Influence of Transient Recovery Voltage from the Parasitic Inductance in Grading Capacitors of Vacuum Circuit Breaker with Triple-interrupters

Xianghao Zeng, Haichuan Zhang, Jiyan Zou and Zhihui Huang

Abstract**—**Under the condition of power frequency, the influence of the parasitic inductance in grading capacitor which connects with multi-vacuum interrupters in parallel is negligible, but when the breakers are opened by power grid break down, the TRV (Transient Recovery Voltage) will appear in high frequency, and the influence of the parasitic inductance on TRV will occur. In this paper, the model of post arc resistance will be established within the research of VCB (Vacuum Circuit Breaker) with triple-interrupters as background, then do simulation on the effect on TRV with different parasitic inductance value by ATP DRAW. When the inductance value is lower than 13μH, the wave form of TRV can be seen as sinusoidal variation, and when the inductance value is higher than 13μH, it can be seen as linear variation with the increase of inductance. As the inductance increased, the influence of voltage sharing is not obvious, but because of the existence of the parasitic inductance, there are inhibitory effects for the rate of TRV in 4μs after the interrupter breaking. At last, the module of VCB with triple interrupters is established, and the correctness of simulation results is proved by experiments.

Keywords**—**parasitic inductance in grading capacitors, transient recovery voltage, VCB with multiple-interrupters.

I. INTRODUCTION

VACUUM circuit breaker (VCB) has been widely used under 40.5kV voltage class because of its advantages, such as small in side, low pollution of the environment, good arc quenching ability. But in the 126kV voltage class and above, the application of VCB is restricted because of its dielectric strength exists saturation effect, so at this voltage level, SF_6 circuit breaker is still dominant. But it is well known that SF_6 is one of the six greenhouses gases which are forbidden to exhaust, thus the development of SF_6 circuit breaker is restricted. So the study on how to develop the VCB in high voltage level to be a replacement for SF_6 circuit breaker will be an important direction in the future.

The study on higher voltage grades of VCB consists of two aspects. One is developing the single VCB according to the research on how to solve the problem of the saturation characteristic of dielectric strength, and another one is to develop the vacuum circuit breaker with multiple interrupters in series. Considering technical and economical limits, the technology of VCB with multiple interrupters is more feasible for future developments, and has become a main subject in many countries [1-7].

There are many issues in the development and industrial application for the VCB with multiple interrupters, one of them is the voltage distribution in the current interruption process. If the voltage distribution is unbalance, the interrupters will be re-striking, and it may cause break failure. In order to improve the breaking capacity and voltage distribution, the study on the dynamic voltage sharing is very important to VCB with multiple interrupters.

Taking VCB with triple-interrupters as background in this paper, the author will do a research on the influence of TRV from the parasitic inductance in grading capacitor of VCB with triple-interrupters.

II. SIMULATION MODEL OF VCB WITH TRIPLE-INTERRUPTERS

A. Vacuum arc model establishment

Using the model of the sheath growth, the ion diffusion equations and ion density equation to form vacuum arc model equations is as follows:

$$l^2 = \frac{4\varepsilon_0 U_0}{9eZN_i}[\sqrt{(1+\frac{u(t)}{U_0})^3} + \frac{3u(t)}{U_0} - 1] \quad (1)$$

$$N_i = N_{i0}\exp(-\frac{t-t_0}{\tau})(\frac{D_{amp}l^2}{D_{gap}^2}+1) \quad (2)$$

$$U_0 = \frac{M_i}{2e}(v_i + \frac{dl}{dt})^2 \quad (3)$$

$$i(t) = \frac{\pi D^2 ZN_i e}{4}(v_i + \frac{dl}{dt}) \quad (4)$$

Equation (1) is the growth function of positive ion sheath. *l* is the sheath thickness of positive ion, ε_0 is the vacuum dielectric constant, U_0 is the ion potential in the edge of sheath, it could be

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calculated through (3), e is the electric charge of an electron, Z is a multiplicity constant the for average charge, N_i is the ion density of the sheath edge, and it could be calculated through (2), $u(t)$ is the voltage across the sheath. We know that the sheath thickness is related to the recovery voltage of the electrode refer to (1).

