Abstract: In this article, the Changji-Guquan ± 1100 kV ultra-high voltage direct current (UHVDC) system has been established by PSCAD software, especially for the arc of the circuit breakers. The AC filter groups and the control strategy have been analysed based on the reactive power demand of this system, AC system voltage amplitude, and harmonic limit. This article mainly studies inrush currents and overvoltage, especially recovery voltage caused by switching circuit breaker of AC filter in the different working conditions. Simulation results show that the currents through circuit breakers are capacitive and contain a variety of harmonics. There will be a high inrush current when a circuit breaker of AC filter is closing, which can be suppressed by phase selection switch device and appropriate closing resistance. A higher DC transmission power and a less short circuit both make the recovery voltage of circuit breakers higher when the AC filters are removed. The maximum transient recovery voltage of circuit breakers of AC filters can be suppressed by adding the parallel opening resistors. In a certain range, higher resistance of opening resistor makes a better suppression effect on recovery voltage.

1 Introduction
Ultra-high voltage direct current (UHVDC) transmission projects have significant advantage of long distance, large capacity, low loss, flexible adjustment, high economic efficiency, and many other aspects [1]. At present, China has built and operated a number of ± 800 kV UHVDC transmission projects. In order to accelerate the development of UHVDC transmission technology and promote the optimal allocation of energy, China is planning to build a UHVDC transmission project of ± 1100 kV level, which has no actual operation experience in the world. The rectifier side of the project is 750 kV AC grid, which is higher than the 500 kV of other HVDC transmission projects [2]. The insulation withstand level of the equipment on AC bus in the rectifier station must also be much higher than the ± 800 kV UHVDC project. Therefore, in the design of the ± 1100 kV UHVDC transmission project, the electrical performance of the equipment needs to be studied.

As one of the main equipment in converter station, the AC filter plays an important role to eliminate the harmonics generated by converters [3] and provide reactive power to make converter work normally. Due to the requirements of reactive power control and filtering performance, the AC filter needs to be switched frequently in operation, which can be completed by circuit breakers. When the circuit breaker of AC filter is closing, there will be a high inrush current with an impact on the internal components of AC filter. During the normal operation, the currents through circuit breakers are capacitive and contain a large amount of harmonic components, because the AC filter is a capacitive device and also a filtering device [4]. However, the general AC circuit breaker is better at cutting off resistive current than capacitive current. Furthermore, due to the large capacity of the filter bank, frequent switching, and high voltage level, AC filter circuit breaker must withstand high recovery voltage and break large capacitive current [5].

In this paper, based on the Changji-Guquan ± 1100 kV UHVDC transmission project, the complete model was established by PSCAD to simulate the working stress of the circuit breaker for 750 kV AC filter in the rectifier station. The electrical properties of AC filter circuit breaker should have been determined such as transient recovery voltage and capacitive breaking current, and provide the basis for the manufacture and selection of AC filter circuit breaker in UHVDC transmission project.

2 Engineering background and model establishment

2.1 Engineering background

The total length of Changji-Guquan ± 1100 kV UHVDC transmission line is about 3324 km. The voltage level of the AC grid in supply terminal is 750 kV, and the receiving terminal with hierarchical connection to 500 kV/1000 kV AC grid, respectively, for high/low terminal. The rated operating voltage of DC system is ± 1100 kV and rated current is 5455 A. Bipolar transmission power is 12,000 MW. In the converter station, DC system uses two 12-pulse converters in series connection for one pole of bipolar system. The schematic of this UHVDC transmission project is shown in Fig. 1.

2.2 Model establishment

2.2.1 Equivalent model of AC system: Since the focus of this paper is the operation condition of the AC filter in the converter station, the AC system can be equivalent to the resistance and inductance in series [6]. As this equivalent model of AC system cannot effectively suppress low frequency oscillation of the system, a high resistance needs to be added parallel with the inductance. The AC equivalent model is adjusted with different operating conditions of this project. The conditions of the AC system are shown in Table 1.

