Research on key technologies in ±1100 kV ultra-high voltage DC transmission

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Abstract: Based on completely mastering ±800 kV transmission technologies, the first ±1100 kV direct current (DC) transmission demonstration project is being constructed in China. Combining theoretical analysis and a large number of experiments, the margin of switching overvoltage in converter stations, the configuration scheme and performance of lightning arresters, the shielding angles of ground lines under different geographical conditions, and the maximum air gap of lines have been determined. The switching impulse flashover characteristics of equipotential sphere and typical rod-plane air gaps are also provided. The external insulation is designed differently for light, medium, and heavy pollution areas. For the ±1100 kV project, if the 8 x 1250 mm² conductors are applied, the pole gap is 26 m and the height of the line is 25 m, all the electromagnetic parameters will meet the requirement of international electromagnetic standards. The key design points of ±1100 kV converter transformers, smoothing reactors, converter valves, and wall bushings are researched and the 75 mH smoothing reactors, ±1100 kV/5000 A converter valves, and ±1100 kV/5523 A wall bushings are successfully made. The optimised hierarchical connection modes and coordination control measure of the ±1100 kV project are studied and the results can provide sufficient technical support for the demonstration project.

1 Introduction

Direct current (DC) transmission technology is widely applied owing to its advantages such as no reactance, negligible influence due to capacitance, low transmission loss, and a lack of synchronous problems. Currently, more than 100 high-voltage DC (HVDC) transmission projects have been put into service. DC transmission technology started in China in the 1960s and has quickly developed because of the large-scale power grid, high power demand, and wide transmission scope. Ten DC projects have been put into operation in China since 2007, including six ±500 kV projects. China has become the country with the largest DC transmission capacity [1].

Developing ultra-high voltage (UHV) alternating current (AC) and DC transmission technology featured by long-distance, large capacity, and high efficiency is an important measure to allocate energy in China. This is because its energy source is far away from its power demand [2–5]. A great deal of research has verified that the DC transmission voltage class series in China should adopt ±500/±800/±1100 kV [6–8].

The economic transmission distance of ±800 kV DC transmission is 2000 km, which meets the requirement of energy allocation in large areas. We started to research key technologies in UHVDC projects in 2005 and completed the constructions of Changping UHVDC Test Base and Xizang High Altitude DC Test Base in 2007 and 2008, respectively. This provided strong support for developing UHVDC transmission technology from theoretical research to engineering application [9–15]. Currently, China has completely mastered ±800 kV transmission technology on overvoltage suppression and insulation coordination [16–19], external insulation [20–25], electromagnetic environment control [26–28], development of core equipment [29–32] and its integration into power systems, and successfully applied them to engineering [33–39]. By December 2017, China had constructed and put into service ten ±800 kV projects and three ones are being constructed. Now 13 ±800 kV projects have finished construction and another three ±800 kV projects will be constructed by 2020.

According to this plan, the development of energy bases will gradually move to the western and northern areas. The transmission distance is from the coal power and renewable energy bases in Xinjiang and the hydropower base in Xizang to the eastern and central areas. This distance is over 3000 km. The transmission distance from China to Russia, or to middle Europe included in the ‘Belt and Road Initiative’, will exceed 4000 km. With the increase of transmission distance, the transmission loss of ±800 kV transmission lines will be larger than 10% and cannot meet the requirement of high-efficiency and economic transmission. Therefore, it is necessary to develop ±1100 kV DC transmission technology.

The ±1100 kV DC transmission technology is power transmission technology with the highest voltage, largest capacity, and longest distance in the world. Its transmission distance can reach 3000–5000 km and its capacity can reach 12 GW. From the 1970s, some countries such as the USA, the former Soviet Union, and Canada have carried out corresponding research on transmission technologies at ±600 kV and above. The application has predominately focused on areas where there are demands of long-distance power transmissions. In the late 1970s and early 1980s, a ±750 kV project was constructed in the former Soviet Union. In 2017, building a ±800 kV transmission line was initiated in India. Additionally, the first stage of Belo Monte ±800 kV transmission line, with a length of 2076 km, has been put into operation in 2017 in Brazil. The second stage of Belo Monte ±800 kV transmission line has a length of about 2518 km and now is being constructed.