Equation (2) describes the ion density of the sheath edge. t_0 is the moment for TRV begins after current zero, and l could be seen as zero when $t< t_0$, N_{i0} is the initial ion density at the moment of $t= t_0$, it depends on the decay of the arc in front of t_0, τ is the decay time of ion diffusion on the edge of sheath, D_{amp} is used to control the distribution of ion space charge which between the two electrodes. So N_i is related to the decay time of ion diffusion and the thickness of sheath.

Equation (3) is the ion potential in the edge of sheath, here, M_i is the mass for ion, v_i is the speed of ion in the edge of sheath and neutral plasma. It could be seen that U_0 depends on the algebraic addition of the drift speed of metal ion and the development rate of sheath.

Equation (4) describes the post arc current in the period of breaking process. In this equation, $i(t)$ is the post arc current, D is the diameter of the arc column, which approximated to the contact diameter in arc diffusion.

In this model, the parameter of ε_0, e, M_i, Z is the constant which depends on the vacuum interrupter, the parameter of $u(t)$, v_i, D, τ, D_{amp} can be calculated by mathematics method, according to the separate oscillogram of voltage and current; the variable N_{i0} would turn to a constant after the first circulation when the time is t_0, the remaining variable l, U_0, N_i, $i(t)$ would be recalculated once again in every step until the end of the simulation.

When $t=t_0$, dl/d$t=0$, combined with (2), (4) can be transform as:

$$i(t_0)=\frac{\pi D^2 Z[N_{i0}\exp(-\frac{t_0-t_0}{\tau})(\frac{D_{amp}l^2}{D_{gap}^2}+1)]e}{4}(v_i+0) \tag{5}$$

So

$$N_{i0}=\frac{4i(t_0)}{\pi D^2 Z v_i e} \tag{6}$$

In this model, the reference value of field strength is set to $E=5*10^7$ V/m, and the reference value of power density is set to $P=2*10^{10}W/m^3$, and the function of field strength in this model is as follows:

$$E_c=2\sqrt{\frac{ZeN_i}{\varepsilon_0}(\sqrt{u(t)U_0+U_0^2}-U_0)} \tag{7}$$

$$P_d=N_i v_i\left(\frac{M_i v_i^2}{2}+Zeu(t)\right) \tag{8}$$

In the simulation, if $E_c>E$ or $P_d>P$, the vacuum circuit breaker would break down.

B. Equivalent model for VCB with triple interrupters

The VCB with triple interrupters takes full advantage of the excellent characteristics of vacuum circuit breaker with small contact gaps, and the breakdown voltage is significantly improved compared with single gap under the same total gap length, according to calculation, the breakdown voltage for VCB with triple interrupters is 1.732 times than that with single interrupter[9-11]. So it can get the current breaking capacity in high voltage level with the interrupter in series in low voltage grade. The voltage distribution of the three vacuum interrupter gaps is influenced by the capacitance of the vacuum gap, so it can get the equivalent circuit model of the VCB with triple interrupters regardless of the influence of arc gap resistance, and the model is shown in Fig. 1[1][2].

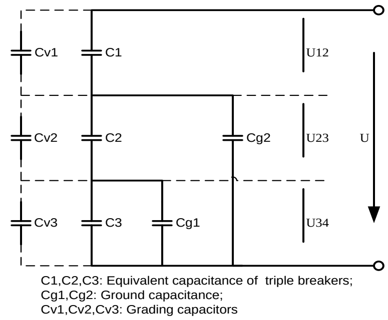

Fig. 1. The equivalent circuit model of the VCB with triple interrupters

In Fig.1, U is the recovery voltage on the VCB with triple interrupters, U_{12}, U_{23} and U_{34} are the voltages of the three interrupters respectively, the voltage value can be obtained by the following equations.

$$U_{12}=\frac{(C_2C_3+C_2C_{g1}+C_2C_{g2}+C_3C_{g2}+C_{g1}C_{g2})U}{C_1C_2+C_1C_3+C_2C_3+C_1C_{g1}+C_2C_{g1}+C_2C_{g2}+C_3C_{g2}+C_{g1}C_{g2}} \tag{9}$$

$$U_{23}=\frac{(C_1C_3+C_1C_{g1})U}{C_1C_2+C_1C_3+C_2C_3+C_1C_{g1}+C_2C_{g1}+C_2C_{g2}+C_3C_{g2}+C_{g1}C_{g2}} \tag{10}$$

$$U_{34}=\frac{(C_1C_2)U}{C_1C_2+C_1C_3+C_2C_3+C_1C_{g1}+C_2C_{g1}+C_2C_{g2}+C_3C_{g2}+C_{g1}C_{g2}} \tag{11}$$

