends on the maintenance line are closed, just as shown in Fig.4. Obviously, at this condition, $U_1=U_2=0$. In addition, the induced current of sending and receiving end of the maintenance lines are equal, which can be drawn by equation (1)~(4),

(8) $$I_1 \approx I_2 \approx -(M_{14}I_A + M_{24}I_B + M_{34}I_C)/L$$

The above equation (8) indicates that when the grounding switches of the two ends on the maintenance line are closed, the induced current is up to the electrostatic induced component. Moreover, the induced current has no relationship with the length of the transmission line, and its value only depends on the transmitted power.

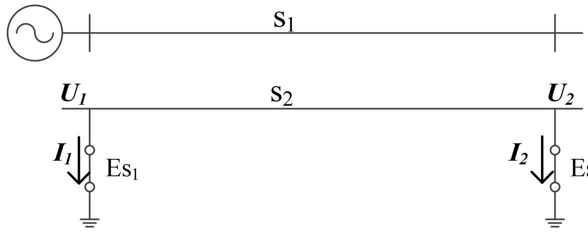


Fig. 4. Both ends of the maintenance lines are closed

Simulation and Experimental investigations

(A) Comparison between the simulation result and theoretical calculation result

A 750kV double-circuit transmission lines adopting three-piece transposition with length of 240km, as shown in Fig. 5, is taken as an example to analyze the electrostatic and electromagnetic coupling effects. In Fig. 5, each ac conductor bundle contains six sub-conductors and the span distance between two adjacent sub-conductors is 400 mm, and the mode of each sub-conductor is LGJ-400/50. OPGW-145 and JLB20A-150 are selected for the ground wire with arrangement of inverse phase sequence. Moreover, at the end of the line, there are shunt reactors, and the compensation degree is 80%.

Based on the parameters of 750kV double-circuit transmission lines, the matrix of capacitance and inductance can be calculated, the results are shown in Tab.1 and Tab.2.

Because of the influence of shunt reactor and conductor transposition, it is feasible but difficult to derive formula of the induced voltage and current accurately. In this paper, an

EMTP-ATP model without shunt reactor and conductor transposition is built firstly, and then the simulation results are compared with theoretical results derived from the above formula to verify the accuracy of the ATP model. Tab.3 shows the simulation result and the theoretical result of the induced voltage under the condition of the grounding switches are closed on the maintenance line.

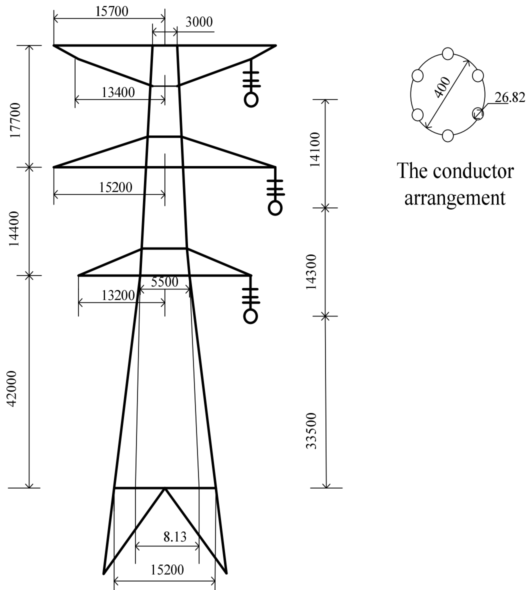


Fig. 5. Arrangement of the conductors of a 750kV double-circuit lines on the same tower

Table 1 The capacitance parameter matrix (μF/km)

Order	1	2	3	4	5	6
1	1.178E-2					
2	2.339E-3	1.211E-2				
3	6.932E-4	2.543E-3	1.246E-2			
4	1.338E-3	7.285E-4	3.570E-4	1.178E-2		
5	7.285E-4	7.744E-4	6.045E-4	2.543E-3	1.211E-2	
6	3.570E-3	6.045E-4	8.632E-4	6.932E-4	2.543E-3	1.246E-2

Table 2 The inductance parameter matrix (mH/km)

Order	1	2	3	4	5	6
1	1.30955					
2	0.55239	1.41016				
3	0.45882	0.65611	1.45375			
4	0.40710	0.49926	0.56815	1.45417		
5	0.42506	0.48862	0.49949	0.65678	1.41111	
6	0.42182	0.42576	0.40478	0.40622	0.55417	1.31245