Based on the successful application of ±800 kV DC transmission technology, China is planning to construct the first ±1100 kV demonstration DC transmission project in the world. The demonstration project will initiate in Changji (Zhundong in Xinjiang) and end in Guquan (Wannan in Anhui), with a total length of 3304.7 km. In comparison to the ±800 kV transmission technology, some unique factors, including higher voltage, increased transmission distance, extra-large capacity, multi-physical field coupling, saturation characteristics of long air gap,
and complex environments, should be considered in constructing ±1100 kV demonstration projects. Research difficulties in key technologies of ±1100 kV projects, such as overvoltage suppression and insulation coordination, external insulation characteristics, electromagnetic environment control, design and manufacture of core equipment, and the integration of the project into the power system, should be addressed. The key design scheme and parameters can be achieved by a large amount of simulation and testing. Currently (September 2018), the project is in commissioning and will be put into operation by the end of 2018. The latest research results for the first ±1100 kV project are described in this paper.

2 Overvoltage suppression and insulation coordination

Compared to ±800 kV projects, the challenges in overvoltage suppression and insulation coordination in 1100 kV projects are more severe and the requirements for the lightning arresters, equipped in converter stations and along transmission lines, are more stringent in their configuration scheme and performances.

2.1 Internal overvoltage suppression

In the DC transmission system, circuit breaker operation or system faults can cause internal overvoltage. The operation mainly includes emergency shutdown, operation mode conversion, switching DC filters, and so on. The faults mainly include commutation failures (such as missing pulses and so on), short-circuit faults in the station, and pole-line grounding faults.

It is critical for UHV converter stations to reduce the switching impulse insulation level, thus reducing the cost of equipment and construction. Both ±1100 and ±800 kV converter stations achieve overvoltage suppression by optimising the configuration scheme and the performance of lightning arresters. The difference lies in the fact that there are more arresters in the configuration scheme of lightning arresters in ±1100 kV stations, and the performance of lightning arresters is better in ±1100 kV stations than that in ±800 kV stations. According to the principle of protection configuration of lightning arresters in UHVDC converter station [40–42] as well as the overvoltage characteristic of ±1100 kV DC converter stations [43], the lightning arresters can be arranged as illustrated in Fig. 1. The main difference between the lightning arresters’ configuration scheme of ±1100 kV converter stations and that of the ±800 kV ones is an A2 arrester is equipped between the specific busbar and the ground in order to reduce the valve-side overvoltage. The specific busbar is the one connecting the positive-pole converter and its transformer. Similarly, another arrester is equipped at the corresponding position at the negative pole. As a result, the insulation level of the equipment at the top end of the converter valve is reduced. The ratios of switching impulse voltages of all arrester varistors are <1.30 and their electric load rates are high. The load rates of the core equipment converter valves are 90%, while the values of the other equipment are 85%. Taking the performance test results and the structural parameters of lightning arresters into account, the parameters of lightning arresters at different locations can be obtained, as shown in Table 1. The arresters DB and DL, CB2, CB1A, A2, M2, M1, and V1–V3 limit the overvoltage levels of DC line, the top of the valve, the 12-pulse bridge, high-end and low-end converter valves and converter valves, respectively, as shown in Table 2. For example, simulation results demonstrate that the lightning arresters with high performance can limit the overvoltage levels of the DC line, the valve top, and the 12-pulse bridge to 1659, 1613, and 832 kV, respectively.

The configuration scheme and performance parameters of lightning arresters at the inverter side are similar to those at the rectifier side, so this topic will not be covered here.