Comparing with (9), (10) and (11), it shows that the voltage values U_{12}, U_{23} and U_{34} are unequal to each other even if all of the three interrupters are the same and have the same equivalent capacitance. Generally speaking, the vacuum interrupter connected with high voltage side will withstand more TRV(transient recovery voltage, TRV), and it could break down at first in the current interruption process, if the other two interrupters could not withstand the TRV that suddenly increased or its endurance is too short for the first interrupter to complete dielectric recovery, the other two interrupters would continuously re-strike and finally the interruption of the VCB with triple interrupters would fail. If the three vacuum interrupters connected grading capacitors (C_{v1},C_{v2},C_{v3}) were in parallel, and the value of the grading capacitors much higher than the value of the equivalent capacitance and the ground capacitance, the voltage values U_{12}, U_{23} and U_{34} would be approximately equal [2][8]. It is shown by the imaginary line in Fig.1. It can be ensured that the TRV for high voltage side is not too high to cause re-strike in the current interruption process, and the three breakers will withstand the TRV equally, then the breaking capacity of the VCB with triple interrupters will be improved.

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III. System Simulation Platform

A. Simulation on the VCB with triple interrupters

System simulation circuit and equivalent circuit of the VCB with triple interrupters are established by ATP draw, and the simulation diagram for VCB with triple interrupters is shown in Fig. 2. In this circuit diagram, the arc resistance model TACS could be considered as post arc model for VCB. C_1, C_2 and C_3 are the grading capacitors that connected with VCB in parallel, and L_1, L_2 and L_3 are the parasitic inductances in grading capacitors, though the influence of the parasitic inductance is negligible under the condition of power frequency, the influence on TRV will occur at the time when VCB suddenly opens, due to its high frequency.

In the ATP circuit, different circuit parameters are set, the fault circuit parameters are gained by iterative computations in simulation process, and the current and voltages of arc model can be get. Input the parameters into TACS to calculate the ECTM, and the arc equivalent conductance or equivalent resistance in next step would be gained.

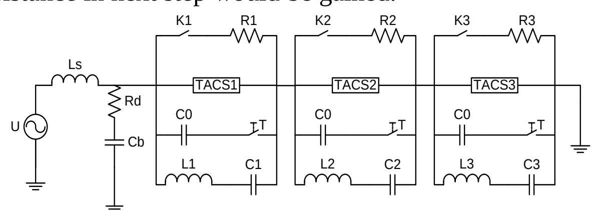

Fig. 2. Simulation diagram for VCB with triple interrupters

Fig. 3 is the flowchart of this simulation system.

Here, L is the sheath thickness of positive ion, and it could be get by measuring and formula (1)(2)(3), the *DL1* is the rate of change of L, and i_c is the current flowing through the interrupters, it can be get by measuring, $i(t_0)$ is the current at the moment of t_0, here, $i(t_0)$=-0.9A. *TIMEX* is a constant, and *TIMEX*>0. *TIME* is the value of t-t_0, and *CTRL* is the control signal, when *CTRL*=1, we know that *TIME*>0 from Fig. 3, it means that the TRV of interrupters begins and the sheath thickness would be increasing. The function of field strength (*Ec*) and power density (*Pd*) in this model could be get by formula (7)(8). *BD* is the criterion of breakdown, and *R* is the arc equivalent resistance. When *BD1*=0, it means the interrupters are not breakdown, and *R* can be calculated by measuring the interrupters' voltage and current. When *BD1*>0, the interrupter are breakdown, and *R* would be a constant.