Table 3 The simulation and theoretical results of the induced voltage

Phase	A/kV	B/kV	C/kV
Simulation result	22.39	8.54	45.63
Theoretical result	20.59	8.11	45.29
Difference	8.74%	5.3%	0.75%

Just as shown in Table 3, there is about 8.74%, 5.3% and 0.75% difference between the simulation and theoretical result for the induced voltage of three phases respectively. The difference is caused by the theoretical formula which ignores some factors, such as shunt reactor and conductor transposition. On the Consideration of Tab.1, the calculation methods of induced voltage and current presented above is right and the simulation result based on ATP model is credible. Therefore, for the calculation convenience, the following research is mainly based on the ATP model.

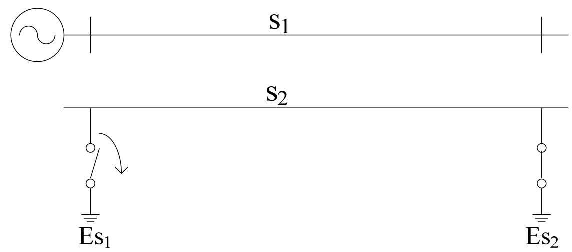
(B) Simulation

The steady-state current and voltages are calculated with the ATP- EMTP when the sending and receiving end of maintenance line are grounded by the grounding switches at different state, the results are shown in Tab.4.

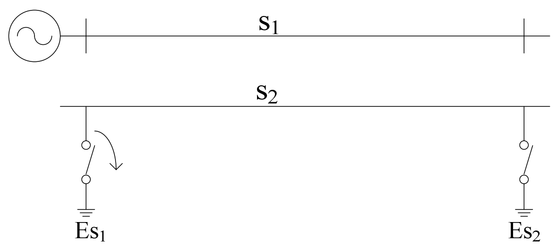
Table 4 Induced voltage and current of 750kV double circuit

Grounding switches state	Induced voltage/kV		Induced current/A	
	Sending end	Receiving end	Sending end	Receiving end
Both open	44.53	42.68	\	\
Grounded in head	\	8.15	15.19	\
Grounded in tail	7.96	\	\	15.02
Both grounded	\	\	122.54	124.79

According to the data shown in Tab.4, the TRVs are also calculated for the following two cases as shown in Fig.6. Case 1 is that the switch at the receiving end is grounded and the switch at the sending end is operated to open. Case 2 is that the switch at the receiving end is at open condition and the switch at the sending end is operated to open. Obviously, the grounding switches are subjected to two different types of stresses at above two conditions. For case1, the operated switch (Es1 in Fig.6 (a)) will interrupt a reactive inductive current, for case2, the operated switch (Es1 in Fig.6 (b)) will interrupt a capacitive current.



(a) Case 1



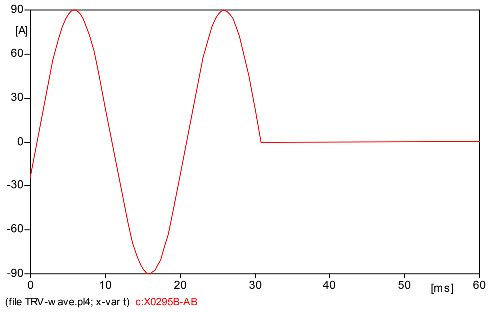
(b) Case 2

Fig.6 Two cases of the grounding switches operation

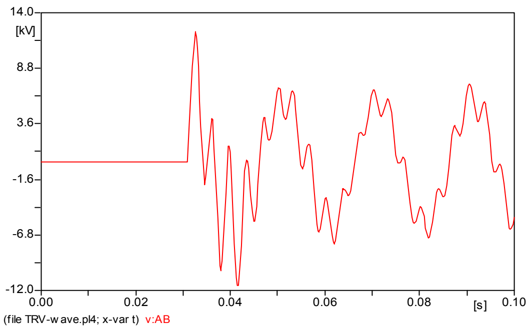
In order to study the transient electrical procedure of the grounding switch during the operation period, the inductive current and the rising rate of the TRV are calculated for above two cases, which are shown in Fig.7.

