Phase-controlled technology for bypass switch of UHV series compensation

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Abstract. The large inrush current occurs when the series compensation capacitor bank is cut off. The inrush current can be effectively suppressed by the phase-controlled technology. The controlled closing strategy for the bypass switch of the series compensation capacitor bank is developed in this paper. The UHV transmission line and capacitor series compensation are established. The arc model of pre-breakdown and time scatter model are established. The closing strategy is simulated in the MATLAB/Simulink. The simulation results show that the closing strategy in this paper can effectively suppress the inrush current of the bypass switch.

1. Introduction
The inductive reactance of the transmission line can be compensated, the transmission capacity can be improved, the reactive power balance can be improved, the system voltage regulation can be improved, and the system stability can be enhanced by the series compensation technology of the AC UHV transmission line.

A fixed capacitor series compensation (FSC) connects the capacitor and the line in series. The bypass switch is connected in parallel with the capacitor, which is used to input and cut off the capacitor bank. Due to the residual voltage of the capacitor, the inrush current is large when the bypass switch is closing, causing the erosion of contacts. The bypass switch has the lower frequency of the current and the larger closing current than the conventional switch used for capacitor. These have a serious impact on the life and reliability of the bypass switch [1-2].

Related research was carried out by some agencies for the special working conditions of the bypass switch. Siemens has developed a 550kV high-voltage bypass switch with double breaks, and the operating mechanism is a spring mechanism. ABB has developed a UHV column bypass switch with the single break and spring mechanism. The closing time is less than 35 ms. The bypass switch structure of Pinggao Group was the double-break parallel shunt branch with the hydraulic mechanism. Pinggao Group solved the problem of serious contact erosion and re-breakdown by optimizing the structure of the interrupter and the buffer mechanism. In summary, the previous research focused on the optimization of the structure and strength of the circuit breaker itself. The closing inrush current cannot be basically suppressed.

The phase-controlled strategy is adopted in this paper to basically suppress the inrush current. The ablation of the contacts by pre-breakdown arc is reduced. This scheme provides a design basis for the low transient inrush current of the bypass switch.
2. Control principle of UHV series compensation

2.1. Principle analysis of series compensation
The equivalent circuit of series compensation is shown in Figure 1. The installation position of the FSC can be determined by factors such as line load, wire type, and power factor [3-4]. The FSC is installed at the end of the line in this paper to illustrate the principle of the series compensation circuit.

\[ U_1 \rightarrow R_L \rightarrow X_L \rightarrow X_C \rightarrow U_2 \]

\[ P + jQ \]

Figure 1. Series compensation circuit.

\( U_1 \) is the power voltage. \( U_2 \) is the terminal voltage of the line. \( R_L \) is the line resistance. \( X_L \) is the line inductance. \( X_C \) is the equivalent capacitive reactance of FSC. The series compensation device is shown in Figure 2. The devices mainly include capacitor bank, MOV, spark gap, series isolation switch, bypass switch, bypass isolation switch, current limiting equipment, etc.

![Series compensation device](image)

Figure 2. Series compensation device.

When the series compensation device is working normally, the series isolation switch is closed, the bypass switch and the bypass isolation switch are opened, and the line current flows through the capacitor bank.

When the series compensation device is cut off, the bypass switch is closed to transfer the line current to the bypass switch branch. Then the bypass isolation switch is closed, and the series isolation switch is opened to transfer the line current to the bypass isolation switch branch.

When the series compensation device is put in, the bypass switch is closed and the series isolation switch is closed. The bypass isolation switch is opened. Then the bypass switch is opened to transfer the line current to the capacitor branch.

It can be seen that the bypass switch is responsible for the input and removal of the capacitor bank. Severe inrush current will occur during the closing process. The control strategy of the bypass switch will be analyzed below to suppress the inrush current.

2.2. The control strategy of the bypass switch
Taking the single-phase transient process in a three-phase symmetric system as an example, the phase-controlled strategy is explained. The equivalent circuit of the closing process is shown in Figure 3. \( U_s \) is the source voltage. \( R_e \) and \( L_e \) are the equivalent impedance of the source and the transmission line. \( R_b \) and \( L_b \) are the equivalent impedance of the load. \( R_d \) and \( L_d \) are the equivalent impedance of the current limiting equipment. \( C \) is the compensation capacitor. \( CB \) is the bypass switch.
The source voltage is set to be $U_s = U_m \sin(\omega t + \theta)$. CB is closed at $t_c$. The circuit before the closing meets the equation

$$u_c = (R_e + R_0)i + (L_e + L_0)\frac{di}{dt} + \frac{1}{C} \int_0^{t_c} i dt$$

(1)

After closing, the capacitor bank and CB form a discharge loop. The following equation is satisfied.

$$u_s = (R_e + R_0)i + (L_e + L_0)\frac{di}{dt} + u_c$$

$$\frac{1}{C} \int_0^{t_c} i dt = i_2 R_d + L_\delta \frac{di_2}{dt}$$

$$u_c = \frac{1}{C} \int_0^{t_c} i dt$$

$$i = i_1 + i_2$$

$$u_c(0+) = \frac{1}{C} \int_0^{t_c} i dt$$

(2)