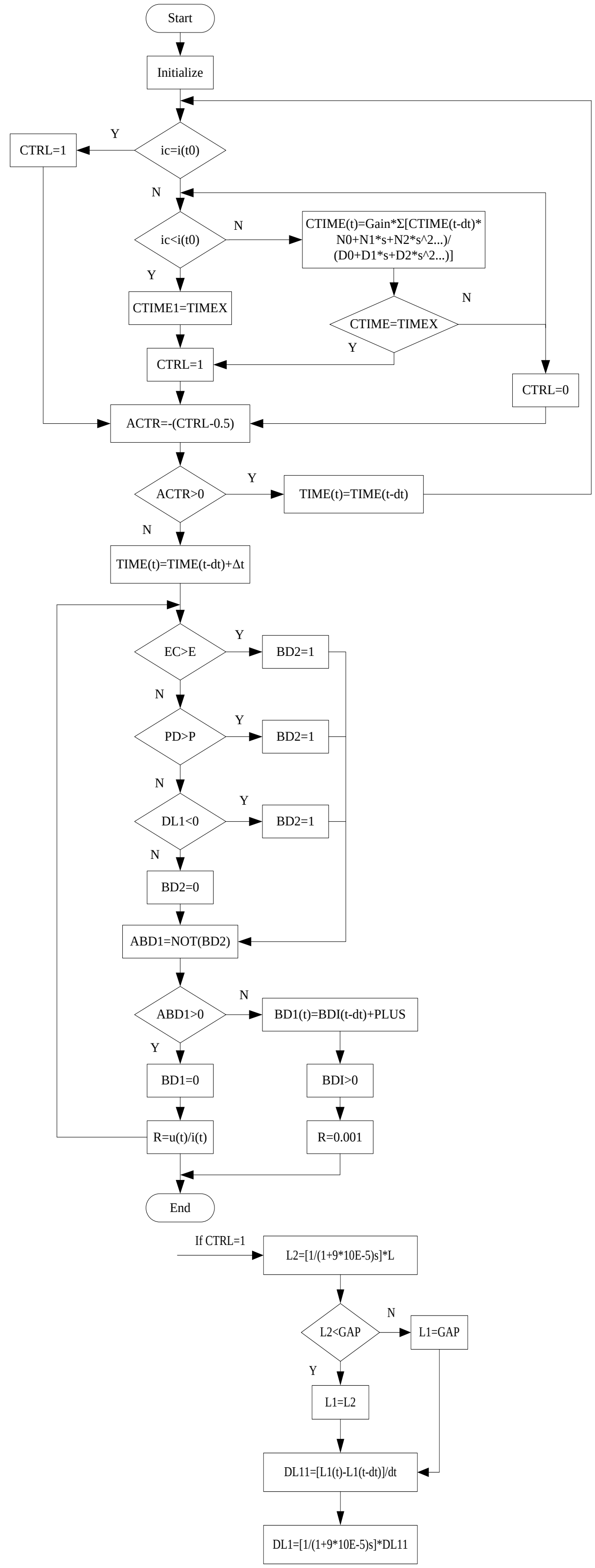

Fig. 3. The flowchart of the simulation system

B. Simulation results

Fig. 4 is the voltage waveform on each interrupter for VCB with triple breakers, the value of grading capacitor

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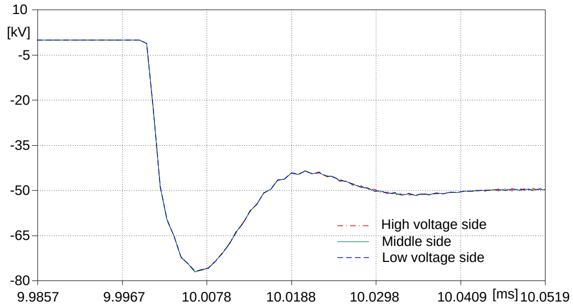
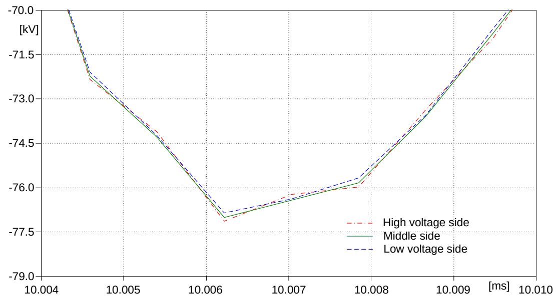
is 1000pf, and its parasitic inductance is 7.5μH.