2.2.2 DC control system: The general control strategy of the UHVDC transmission project is constant current in rectifier side and constant gamma in inverter side. Based on the real project, this
2.2.4 Circuit breaker: When circuit breakers cut off the fault current, there will be an arc generated between contacts in the process of separating. Usually, the equivalent model in which resistance and inductance are in series with ideal switch is used to calculate overvoltage, but in fact, the resistance of arc is non-linear and changed constantly with the voltage and current. In order to accurately describe the arc, this paper uses Mayr–Cassie arc model, which describe arc as a non-linear time-varying resistance changed with current [10]. The equivalent resistance is expressed as formula 1.

\[ R = e^{\left(\frac{\alpha}{\beta}\right)} \]  

(1)

where \( N_\theta \) is the power dissipation factor valued 7MW. \( \theta_0 \) is arc time constant valued 15.5ms. \( \alpha \) and \( \beta \) are constant, respectively, 0.27 and 0.59.

### 3 Current for circuit breaker switching

#### 3.1 Breaking capacitive current

The circuit breaker is worse at breaking capacitive current than resistive current. However, because AC filter is capacitive equipment, the current through AC filter is mainly capacitive. In theory, the circuit breakers should have a greater capacity to open capacitive current. Normally, the requirement of breaking capacitive current can be calculated by the following formula:

\[ I = \frac{Q}{\sqrt{3}U_{ac}} \frac{U_{acmax}}{U_{ac}} \]  

(2)

where \( Q \) is the rated reactive capacity of AC filter (group), \( U_{ac} \) is the rated operating voltage of AC system, \( U_{acmax} \) is the maximum operating voltage of AC system, and \( k \) is the safety factor of harmonic and voltage deviation, generally 1.15.

As the real project is more complicated than the theory, it contains not only the frequency capacitive current, but also harmonic current. Accordingly, the currents through AC filter circuit breaker are accurately determined by PSCAD simulation model, which is compared with the calculation by formula.

According to the simulation results, power frequency currents through circuit breakers of AC filters (groups) with the same reactive capacity are essentially equal, but harmonic currents are different, due to the different amplitude-frequency responses of the AC filters. When the project is operating normally, the currents through circuit breakers of AC filters group can reach 1936.5A, and the maximum of the current through circuit breakers of AC filter is 432.5 A. The IEC 62,271 provides that 800 kV circuit breaker must cut off capacitive current of 900 A, which meets the requirements of the circuit breakers of AC filters [11], but the capacity of AC filter groups is too large and there is still a possibility for circuit breakers of AC filter groups to be cut under abnormal operation. The circuit breakers of AC filter groups must have ability to cut high capacitive current.

At the same time, the circuit breaker must be equipped with a capability of anti-harmonic interference, which the harmonic current is shown in Table 3. As the project uses 12-pulse inverter which can only produce the 12k±1th harmonic current, the currents through circuit breaker of AC filter mainly contain power frequency current and 11, 13, 23, 25, 35, and 37th harmonic current. As of the equivalent resistance and inductance of the AC control system also includes AMAX, OVL, VDCOL, RAML, and other special segments of control and protection system [7-9]. In Changji station, the voltage balance of the group depends on identical control of trigger angle and converter transformer tap changer. However, in Guquan station, the 1000 kV layer and 500 kV layer are independently controlled. The basic parameters of the control system are shown in Table 2.

#### 2.2.3 Parameters and grouping of AC filters: In rectifier station, AC filter models include four types, such as BP11/BP13 (a BP11 and a BP13 are parallel in a group), HP24/36 (double-tuned generated and provide reactive power). When the DC transmission station, AC filter models include four types, such as BP11/BP13 (a

### Table 1 Conditions of the AC system

| Operating conditions | Changji station | Guquan station (high) | Guquan station (low) |
|----------------------|-----------------|-----------------------|----------------------|
| rated operating voltage/kV | 775 | 510 | 1050 |
| maximum steady-state voltage/kV | 800 | 525 | 1070 |
| minimum steady-state voltage/kV | 750 | 490 | 1000 |
| the maximum short circuit of AC bus/kA | 63 | 63 | 63 |
| the minimum short circuit of AC bus/kA | 33.5 | 36.2 | 22.8 |
| steady frequency/Hz | 50 | 50 | 50 |

### Table 2 Parameters of the control system

| Parameter | Description | Range/value |
|-----------|-------------|-------------|
| \( \alpha_N \) | rated trigger angle | 15° |
| \( \Delta \alpha \) | the steady range of \( \alpha \) | ± 2.5° |
| \( \alpha_{min} \) | minimum of trigger angle | 5° |
| \( \gamma_N \) | rated extinguishing angle | 17° |