2.2 Lightning overvoltage protection

UHV/EHV operational experience indicates that towers are more vulnerable to lightning strikes. As a result, effective lightning protection measures should be taken. In fact, compared to ±800 kV UHVDC projects, the line insulator strings of ±1100 kV projects are longer, and back flashover on the transmission lines does not occur as easily. However, shielding failure on the transmission lines can easily occur, and reliable lightning protection measures must be taken. The shielding angle is usually negative. The national standard of China, GB 50790-2013, Code for designing of ±800 kV DC overhead transmission line, has specified that many factors, such as the operational experience, characteristics of regional lightning activity, features of topography and geomorphology, and the value of soil resistivity, should be considered in the lightning protection design. Considering technology and economy, the reasonable lightning protection scheme is determined based on the calculation results of the lightning withstand level. For ±800 kV transmission lines, the lightning protection measures outline that double ground lines should be constructed along the whole transmission line and the shielding angle should be negative. In mountainous areas, the shielding angle should not be larger than −10°. For safety’s sake,

![Fig. 1 Main electrical connection and configuration scheme of lightning arresters for a DC field](http://creativecommons.org/licenses/by/3.0/)

Table 1 Parameters of typical lightning arresters at the rectifier side in a ±1100 kV DC converter station

<table>
<thead>
<tr>
<th>Lightning arresters</th>
<th>Stable operating voltage (maximum value), kV</th>
<th>Load rates, %</th>
<th>8 mADC reference voltage (maximum value), kV</th>
<th>1 kA switching impulse residual voltage (maximum value), kV</th>
<th>20 kA lightning impulse residual voltage (maximum value), kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB/DL</td>
<td>1101</td>
<td>85</td>
<td>1295</td>
<td>1657</td>
<td>1883</td>
</tr>
<tr>
<td>CB2</td>
<td>1145</td>
<td>85</td>
<td>1347</td>
<td>1700</td>
<td>—</td>
</tr>
<tr>
<td>CB1A</td>
<td>552</td>
<td>85</td>
<td>649</td>
<td>819</td>
<td>—</td>
</tr>
<tr>
<td>M2</td>
<td>878</td>
<td>85</td>
<td>1033</td>
<td>1304</td>
<td>—</td>
</tr>
<tr>
<td>M1</td>
<td>329</td>
<td>85</td>
<td>387</td>
<td>445</td>
<td>—</td>
</tr>
<tr>
<td>A2</td>
<td>1171</td>
<td>85</td>
<td>1378</td>
<td>1739</td>
<td>—</td>
</tr>
<tr>
<td>V1</td>
<td>333</td>
<td>90</td>
<td>370</td>
<td>426</td>
<td>—</td>
</tr>
<tr>
<td>V2</td>
<td>335</td>
<td>90</td>
<td>364</td>
<td>419</td>
<td>—</td>
</tr>
<tr>
<td>V3</td>
<td>334</td>
<td>90</td>
<td>363</td>
<td>418</td>
<td>—</td>
</tr>
</tbody>
</table>
The project team studied the lightning performance of the Changji-Guquan ±1100 kV UHVDC transmission line. Based on the electrical geometry model method, the shielding failure flashover rate, at different terrain conditions and different shielding angles, were estimated. The research results show that when the shielding angle is ~10°, the ground lines can shield the pole lines effectively. The shielding failure rate is zero in plain and hill areas. The ground lines cannot shield the conductors effectively and the shielding failure rate is above zero in mountainous and high-mountainous areas. The total flashover rate of the Changji-Guquan ±1100 kV UHVDC transmission line is 0.088 times/(100 km·a), which satisfies the safe requirements. For a ±1100 kV UHVDC transmission line limit the overvoltage at the ends. As a result, the overvoltage at the middle of the line is higher than that at the two ends. When no lightning arrester is installed, the grounding resistance is 5.7 Ω, the capacitance of simplified filters is 0.8 μF, the transmission capacity is 12 GW, and the single-pole grounding fault occurs at the middle of the line, the simulation results show that the overvoltage at the middle of the healthy line is the highest, with a value of 1.57 p.u. (1 p.u. = 1.02 × 1100 kV = 1122 kV), as shown in Fig. 2. Many simulations are conducted to optimise the configuration scheme of lighting arresters, and the results show that the overvoltage of the healthy line can be limited below 1.5 p.u. if a two-column lightning arrester is installed in the middle and three single-column lightning arresters are installed at 40.5, 45.3, and 56% length of the line, respectively. For a specific project, the flashover rate of transmission lines are calculated according to the connection mode, the configuration scheme, and performance of lightning arresters. Generally, the switching impulse voltage margin of the equipment in ±1100 kV converter stations can be taken as 1.15.