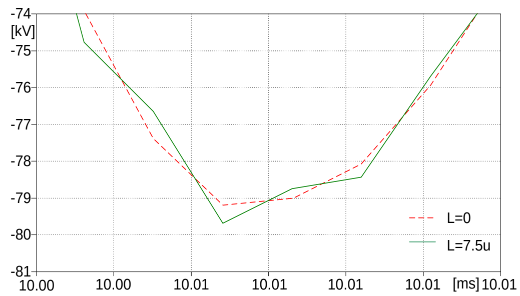
(a) Voltage on each breaker



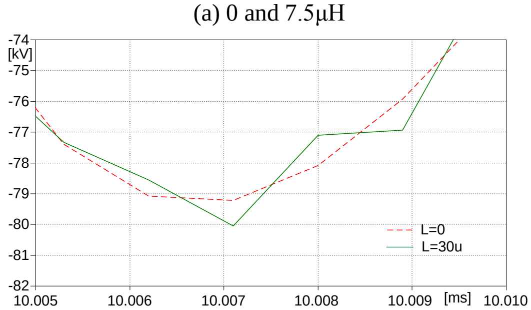
(b) Partial enlarged drawing for peak in (a)

Fig. 4. The waveform of voltage-sharing for VCB with triple interrupters

The contrast of voltage on high voltage side between parasitic inductance 0 and 7.5μH is shown in Fig. 5 (a), and the contrast of voltage on high voltage side between parasitic inductance 0 and 30μH is shown in Fig. 5 (b), whose value of grading capacitor is 1000pf.



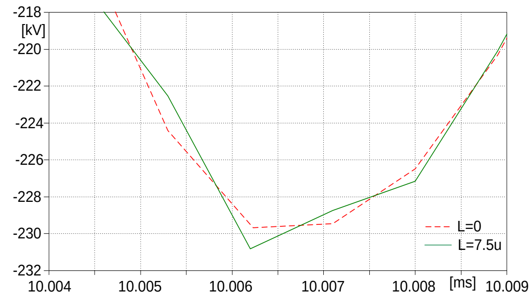
(a) 0 and 7.5μH



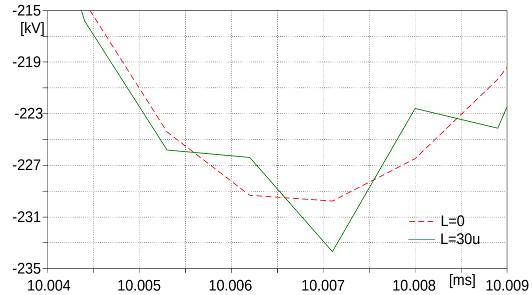
(b) 0 and 30μH

Fig. 5. Voltage on high voltage side with different parasitic inductances

Fig. 6 is the waveform of TRV for VCB with triple breakers, which vary with different parasitic inductances with the grading capacitor 1000pf.



(a) 0 and 7.5μH



(b) 0 and30μH

Fig. 6. TRV for VCB with triple breakers with different parasitic inductances

Fig. 7 is the waveform of TRV changing in first 4 μs with the grading capacitor 1000pF, and the value of parasitic inductance is 0μH, 15μH and 30μH.

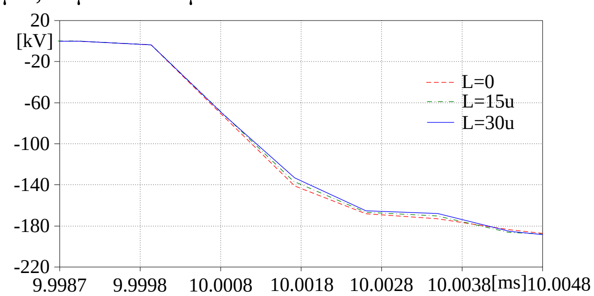


Fig. 7. The waveform of TRV changing in first 4 μs

Fig. 8 is the current waveform in parasitic inductance which is connected with high voltage side, at the time of VCB interruption. Fig. 9 is the partial enlarged drawing for the first peak of current in Fig. 8, and Fig. 10 is the partial enlarged drawing for current in parasitic inductances corresponding to TRV peak in Fig. 8.

