Application Research of 35kv Switching Shunt Capacitor Banks with Phase-Controlled Circuit Breakers

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Abstract. In recent years, two series reactor faults occurred when a 35kV shunt capacitor bank was cut by a circuit breaker in a 500kV substation in Shenzhen. The reason is analyzed that the large inrush current and overvoltage generated during the switching process caused interturn short circuit fault of the reactor, which seriously threatens the safe operation of the system. To avoid such faults, intelligent phase-controlled short-circuit breakers were used to suppress the closing inrush current and reduce the probability of reignition. To verify the effectiveness of the technology, this paper introduces the causes of switching inrush current and over-voltage and the principle of phase-controlled suppression technology, and then applies the technology to a 500kV substation in Shenzhen. Multiple switching tests are carried out on the intelligent and ordinary circuit breakers respectively. The results show that the maximum inrush current generated by the ordinary circuit breaker is 4.2p.u., and the overvoltage is 1.81p.u. While the maximum inrush current of the intelligent phase-controlled circuit breaker is 2.3p.u., and the overvoltage is 1.4p.u. The results confirm that the application of the intelligent phase-controlled switching technology can suppress the inrush current and overvoltage, thus fundamentally improving the reactive switching efficiency and system safety.

1. Introduction
For the 35kV system of a 500kV substation, the large single-unit capacity of the capacitors and reactors, and high switching frequency causes large and frequent disturbances to the power grid. Accidents caused by abnormal switching of capacitor banks are common, which poses a great threat to the power quality and the safe operation of the equipment. The main problems can be summarized as follows:

- Capacitors are switched frequently, the capacitor capacity three-phase unbalance protection trips to switching failure, main insulation breakdown, fuse blown, service life is shortened, and power supply reliability is reduced.
- Capacitors and reactor bodies are damaged or even burned.
- Reactive power equipment is reignited severely and its service life is greatly shortened.

The main reason of the above problems is the closing current and the overvoltage of the opening during the switching process of the capacitor [1-4]. Domestic and foreign scholars have conducted a lot of research on the accidents caused by switching parallel capacitor banks [5-9]. In recent years, phase control technology has been gradually applied to reactive power compensation systems of various voltage levels to suppress the closing inrush current and the opening overvoltages when switching the capacitor banks [10-13]. In reference [14], a phase-controlled vacuum circuit breaker applied in the field of medium and low voltage was developed and simulated. In reference [15], the...
application of phase-controlled circuit breaker in switching 10kV shunt capacitor bank was studied. The effectiveness of phase-controlled circuit breaker was verified in the actual power system.

However, there is no research on the field test of the phase-controlled circuit breaker in the actual 35kV reactive power compensation system. Therefore, this paper firstly analyses the cause of the switching inrush current and the over-voltage of the switching capacitor bank, and introduces the principle of phase-controlled switching technology. Secondly, the application scheme and system commissioning of phase-controlled circuit breaker in 35kV reactive power compensation system of a 500kV substation are introduced. Finally, through a series of field comparison tests, the phase-controlled circuit breaker is verified to suppress the inrush current and overvoltage.

2. Analysis of the switching inrush current and overvoltage

2.1. Fault process
When a 35kV capacitor bank of a 500kV substation in Shenzhen (Type: CKDK-35/1000-5; Capacity: 3000kvar; Insulation & temperature tolerance level: F; Service time: 4 years) was put into operation, an interturn short circuit fault occurred at the C-phase of the series dry-type hollow reactor within 30s. The short circuit current in the C-phase of the series reactor caused the temperature at the fault to rise rapidly, and the high temperature caused the internal aluminium coil to melt and smoke. The soot containing aluminium metal spread upward and around, causing the insulator to flash above the fault point, and a phase-to-phase short circuit fault was developed lastly. The strong electrodynamic force caused by the phase-to-phase short circuit current broke the connecting wire and threw the phase A reactor to the ground as a whole.

2.2. Cause analysis
Several 35kV dry-type hollow shunt reactors after fault were disassembled to analyze the fault cause. It is found that the main cause is the breakdown and discharge of the reactor, and the interturn insulation fault of the reactor is mainly generated by the inrush current and overvoltage during the switching process.

Affected by capacitor characteristics, when a shunt capacitor is put into the power grid, the generated transient inrush current can be up to 20 times of the rated current. When the capacitor exits the power grid, after the main contact of the circuit breaker is disconnected, the capacitor, the series reactor and the ground stray will form a high-voltage oscillation circuit, causing a high-frequency pulse potential difference with the power supply on the other side. If the main contact opening distance is small and the withstand voltage between the contacts is insufficient, arc reignition will occur, resulting in reignition overvoltage. The busbar overvoltage can be 2.5 times of the rated voltage, and the terminal overvoltage of the capacitor can be up to 3 to 5 times of the rated voltage. In addition, due to the large interception current value and the high reignition rate of the vacuum circuit breaker, overvoltage occur easily, and its peak value can easily exceed 3 times of the rated voltage without control, which is a serious threat to the safe operation of relevant equipment.