Just as indicated in Fig.7, the induced inductive current and the rising rate of the TRV are relatively high for case1, but the peak value of the TRV remains small because the receiving end of the maintenance line is still grounded. Oppositely, the induced capacitive current is relatively small and the TRV rises slowly for case2, but the peak value of the TRV is much higher than that of case1.

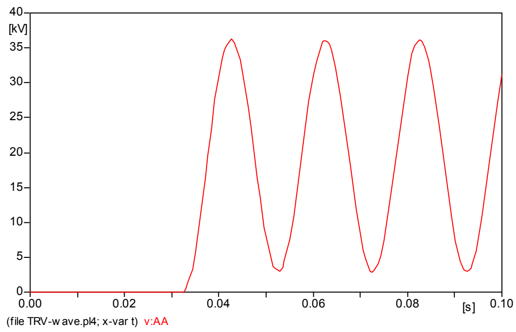
The induced voltage and current of the maintenance line and the TRV of grounding switch under different condition are shown in Table 5 to Table 8.



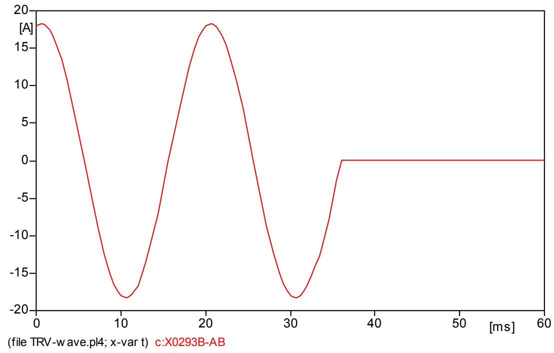
(a) Current (before open the ES1) for case1



(b) TRV for case1



(c) Current (before open the ES1) for case2



(d) TRV for case2

Fig.7 The current and TRV for case1 and case2

Tab.5 Induced voltage and current of 750kV double circuit at the peak load with different compensation degree (Case1)

Length of the line	Compensation degree	Case1 I_{EM}	U_{EM}	U_{REM}	RRRV
114km	0	122.1	4.944	7.61	13.246
	70%				
	80%				
	90%				
192km	0	124.69	6.58	9.45	13.465
	70%				
	80%				
	90%				
240km	0	124.79	8.134	16.79	13.649
	70%				
	80%				
	90%				

Table 6 Induced voltage and current of 750kV double circuit at the peak load with different compensation degree (Case2)

Length of the line	Compensation degree	Case2 I_{ES}	U_{ES}	U_{RES}
114km	0	11.72	17.49	33.46
	70%	11.25	37.99	68.44
	80%	11.21	45.72	90.0
	90%	11.19	57.52	110.14
192km	0	15.19	17.08	32.81
	70%	14.41	36.98	68.03
	80%	14.36	44.76	88.74
	90%	14.29	56.82	112.37
240km	0	15.19	17.08	32.81
	70%	18.95	36.67	68.55
	80%	17.95	44.53	87.39
	90%	17.65	56.81	111.37

Table 7 Induced voltage and current of 750kV double circuit at the different load with different compensation degree (Case1)

Transmitted power	Compensation degree	Case1 I_{EM}	U_{EM}	U_{REM}	RRRV
1200MW	0	71.79	2.89	4.02	6.686
	70%				
	80%				
	90%				
1800MW	0	107.0	4.34	6.56	10.114
	70%				
	80%				
	90%				
2200MW	0	111.4	5.34	8.35	12.020
	70%				
	80%				
	90%				

Table 8 Induced voltage and current of 750kV double circuit at the different load with different compensation degree (Case2)

Length of the line	Compensation degree	Case2 I_{ES}	U_{ES}	U_{RES}
1200MW	0	11.38	16.98	32.38
	70%	11.11	37.57	67.65
	80%	11.09	45.22	88.97
	90%	11.07	56.92	108.6
1800MW	0	11.62	17.34	33.14
	70%	11.21	37.85	68.19
	80%	11.18	45.56	89.72
	90%	11.15	57.32	109.7
2200MW	0	11.78	17.59	33.67
	70%	11.28	38.08	68.61
	80%	11.24	45.83	90.29
	90%	11.21	57.67	110.5

Note: In the Tab.5-8, I_{EM}、I_{ES} represents the induced current at case1 and case2 respectively, with unit A. U_{EM}、U_{ES}、U_{REM}、U_{RES} represents the induced voltage and the peak value of the TRV at case1 and case2 respectively, with unit kV. RRRV represents the rate of rise of the TRV, with the unit V/μs。

From the data shown in Tab.5-Tab.8, the following results can be drawn.