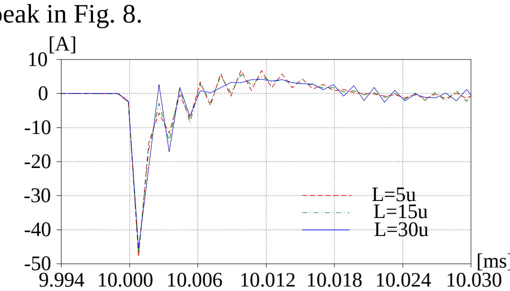


Fig. 8. The current in parasitic inductances

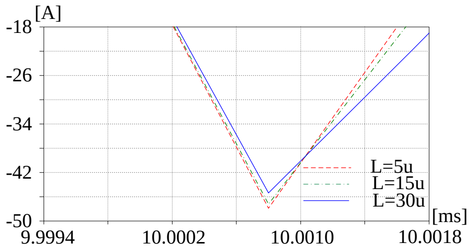


Fig. 9. Partial enlarged drawing for the peak of current in Fig.8

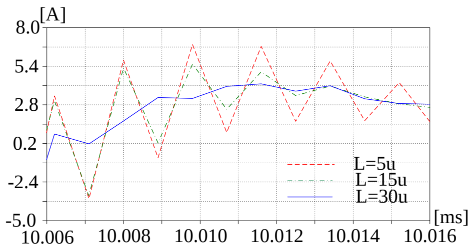


Fig. 10. Partial enlarged drawing for current in parasitic inductances corresponding to TRV peak in Fig.8

Fig. 11 is the peak value of TRV for VCB with triple interrupters corresponding to different parasitic inductance value, under the condition of grading capacitor 1000pF.

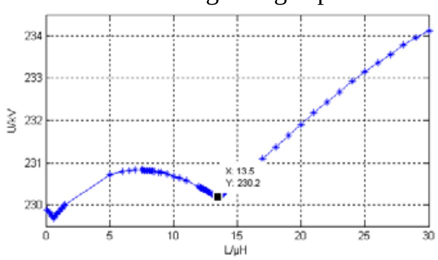


Fig. 11. The value of TRV corresponding to different parasitic inductance value

IV. Analysis for Simulation

From Fig.4, it can be seen that there are little differences on the results of voltage-sharing whether the parasitic inductance exists or not. Because of the parasitic inductance exists in grading capacitor, the total impedance can be get from the equation shown as follows:

$$R = \omega L + \frac{1}{\omega C} \quad (12)$$

It is observed that the total impedance of the grading capacitor on each breaker is equal, though parasitic inductance exists in grading capacitor, so the voltage value for each breaker in VBC with triple interrupters is approximately equal. It means that the influence of the parasitic inductance in grading capacitor on voltage-sharing in VCB with triple interrupters can be ignored.

From the Fig. 5 and Fig. 6 we can know that the TVR on VCB with triple interrupters fluctuates due to the presence of parasitic inductance. It caused that the peak value of TVR on each interrupters increased.

In Fig. 7, it can be seen that when the VCB breaking, there is some inhibitory effect for TRV build-up rate in the first 4μs because of the parasitic inductance exists, and this inhibitory effect is more obvious as the value of parasitic inductance increased.

In Fig. 5 and Fig. 6, the peak value of TRV on VCB fluctuates due to the presence of parasitic inductance. Combining with Fig. 8, Fig. 9, Fig. 10 and Lenz's law, it shows that the fluctuation is related to the electric current which flows into parasitic inductance. This current would have a drastic change at the time of interruption, and the inductance will generate counter electromotive force to restrain this change. And this counter electromotive force will have superimposed effect on TRV, and the peak value fluctuates.

The waveform of TRV on VCB with triple interrupters corresponding to different parasitic inductance values is shown in Fig. 11. It is observed that the TRV is sinusoidal variation with the increase of parasitic inductance when the value of inductance is lower than 13μH, and the TRV changes linearly as parasitic inductance increases when the value of inductance is higher than 13μH. From the equation shown as follows:

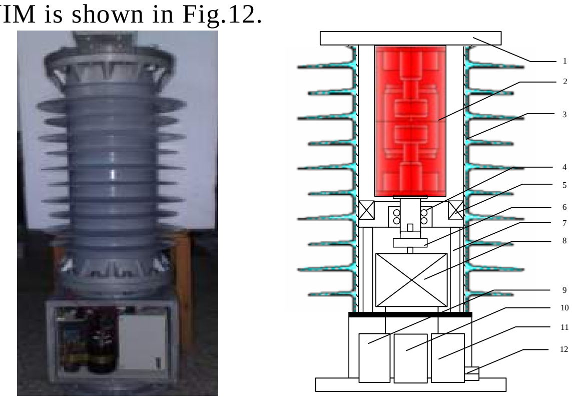
Error! Bookmark not defined. $\varepsilon = -L\frac{di}{dt}$ (13)