![Figure 1. Capacitor bank switching equivalent circuit](image-url)
The equivalent circuit diagram of switching the 35kV shunt capacitor bank is shown in Figure 1. After the main contact of the circuit breaker is disconnected, the capacitor bank, the series reactor and the stray capacitance to the ground will form a high-frequency oscillation circuit, causing a high-frequency pulse potential difference with the power supply on the other side. Therefore, if the opening distance of the main contact is small and the withstand voltage between the contacts is insufficient, the phenomenon of arc reignition will occur, and the frequency of the arc can be as high as 1MHz, which greatly increases the difficulty of arc extinguishing of the circuit breaker and the loss of the main contact. If the vacuum interrupter is not clean enough, it may cause arc extinguishing failure.

The transient shocks such as inrush current and overvoltage generated during the switching of the 35kV shunt capacitor bank cause great insulation damage to the series reactor main body, and the cumulative effect of the inter-turn insulation damage of the reactor is gradually generated during the operation of the equipment. Accumulation and expansion eventually lead to faults.

3. Phase-controlled suppression technology

In order to solve the transient shock problem of 35kV capacitor switching in 500kV substation, 72.5kV SF6 open-type outdoor breaker is widely used to switch the capacitor bank. Although the SF6 switch is more resistant to inrush current and overvoltage than the vacuum switch, its switching mode is still a three-phase linage random switching method, generating inrush current and overvoltage which are not suppressed during the switching process. Therefore, it cannot solve the problem of switching reactive power equipment fundamentally, which bring in safety risks, and the transient shock problem still exist when switching capacitors.

At the moment when the circuit breaker is disconnected, the phase angles of the system voltage are usually random and uncertain, which often results in overvoltage and inrush current when switching certain primary devices. Phase-controlled suppression technology is in response to the demand, using accurate phase control technology to achieve effective suppression of operating overvoltage and inrush current. There are different causes of overvoltage and inrush current due to loads with different characteristics, so different control strategies must be adopted to effectively suppress overvoltage and current generated by operating the circuit breaker. For capacitive loads, the overvoltage and inrush current are caused by the sudden change of the voltage across the capacitor at the instant of switching. Therefore, the strategy to prevent overvoltage and inrush current should be separating the capacitor at the zero-cross point of capacitor voltage [16].

3.1. Principle of phase-controlled closing technology

The principle of phase-controlled closing capacitive load is shown in Figure 2, where \( t_c \) is the input moment of the external closing operation command, \( t_0 \) is the moment when the voltage is zero, \( t_p \) is the selected target closing phase (different for three phase), and \( t_m \) is moment when the metal contacts are in contact. At the same time, the switch phase delay time \( t_d \) can be obtained by the switch three-phase closing time and the target closing phase \( t_p \). After the delay \( t_d \), the controller triggers the closing operation, and the switch contacts are closed at the time \( t_m \), to realize voltage of different phases switching at respective zero point.

![Figure 2. Phase-controlled closing technology with capacitive load](image)
3.2. Principle of phase-controlled opening technology

The principle of phase-controlled opening capacitive load is shown in Figure 3, where $t_c$ is the input moment of the external opening operation command, $t_s$ is the moment of the switch contact separation, $t_z$ is the moment of arc extinguishing when the current is zero, and $t_{arc}=t_z-t_s$ is the arcing time (minimum arcing time are determined according to the switch interrupter and the load characteristics). At the same time, the three-phase delay triggering time $t_d$ is obtained by the switch three-phase opening time and the pre-set arcing time $t_{arc}$. After the delay $t_d$, the controller triggers the opening coil, and the switch contacts start to separate at the moment $t_s$, so that the arc can be extinguished at the moment $t_z$. The opening distance of the switch contacts $d$ is long enough to withstand the transient voltage of the system, and the load can be broken reliably.

Figure 3. Phase-controlled opening technology with capacitive load

In conclusion, the phase-controlled suppression technology can be used for suppressing the impact of the transient shocks such as inrush current and overvoltage generated during the switch operation, thus improving the power quality, increasing the breaking capacity of the circuit breaker, and prolonging the service life and maintenance period of the equipment.