#### Fig. 2 Circuit graphs of AC filters on the rectifier station

The main function of AC filter is to eliminate the harmonics generated and provide reactive power. When the DC transmission power rises or falls, the switching of AC filter must follow certain principles to ensure safe operation for system from three aspects included voltage, reactive power, and harmonics. The main control strategy and priority are shown as follows:

- **Overvoltage control**: when the voltage of AC bus reaches the reference value, the AC filter is quickly removed to the Abs min filter.
- **Abs min filter**: the AC filter is input according to the rated parameters (necessary conditions for normal work)
- **\( U_{Max}/U_{Min} \)**: to monitor and limit the voltage of AC bus in converter station.
- **\( Q_{Max} \)**: to limit the number of AC filter based on reactive power conditions.
- **Min filter**: to meet the requirements of harmonics.
- **\( Q_{control}/U_{control} \)**: to set voltage of AC bus and reactive power exchange between the converter station and AC system within the reference range.
system in this study, there will be no three harmonics. Therefore, the full currents through the circuit breaker do not contain three harmonic components. In addition, since equivalent impedance angles of each AC filter are slightly different, the peak time for the same harmonic current of each AC filter is also different. The harmonic current through circuit breakers of AC filter group is slightly less than the sum of each AC filters’.

### 3.2 Inrush current

In the moment of closing operation for circuit breaker, the capacitor of AC filter is uncharged and the currents flowing into AC filters only limited by the impedance of the branch. Therefore, there will be a high inrush current when circuit breakers of AC filters are closing. According to the control strategy, all AC filters need to be removed when the converter is locked. In the starting process, the AC filter is input gradually with the increase of transmission power to meet the requirements of reactive power and harmonics. Moreover, when the voltage of AC bus is lower than 0.9 p.u, it also needs to input a certain number of AC filters in turn until the voltage arrives to the requirement.

In the simulation, considering the most serious situation, the inrush current through the circuit breaker of the last AC filter is the highest. In order to get maximum inrush current, the voltage of AC bus is adjusted to the maximum of 800 kV. By using multiple run facilities of PSCAD, circuit breakers of four kinds of AC filters close 120 times at random in a period.

![Circuit graphs of breaker with closing resistor](image)

From Table 4, it can be seen that the inrush currents are almost equal for bipolar and monopolar. As the inrush currents are only related to the equivalent impedance of the AC filter and the voltage of AC bus at the moment of the closing circuit breakers.

![Inrush currents that have high frequency and large amplitude can cause damage to the equipment in converter station](image)

The inrush currents that have high frequency and large amplitude can cause damage to the equipment in converter station, especially to the circuit breaker and the current transformer [12]. In order to protect the equipment in the converter station from being damaged, the closing resistor is installed with circuit breaker. The equivalent circuit diagram is shown in Fig. 3. The breaking process is closing auxiliary gap – 10 ms – closing main gap. The inrush current for different closing resistance is shown in Fig. 3 and 4.

The inrush current controller is installed in circuit breakers, the inrush current of the circuit breaker will change and be suppressed greatly.