It can be seen that the counter electromotive force is related to the value of inductance and the change rate of current. When the inductance value is lower than 13μH, the change rate of current reduces as the inductance value increases, because the ability of block the current changes is enhanced. At this time, the TRV on VCB with triple interrupters is affected by two aspects, one is the inductance value increased, and the other is the change rate of current reduced, then the peak value of TRV is sinusoidal variation under the influence of these two aspects. When the inductance value is higher than 13μH, it is considered that the influence of the inductance on current changes tends to be saturated, so the TRV on VCB with triple interrupters is influenced by changing inductance value, and the peak value of TRV changes linearly as the inductance value increases.

V. Experimental Results and Discussion

A. *Module of VCB with triple interrupters*

In this paper, VCB with triple interrupters was set up by 40.5kV fiber-controlled vacuum interrupter modules (FCVIM) in series, the appearance and internal structure of FCVIM is shown in Fig.12.



(a) Appearance of FCVIM (b) The internal structure of FCVIM

Fig. 12. Module of fiber-controlled vacuum interrupter module

In Fig.12 (a), the length of this module is 90 cm, its diameter is 33 cm, and it weighs 100 kg. In Fig.12 (b), it could be seen the internal structure of FCVIM, here, 1 is end cover flange, 2 is vacuum interrupter, 3 is epoxy insulating tube, 4 is silicone rubber insulated, 5 is rolling connection, 6 is current transformer, 7 is Belleville-spring, 8 is conducting rod, 9 is permanent magnetic operating mechanism, 10 is storage battery, 11 is controller, 12 is capacitor, and 13 is fiber interface.

FCVIM includes 4 parts. First one is the power source, including current transformer, capacitors and storage battery. The power source will get the current from the grid by current transformer, and it will charge the capacitors and storage battery by the power management in controller. Second one is the controller. The controller will receive the single of action directive from low potential by optical fiber, and command the module to implement instruction, at last the controller will feedback the information of module status to the intelligent control system on low potential through the optical fiber. Third one is insulated part, including vacuum arc-extinguishing chamber and epoxy insulating tube, and this kind of complex insulating structure will be more reliable. The last one is permanent magnetic operating mechanism. When the controller sends out the controlling signal, the electronic power switch will be triggered, and the capacitors will discharge to the coils of permanent magnetic mechanism to complete the operation.

VCB with triple interrupters used three FCVIMs in series, these FCVIMs were built in U-shaped type, and every FCVIM was connected with grading capacitors in parallel, as shown in Fig.13.

Fig. 13. Module of VCB with triple interrupters

B. Test Circuit for VCB with triple interrupters

The test circuit for VCB with triple interrupters adopts synthesis loop. It is made up of current source and voltage source, what is shown in Fig.14. The test parameters of current supply are shown in Tab.1, and the test parameters of voltage source are shown in Tab.2. From these parameters, the parameters of prospective TRV would be get, what is shown in Tab.3.

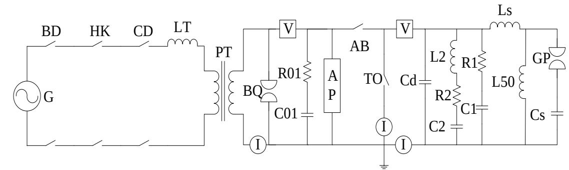


Fig. 14. Test circuit for VCB with triple interrupters

In Fig.14, G means impact generator, BD is protective circuit breaker, HK represents closing switch, CD is operation circuit breaker, AB is auxiliary circuit breaker, PT means potential transformer, BQ is protective sphere gap, R is resistance, L is inductor, C is capacitor, TO means test object, GP is High voltage ignition, AP means arc prolong circuit, V and I are measuring equipments of voltage and current.

C. Test Data

Do tests for VCB with triple interrupters through the circuit shown in Fig.14, and the parameters of the circuit were shown in Tab.1 and Tab.2.