4. Application scheme of the phase-controlled circuit breaker

4.1. Application scheme

The first group capacitor 344 of 35kV 4M in a 500kV substation in Shenzhen was carried out the transformation to phase-controlled mode. The original Siemens open-type linkage circuit breaker was replaced with Siemens open-type three-phase phase-separated circuit breaker, and a set of microcomputer inrush suppressor device was added. Normally, when the capacitor is switched, the automatic voltage reactive power control system (AVC) or the monitoring background sends an opening or closing command to the protection and monitoring device. The device receives the command and sends the opening or closing pulse to the circuit breaker. With the inrush suppressor device, it is equivalent to bypassing an inrush suppressor between the protection and monitoring device and the circuit breaker. The switching flowchart of the circuit breaker with phase-controlled technology is shown in Figure 4.

Figure 4. Phase-controlled circuit breaker switching flowchart
After the inrush suppressor receives the switching operation command, the device performs calculation and then sends the switching pulses to the opening and closing coil operating circuit of the 35kV capacitor breaker, to carry out phase-controlled switching operation of three-phase on the capacitor.

4.2. **System commissioning**

In order to realize the switching of the circuit breaker at the zero point of three-phase, the phase-controlled device needs to control the closing of A, B and C-phase according to the specified timing. The closing sequence of the 344 phase-controlled switch is C-phase, B-phase and A-phase, respectively. The delay is 1.67ms and 6.67ms.

Before the test, the three-phase switch is tested for switching characteristics, including the opening and closing times, phase-to-phase non-synchronize and opening and closing speed. The test data is applied to optimize the phase selection accuracy and stability of the phase-controlled device. The results of the random switching test are shown in Table 1.

**Table 1.** Three phase switching characteristic test result (random mode).

| Reference phase | Closing time (ms) | Opening time (ms) | Closing speed (m/s) | Opening speed (m/s) |
|----------------|------------------|------------------|---------------------|--------------------|
| A-phase        | 61.3             | 26.8             | 3.46                | 4.72               |
| B-phase        | 59.7             | 26.9             | 3.44                | 4.09               |
| C-phase        | 60.6             | 26.6             | 3.13                | 4.64               |
| Three-phase synchronous difference | 1.6 | 0.3 | / | / |

The closing time in phase-controlled mode is shown in Table 2.

**Table 2.** Three phase switching characteristic test result (phase-controlled mode).

| Reference phase | A-phase | B-phase | C-phase |
|----------------|---------|---------|---------|
| Closing start time (ms) | 20      | 21.677  | 26.675  |
| Actual delay (ms)       | 0       | 1.677   | 6.675   |

The actual maximum error of the phase-controlled device switching time is about 0.007ms, which meets the requirements of field application.

5. **Field test research**

5.1. **Testing program**

The key parameters of the phase-controlled switching test of the 35kV capacitor bank are the transient voltage of the high-voltage end of the capacitor port and the three-phase transient current of the circuit breaker, which can be measured by the secondary side of the capacitor body discharge PT and the secondary side of the CT of the circuit breaker. Close and open the circuit breaker of the capacitor, and record the inrush current and overvoltage during the switching. The operation flow is as follows:

- Without phase control (three-phase linkage random mode), switch the circuit breaker once every 5 minutes to check whether the recorded waveform shows reignition. If there is no reignition, test for 5 times.
With phase control (individual phase control mode), switch the circuit breaker once every 5 minutes to check whether the recorded waveform shows reignition. If there is no reignition, test for 5 times. The test site is shown in Figure 5.

The test site is shown in Figure 5.

5.2. Test results and analysis
Switching tests were carried out for 10 times on the first group capacitor 344 of 35kV 4M in a 500kV substation in Shenzhen. The data detected in the test are the secondary voltage of the high voltage end of the capacitor to the ground and the secondary current of the three-phase current of the circuit breaker. The typical recording results of random closing, phase-controlled closing, random opening and phase-controlled opening are shown in Figure 6 and Figure 7, respectively.

![Figure 6. Random closing recorded waveforms](image)

![Figure 7. Phase-controlled closing recorded waveforms](image)

The results of random closing test and phase-controlled closing test are shown in Table 3 and Table 4, respectively, where p.u. is the ratio of the transient peak to the steady state peak. Combined with the
test data and recorded waveforms, in normal operation without inrush current suppression, the circuit breaker is controlled by random mode. The maximum inrush current of the capacitor operation is 4.2p.u., and the overvoltage is 1.81p.u. While in normal operation with inrush current suppression, the phase-controlled method is applied to control the circuit breaker switching. The maximum inrush current of the capacitor operation is 2.3p.u., and the overvoltage is 1.4p.u. Compared to random mode, phase-controlled inrush current is reduced by 42% and overvoltage is reduce by 28%.