### Table 3 Current through circuit breakers of AC filters (groups)

| Tape | Q/Mvar | Capacitive current peak/A theory | Capacitive current peak/A simulation | Power frequency current peak/A | Harmonic current peak/A |
|------|--------|---------------------------------|-------------------------------------|-------------------------------|------------------------|
|      |        |                                 |                                     |                               | 11th                   |
|      |        |                                 |                                     |                               | 13th                   |
|      |        |                                 |                                     |                               | 23rd                   |
|      |        |                                 |                                     |                               | 25th                   |
|      |        |                                 |                                     |                               | 35th                   |
|      |        |                                 |                                     |                               | 37th                   |
| A    | 1675   | 2094.9                          | 1844.9                              | 1769.5                        | 90.1                   |
|      |        |                                 |                                     |                               | 53.3                   |
|      |        |                                 |                                     |                               | 32.1                   |
|      |        |                                 |                                     |                               | 25.8                   |
|      |        |                                 |                                     |                               | 13.4                   |
|      |        |                                 |                                     |                               | 12.0                   |
| B    | 1675   | 2094.9                          | 1936.5                              | 1769.7                        | 162.3                  |
|      |        |                                 |                                     |                               | 101.4                  |
|      |        |                                 |                                     |                               | 30.0                   |
|      |        |                                 |                                     |                               | 24.1                   |
|      |        |                                 |                                     |                               | 13.1                   |
| BP11/BP13 | 305 | 381.4                          | 428.3                              | 322.4                         | 76.7                   |
|      |        |                                 |                                     |                               | 51.5                   |
|      |        |                                 |                                     |                               | 2.5                    |
|      |        |                                 |                                     |                               | 2.2                    |
|      |        |                                 |                                     |                               | 0.3                    |
|      |        |                                 |                                     |                               | 0.4                    |
| HP24/36 | 305   | 381.4                          | 372.6                              | 322.1                         | 10.5                   |
|      |        |                                 |                                     |                               | 7.3                    |
|      |        |                                 |                                     |                               | 20.8                   |
|      |        |                                 |                                     |                               | 19.1                   |
|      |        |                                 |                                     |                               | 8.0                    |
|      |        |                                 |                                     |                               | 8.9                    |
| HP3  | 305    | 381.4                          | 323.7                              | 322.1                         | 1.4                    |
|      |        |                                 |                                     |                               | 0.7                    |
|      |        |                                 |                                     |                               | 0.4                    |
|      |        |                                 |                                     |                               | 0.5                    |
|      |        |                                 |                                     |                               | 0.1                    |
|      |        |                                 |                                     |                               | 0.1                    |
| SC   | 380    | 474.9                          | 432.5                              | 401.5                         | 11.3                   |
|      |        |                                 |                                     |                               | 7.0                    |
|      |        |                                 |                                     |                               | 8.8                    |
|      |        |                                 |                                     |                               | 10.6                   |
|      |        |                                 |                                     |                               | 4.0                    |
|      |        |                                 |                                     |                               | 6.1                    |

### Table 4 Maximum inrush current through circuit breaker

| AC filter tape controlled by circuit breaker | Inrush current/kA |
|--------------------------------------------|-------------------|
|                                            | Bipolar | Monopolar   |
| BP11/BP13                                   | 3.30    | 3.18        |
| HP24/36                                     | 5.94    | 5.78        |
| HP3                                         | 0.71    | 0.75        |
| SC                                          | 11.92   | 10.97       |

### Table 5 Minimum inrush current through circuit breaker

| AC filter tape controlled by circuit breaker | Inrush current/kA |
|--------------------------------------------|-------------------|
|                                            | Bipolar | Monopolar   |
| BP11/BP13                                   | 0.57    | 0.54        |
| HP24/36                                     | 0.53    | 0.49        |
| HP3                                         | 0.46    | 0.46        |
| SC                                          | 0.65    | 0.61        |
breakers is slightly different. For example, due to the big equivalent impedance of the HP3 branch, the suppression effect of closing resistance on the inrush current is small. Therefore, the closing resistance as big as possible is not a good choice. The suppression effect of closing resistance on inrush current is related to the equivalent impedance of AC filter. According to the simulation results, the optimum value of the closing resistance is 500–1000 Ω for different kinds of AC filter and there is almost no inrush current at this time.

### 4 Recovery voltage of circuit breaker

#### 4.1 Recovery voltage of circuit breaker in different working conditions

According to the protection strategy, the converter must be locked in some cases, which reduces the reactive power consumption of the converter and increases the voltage of the AC system. In order to ensure the voltage stability of the AC system, a certain number of AC filters need to be removed [13]. In addition, when the capacitors of AC filters break down, the current through the damaged AC filter will rise sharply. In order to prevent the fault of other component, the circuit breaker must be opened in a short time. According to the above, there are four possible operations of AC filter:

- **Working Condition 1:** Due to the permanent grounding fault in the DC transmission line, the converter is locked, and AC filters are removed 40 ms later.
- **Working Condition 2:** When permanent grounding fault of A phase occurs in AC system, the converter is locked 10 ms later after the single-phase reclosing failure, and then AC filters are removed 40 ms later.

### Table 6 Maximum recovery voltage in different working conditions

| Working Condition | Bipolar | Monopolar |
|-------------------|---------|-----------|
| 1                 | 1426.4  | 1370.3    |
| 2                 | 1896.6  | 1579.8    |
| 1                 | 963.7   | 825.5     |
| 2                 | 1130.9  | 1113.0    |

#### 4.2 Influence factor

##### 4.2.1 Opening resistor:

The diagram of circuit breaker with break resistance is the same as Fig. 3, except for closing resistor replaced with opening resistor. The breaking process is breaking main gap – 20 ms – breaking auxiliary gap. Considering the structural characteristics of the circuit breaker and the characteristics of recovery voltage in the transient process, the value of break resistance is about 100–3000 Ω. Under this condition, the influence of break resistance on recovery voltage is studied. The changed curve of the recovery voltage with the value of the breaking resistance is shown in Fig. 6.