According to the switching law, $u_c(0+) = u_c(0-)$. When $u_c(0+) = 0$, the transient component of $i_2$ is 0, and there is no inrush current. For a three-phase system, the theoretical closing point of each bypass switch is $u_c(0+) = 0$. If the initial phase of the phase A is 0°, phase B and phase C are sequentially delayed by 120° and 240° of phase A. When phase A is first closed at $u_c(0+) = 0$, since the phase A capacitor is short-circuited after the closing, the three phases are in an asymmetrical state, so the theoretical closing points of phase B and phase C are not delayed by 120°. Instead, it is necessary to determine the specific theoretical closing points through the transient calculation.

3. Coupling model of FSC and transmission line

3.1. The coupling model

The UHV AC transmission source voltage is 1100 kV. The length of the line is 15 km. LGJ-240 wire is used. The total load is $38.7 \times 10^6$ MVA. The power factor is 0.9. FSC is installed at the end of the line. The coupling model is shown in Figure 4.

The series compensation level is defined as the ratio of the equivalent capacitive reactance of FSC and the equivalent reactance between the system and the installation point, that is

$$k = \frac{X_c}{X_0}$$

(3)

The relationship between the compensation level $k$, $U_1$ and $U_2$ is

$$k = 1 - \frac{PR_e - (U_1 - U_2) \times U_2}{QX_0}$$

(4)

When $k$ is [1.5, 2], it is called high compensation. When $k$ is [1.0, 1.5], it is called moderate compensation. When $k$ is about 0.5, it is called low compensation. The series compensation level is $k=1$ in this paper.
3.2. The model of pre breakdown and closing time scatter

When the moving contact has not touched the static contact, the gap will break down and be electrically conductive by the external voltage [5-6]. This effect is called the pre-breakdown effect. The closing time scatter of VCB satisfies the probability distribution of 3σ, that is, the actual closing position obeys the normal distribution with the standard deviation of σ at the range of 3σ. The intersection of the pre-breakdown characteristic line and the external voltage is the arcing moment. The phase controller has a time scatter of ±1 ms. The closing window is shown in Figure 5.

![Figure 5. Pre-breakdown closing window.](image)

Mayr model is used in pre-breakdown arcing model. The Mayr model assumes that the arc channel is constant. The dynamic equation of the Mayr arc is

\[
dG/G dt = 1/\tau (ui/P_0 - 1)
\]

Where \( u \) is the arc voltage, \( i \) is the arc current, \( P_0 \) is the dissipation power, \( \tau \) is the time constant, \( G \) is the dynamic conductance of the arc.

4. Analysis of the inrush current

4.1. The effect of suppression at the theoretical closing points

It can be found from Equation (3) that the inrush current is closely related to the capacitor voltage at the closing time. Random closing can cause severe closing inrush current. When the closing points are the peak voltage of each phase, the current in bypass switch is shown in Figure 6.
The damping coefficient of the current limiting equipment is 0.45. The peak current of phase A is the highest, reaching 170 kA, accompanied by high-frequency current oscillation. The arc after the pre-breakdown is repeatedly re-striking until the contacts are in contact, causing severe ablation of the contacts. The closing points of switches are adjusted to the theoretical closing points, and the current after closing is shown in Figure 7.

Under the same condition of the current limiting equipment, the peak current of the theoretical phase points is only 12.5 kA. The direction of the high frequency current is not changed. The impact of current is reduced.

4.2. The effect of pre-breakdown on the inrush current
Considering the effect of pre-breakdown and time scatter, the bypass switch is arc-conducted within $\pm 1 \text{ ms}$. The inrush current of bypass switch is shown in Figure 8 and Figure 9.
As can be seen from the figure, the peak value of the negative current reaches a maximum of -58 kA. The peak value of the positive current reaches a maximum of 48 kA. Inrush current is greatly reduced compared to the closing points at peak voltage. Through multiple simulations, if the time scatter of each switch is 1 ms, the peak value of the inrush current is between -58 kA and 48 kA, and the control strategy effectively suppresses the inrush current.

5. Conclusion

The principle and operating conditions of the bypass switch in the UHV series compensation device are analyzed in this paper. The phase-controlled strategy of bypass switches for FSC is developed. The model of transmission line and FSC is established in MATLAB/Simulink. The closing strategy is simulated combining the pre-breakdown arc model and the time scatter of the circuit breaker. Simulation results show that random closing is possible to achieve an inrush current of 170 kA, which is 20~30 times of the normal current. The arc after the pre-breakdown is repeatedly re-striking, causing severe ablation of the contacts. After the control strategy is adopted, the peak current will be between -58 kA and 48 kA, and the inrush current is well suppressed. At the theoretical points, the peak inrush current is only 12.5 kA. This paper provides guidance for bypass switch to cut series compensation capacitor banks.

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