For case1, the amplitude of TRV is about 1.5 times that of induced voltage. The amplitude of TRV is in proportion to the length of the line and the transmitted power, while the rising rate of the TRV is independent with the length and the compensation degree of the line, and it is in proportion to the induced current or the transmitted power of the working line. For case2, the amplitude of TRV is about 2 times that of induced voltage, and it is independent with the length and the transmitted power of the line.

(C) Experimental investigations

According to above part (B), the ATP simulation result shows that the grounding switch has to interrupt a maximum inductive current of 125A. The peak value of TRV is of 17kV and the rising rate is of 14 V/μs in case1. The grounding switch has to interrupt a max capacitive current of 19A and the TRV has a peak value of 113kV in case2.

In order to test the switching capability of the 800kV grounding switches, a test circuit which can simulate the inductive current interruption is designed, which is shown in Fig.8. Initially, the value of resistor R and capacitor C are selected to make the peak value and the rising rate of TRV considerably higher than that required. The electrical values gained for the inductive case are: I=400A, Us=39kV, U_{REM}=79kV, $RRRV$=29 V/μs. Furthermore, a test circuit which can simulate the capacitive current interruption is also designed, which is shown in Fig.9. The capacitances are chosen to make the capacitive current through the test object is of 100A, and the other electrical values gained for the capacitive case are: U_C=100kV, U_{REM}=260kV.

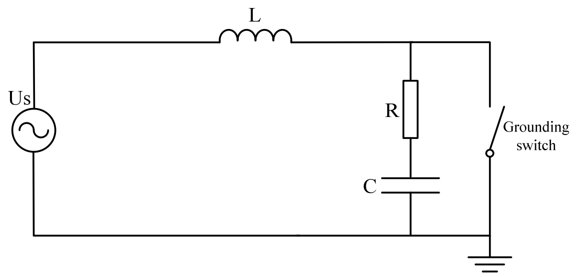


Fig.8 Test circuit for inductive switching U_S=*39kV* X_L=*65Ω C=6μF R=38Ω*

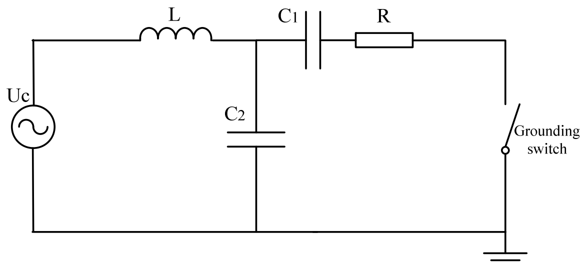
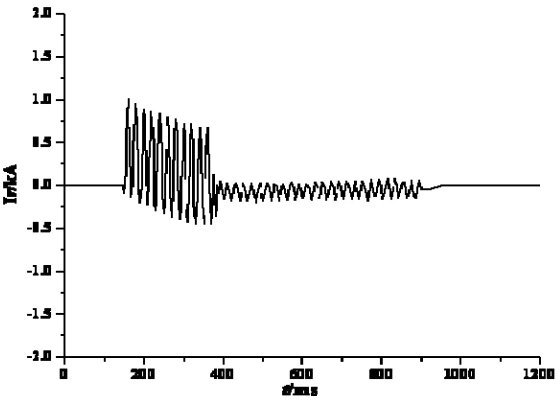
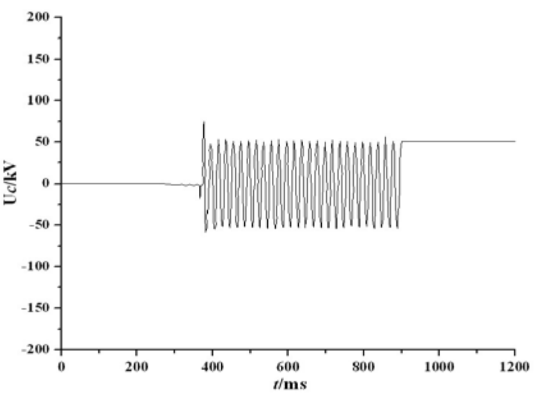