Table 3. Random switching test result.

|                  | A-phase | B-phase | C-phase | A-phase | B-phase | C-phase | A-phase | B-phase | C-phase |
|------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Closing inrush current peak value (A) | 1.66    | 1.75    | 1.03    | 226.15  | 212.85  | 181.69  | 46.65   | 174.74  | 126.31  |
| 2nd operation    | 1.15    | 1.68    | 1.75    | 188.9   | 224.23  | 205.51  | 172.58  | 129.85  | 44.13   |
| 3rd operation    | 1.87    | 1.06    | 1.22    | 228.30  | 182.33  | 204.69  | 173.08  | 128.54  | 44.74   |
| 4th operation    | 1.53    | 1.64    | 1.73    | 225.49  | 210.05  | 222.86  | 126.92  | 45.71   | 171.45  |
| 5th operation    | 1.60    | 1.57    | 1.80    | 226.98  | 204.43  | 229.81  | 46.32   | 174.9   | 126.97  |
| Transient peak   | 1.87    | 1.75    | 1.80    | 228.3   | 224.23  | 229.81  | 173.08  | 174.9   | 171.45  |
| Steady state peak| 0.448   | 0.448   | 0.448   | 127.1   | 127.1   | 127.1   | 127.1   | 127.1   | 127.1   |
| Rate (p.u.)      | 4.2     | 3.9     | 4.0     | 1.80    | 1.76    | 1.81    | 1.36    | 1.38    | 1.35    |

Table 4. Phase-controlled switching test result.

|                  | A-phase | B-phase | C-phase | A-phase | B-phase | C-phase | A-phase | B-phase | C-phase |
|------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Closing inrush current peak value (A) | 0.95    | 1.03    | 0.71    | 178.5   | 163.3   | 147.48  | 172.9   | 128.3   | 46.29   |
| 2nd operation    | 0.81    | 0.99    | 0.78    | 161.37  | 161.5   | 156.56  | 172.5   | 128.04  | 45.46   |
| 3rd operation    | 0.80    | 1.06    | 0.78    | 165.16  | 163.6   | 155.58  | 171.4   | 127.8   | 45.9    |
| 4th operation    | 0.73    | 0.99    | 0.78    | 145.8   | 160.22  | 156.23  | 171.7   | 128.3   | 45.6    |
| 5th operation    | 0.87    | 1.06    | 0.71    | 157.7   | 165.6   | 152.4   | 171.5   | 128.2   | 46.1    |
| Transient peak   | 0.95    | 1.06    | 0.78    | 178.5   | 165.6   | 156.5   | 172.9   | 128.3   | 46.29   |
| Steady state peak| 0.448   | 0.448   | 0.448   | 127.1   | 127.1   | 127.1   | 127.1   | 127.1   | 127.1   |
| Rate (p.u.)      | 2.1     | 2.3     | 1.7     | 1.40    | 1.3     | 1.23    | 1.36    | 1.01    | 0.36    |

In conclusion, by the field application of microcomputer inrush current suppression technology, the inrush current and overvoltage of the capacitor are controlled within the rated range. Compared with the original three-phase linkage operation mode, the transient inrush current and the operating overvoltage during the switching process of reactive power equipment are greatly suppressed. It reduced the insulation loss and the impact on the primary equipment during the switching, and verifies that the microcomputer inrush suppression technology is feasible for the phase-controlled switching suppression of the 35kV large-capacity shunt capacitor.

6. Conclusion
With the phase-controlled circuit breaker switching the 35kV shunt capacitor bank, the closing inrush current is below 2.3p.u., and the overvoltage is below 1.4p.u. While with an ordinary SF6 circuit breaker, the closing inrush current is below 4.2p.u., and the overvoltage is below 1.81p.u. Compared with ordinary SF6 circuit breakers, the phase-controlled inrush current is reduced by 42% and overvoltage is reduce by 28%. Compared with the traditional random switching capacitor bank, the closing inrush current of the switching capacitor bank with the phase-controlled switch is significantly reduced, and the impact on the reactor is greatly reduced. The reignition probability is lower, and the service life of the switch and operation safety are improved. The harmonics are reduced during the switching process, and the busbar voltage quality is significantly improved.

Controlling the switching of 35kV capacitors in 500kV substation by inrush current suppression technology, can effectively suppress the switching inrush current and overvoltage of the capacitor bank, stabilize the bus voltage, avoid switching transient problems and secondary accidents, and extend the service life of the reactive power equipment and the circuit breaker. The technology can provide certain technical and economic benefits, which deserves promotion and application in other engineering projects.

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