Tab.1. The test parameters of current supply

Type of experiment	T30	T60	L70	L90
Power (MVA)	945	945	945	945
Frequency (Hz)	50	50	50	50
Phase	Single	Single	Single	Single
Voltage (kV)	17	17	17	21
Current (kA)	12	24	30	36
Power factor	<0.15	<0.15	<0.15	<0.15
Impedance (Ω)	1.42	0.71	0.56	0.58
Neutral	Earthed	Earthed	Earthed	Earthed

Tab.2 The test parameters of voltage source

Type of experiment	T30	T60	L70	L90
Cs (pF)	2.9	2.9	17.4	17.4
Ls (mH)	29.4	29.4	5.91	5.91
R1 (Ω)	3046	3046	16.2	16.2
C1 (pF)	0.103	0.103	0.41	0.41
L2 (mH)	/	18.8	3	3
R2 (Ω)	/	11	958	958
C2 (pF)	/	0.1	0.23	0.23
Cd (pF)	0.01	0.01	0.01	0.01
f2 (Hz)	545	578	496	496
Us (kV)	138	139	108	230

We can get the parameters of the prospective TRV from the parameters provided by Tab.1 and Tab.2, and it is shown in Tab.3.

Tab.3 The parameters of prospective TRV

Type of experiment	T30	T60	L70	L90
Ur (kV)	95	95	72.5	72.5
kaf	1.53	1.5	1.4	1.4
u1(kV)	/	100	77	77
t1(μs)	/	33	38	38
uc (kV)	205	201	144	144
t3(μs)	41	198	152	152
td(μs)	2	2	2	2
RRRV(kV/μs)	5	3	2	2

The data of the grading capacitors is shown in Tab.4. The data of the TRV getting from the tests is shown in Tab.5.

Tab.4 The parameters of grading capacitance

Grading capacitors	Value of capacitors (pF)	Value of parasitic inductance (μH)
C_1	1003	1.55
C_2	1001	1.61
C_3	1000	1.58

Tab.5 Test data

Type of experiment	T30	T60	L70	L90
Ucs(kV)	16.9	16.9	16.5	14.5
I(kA)	13.1	24.2	30.5	36
Ta(ms)	5.2	8.5	9.2	7.9
Tb(ms)	45.1	48.7	48.6	48.9
To (ms)	39.9	40.2	39.4	41
us(kV)	138	139	108	110
uc(kV)	208	205	145	151
Ur(kV)	97	96	75.5	73.1

From the test data, it can be seen that the value of TRV actual measurement is not the same with the value of prospective TRV. The prospective value of power frequency recovery voltage in T30 is 97kV, and T60 is 96kV, L75 is 72.5kV, L90 is 72.5kV. The prospective values of TRV peak in these tests are 208kV, 205kV, 144kV and 144kV respectively. From Tab.5 we know that the parameters in actual tests are bigger than the values of prospective TRV which shown in Tab.3. So the influence of TRV from the parasitic inductance in grading capacitor of VCB with triple-interrupters could be verified.

VI. Conclusion

In this article, the simulation model of the VCB with triple interrupters was established by ATR Draw, and the breaking simulation results of the VCB with triple interrupters in series were achieved by taking advantages of TACS.

The simulation results show that:

1, There is little impact on voltage-sharing in VCB with triple interrupters in series due to the presence of the parasitic inductance in grading capacitor.

2, There is some inhibitory effect for TRV build-up rate in the first 4μs when the VCB breaking because of the parasitic inductance exists.

3, There is a fluctuation on TRV due to the presence of the parasitic inductance in grading capacitor.

4, Peak value of the voltage on each breaker is increased, and the possibility of re-strike gets promoted because of the fluctuation on TRV.

5, The TRV is sinusoidal variation with the increase of parasitic inductance when the value of inductance is lower than 13μH, and the TRV changes linearly with the increase of parasitic inductance when the value of inductance is higher than 13μH.

At last, create the test platform for the VCB with triple-interrupters to research the influence of TRV from the parasitic inductance in grading capacitor and verify the correctness of the simulation.

So the parasitic inductance can not be ignored at the breaking time. In practice, the value of parasitic inductance in grading capacitor would be measured and we should choose the grading capacitor with appropriate parasitic inductance.

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