Fig.9 Test circuit for capacitive switching U_S=*100kV* C_1=*3.73μF* C_2=*3.19μF R=38Ω*



(a) Inductive current

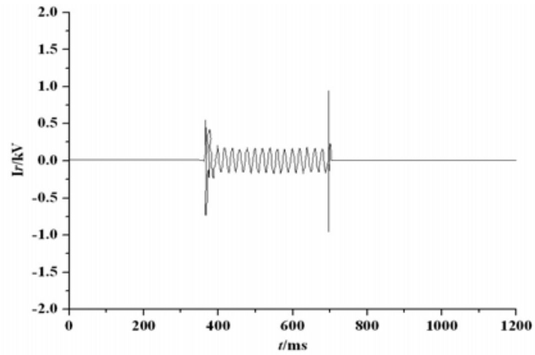


(b) TRV

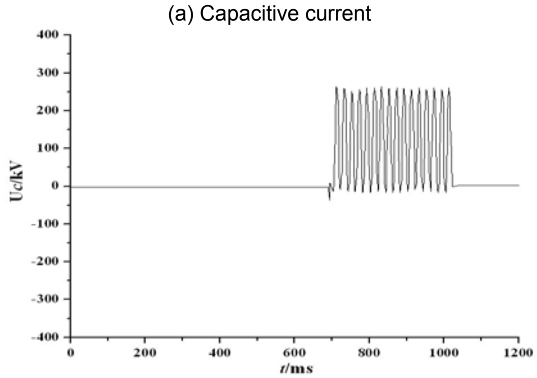
Fig.10 Interruption of inductive current- current and TRV

Fig.10 shows the current and the TRV measured from the inductive test circuit. The total operation number of grounding switch is 10. From Fig.10 it can be seen that the grounding switch can interrupt the inductive current successfully. This is an excellent proof that the grounding switch operates very reliably even under such severe condition.

Fig.11 shows the current and the TRV measured from the capacitive test circuit. The total operation number of grounding switch is also 10, only one re-strikes is observed, multiple re-strikes are never observed. In addition, the only re-strike does not cause any over-voltage. Therefore, the grounding switch can also interrupt the capacitive current successfully. This is another proof that the grounding switch is reliable.



(a) Capacitive current



(b) TRV

Fig.11 Interruption of capacitive current-current and TRV

Conclusion

In this paper, an equivalent electrical model has been introduced to study the electrostatic and electromagnetic coupling effect of 750kV double circuit transmission lines. Based on the equivalent electrical circuit, the formula of the induced voltage and current are drawn under different condition of grounding switch installed on the maintenance line. In order to clarify the characteristics of every electrical parameter, such as induced voltage and current, the value and the rising rate of TRV, after calculating the capacitance and inductance matrix of 750kV double circuit transmission lines, simulation research is conducted using EMTP-ATP. Based on the results obtained by the simulation, the experimental circuits are also designed to test the capability of grounding switch to interrupt capacitive and inductive current. The following conclusions can be drawn:

1) when the sending and receiving end of maintenance line are grounded by the grounding switches under different condition, the level of induction parameter of the 750kV double circuit lines is as followed: electrostatic induction voltage, 44.53kV, electromagnetic induction voltage, 8.15kV, electrostatic induction current,15.9A, electromagnetic induction current, 124.79A.

2) As one of the grounding switches is operated to open while the other remains closed, a saw-tooth type of TRV,

whose value is 1.5 times that of steady-state induced voltage, appears at the time of the break of the grounding switch. Moreover, the maximum inductive current is 125A, the peak value and rising rate of TRV is 17kV and 14V/μs respectively.

3) As one of the grounding switches is operated to open while the other remains open, the peak value of TRV is 2 times that of the steady-state induced voltage. In addition, the maximum capacitive current is 19A, and the TRV has a peak value of 113kV.

4) The tests for switching capacitive and inductive currents with grounding switches are carried out in laboratory. The grounding switch successfully interrupted the inductive and capacitive current with the specific worst value respectively, which verifies that this type of grounding switch can be used in the 750kV double circuit lines reliably.

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