Based on the theoretical analysis, when circuit breaker installed breaking resistance is in breaking operation, the main gap is first disconnected and breaking resistance accesses AC filter branch, which will limit the recovery voltage across the main break. Therefore, the smaller the resistance is, the lower the recovery voltage of the main break is. The oscillation frequency is mainly the power frequency. Single-phase earth fault of AC system can lead to high power frequency voltage of sound phases. When it appears reclosing fault in AC system, the converter will be locked and the voltage of sound phases will be higher.

### Fig. 5 The maximum recovery voltage in different working conditions

(a) Condition 1, (b) Condition 2

### Fig. 6 Relationship between recovery voltage and opening resistance in different working conditions

Based on the three working conditions, the overvoltage of circuit breakers is calculated when the AC filters are removed. The maximum recovery voltage between the breaks of circuit breaker and voltage to ground in the working conditions 1 and 2 is shown in Fig. 5.

For the reason that transmission power in bipolar operation is larger than monopole operation, the voltage of AC bus is higher when the converter is locked in bipolar operation and the recovery voltage is also higher. The maximum recovery voltage is 1896.6 kV and the maximum voltage to ground is 1130.9 kV in the working condition 2. The oscillation frequency is mainly the power frequency. Single-phase earth fault of AC system can lead to high power frequency voltage of sound phases. When it appears reclosing failure in AC system, the converter will be locked and the voltage of sound phases will be higher.
Based on the above analysis, it can be seen that the influence of the breaking resistance on the recovery voltage of the circuit breaker is from two aspects: within a certain range of resistance, the larger the resistance is, the lower the recovery voltage is and it is contrary to the regularity when the resistance is out of range. The calculated value of the resistance is about 1400 Ω.

4.2.2 Short-circuit current of AC bus: In order to analyse the influence of AC-side power supply capacity on the recovery voltage during the operation of AC filter circuit breaker, the maximum recovery voltage of the circuit breaker is calculated and analysed under the condition of different three-phase short-circuit current when the converter is locked in bipolar operation. The results are shown in Table 7.

As the short-circuit current of AC system increases, the recovery voltage of circuit breaker gradually decreases, indicating that the recovery voltage of circuit breaker is related to the power supply capacity of AC system. The smaller the short-circuit current is, the larger the equivalent impedance of the AC system is. In order to maintain the rated operating voltage of the AC bus, the amplitude of the equivalent power voltage needs to be higher and the voltage of AC bus increases more obviously when the converter station is locked, which results in higher recovery voltage. Therefore, the minimum short-circuit current should be considered to determine the tolerance to recovery voltage of AC filter.

4.2.3 Transmission power: When the DC transmission power is greater, the reactive power consumed by the converter station and the number of AC filters involved are also greater. Therefore, the voltage of AC bus will increase, when the converter is locked in different working conditions, which makes the recovery voltage of circuit breaker relatively rise (Table 8).

5 Conclusion

Through the simulation model of Changji-Guquan ±1100 kV UHVDC transmission project, the current and voltage by switching the circuit breaker of 750 kV AC filters in rectifier station are studied and following outcomes were achieved:
(i) The currents through circuit breaker of AC filter are capacitive and contain harmonics. The circuit breaker of AC filter group must cut off capacitive current more than 2 kA and have a capability of anti-harmonic interference.

(ii) When the converter must be locked in some cases, the circuit breaker must be opened in a short time. There is a recovery voltage between the breaks of circuit breaker, the maximum of which is 1896.6 kV when permanent grounding fault of a phase occurs in AC system. A higher DC transmission power and a less short circuit both make the recovery voltage of circuit breakers higher when the AC filters are removed.

(iii) The maximum transient recovery voltage of circuit breakers of AC filters can be suppressed by adding the parallel opening resistors. In a certain range, higher resistance of opening resistor makes a better suppression effect on recovery voltage. Within a certain range of resistance, the larger the resistance is, the lower the recovery voltage is and it is contrary to the regularity when the resistance is out of range. The calculated value of the resistance is about 1400 Ω.

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