For ±1100 kV transmission lines, lightning arresters installed along the lines can effectively limit overvoltage. The Changji-Guquan transmission line can be used as an example. When grounding faults occur along a DC pole line, the maximum overvoltages along the healthy pole line are distributed like an umbrella. This is because the lightning arresters at the ends of the transmission line limit the overvoltage at the ends. As a result, the overvoltage at the middle of the line is higher than that at the two ends. When no lightning arrester is installed, the grounding resistance is 5.7 Ω, the capacitance of simplified filters is 0.8 μF, the transmission capacity is 12 GW, and the single-pole grounding fault occurs at the middle of the line, the simulation results show that the overvoltage at the middle of the healthy line is the highest, with a value of 1.57 p.u. (1 p.u. = 1.02 × 1100 kV = 1122 kV), as shown in Fig. 2. Many simulations are conducted to optimise the configuration scheme of lighting arresters, and the results show that the overvoltage of the healthy line can be limited below 1.5 p.u. if a two-column lightning arrester is installed in the middle and three single-column lightning arresters are installed at 40.5, 45.3, and 56% length of the line, respectively. For a specific project, the flashover rate of transmission lines are calculated according to the performance criteria permitted by the project. Then, it can be determined whether lightning arresters should be installed.

The insulation coordination is key technology in deep overvoltage suppression and reducing difficulties in equipment development and manufacturing. It is also the decisive factor in the construction of the entire project. The insulation coordination of the ±1100 kV converter station generally makes that of ±800 kV stations for [44, 45]. Its overvoltage level can be achieved by the protection level of lightning arresters multiplying the coordination margin.

According to experience on the insulation coordination of ±800 kV DC equipment, the switching impulse margin can be 1.15 and the lightning impulse margin of DC pole bus can be 1.20. The equipment parameters, line length, and configuration scheme of lightning arresters are different for different DC projects. Therefore, the maximum overvoltages of the equipment are different and the requirement of withstanding voltages of equipment may be different. The switching overvoltages of equipment in ±1100 kV converter stations have been calculated in [46, 47]. For a specific project, the switching overvoltage levels of equipment can be determined according to the connection mode, the configuration scheme, and performance of lightning arresters. Generally, the switching impulse voltage margin of the equipment in ±1100 kV converter stations can be taken as 1.15.

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### Table 2  Lightning arresters and the equipment protected by them

<table>
<thead>
<tr>
<th>Lightning arresters</th>
<th>Equipment being protected</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB</td>
<td>positive pole line and equipment in DC switching field</td>
</tr>
<tr>
<td>DL</td>
<td>positive pole line and equipment in DC switching field</td>
</tr>
<tr>
<td>CB2</td>
<td>equipment connected with positive pole bus line</td>
</tr>
<tr>
<td>CB1A</td>
<td>equipment connecting with DC bus line between the high-voltage and the low-voltage 12-pulse valve groups</td>
</tr>
<tr>
<td>A2</td>
<td>high-voltage terminal of the valve-side Y-winding of converter transformer</td>
</tr>
<tr>
<td>M1</td>
<td>DC bus line between the two 6-pulse converter bridges and the valve-side Y-winding of the low-voltage converter transformer</td>
</tr>
<tr>
<td>M2</td>
<td>DC bus line between the two 6-pulse converter bridges and the valve-side Y-winding of the high-voltage converter transformer</td>
</tr>
<tr>
<td>V1–V3</td>
<td>valves parallel with them</td>
</tr>
</tbody>
</table>

### Table 3  Maximum lightning intruding overvoltage and lightning impulse withstand levels of the equipment at DC side of converter station

<table>
<thead>
<tr>
<th>Measuring position</th>
<th>Lightning impulse withstand levels, kV</th>
<th>Maximum lightning intruding overvoltages Computation value, kV</th>
<th>Margin, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC epipolar (10)</td>
<td>2400</td>
<td>1943</td>
<td>23.5</td>
</tr>
<tr>
<td>DC valve top (92)</td>
<td>2365</td>
<td>1693</td>
<td>39.7</td>
</tr>
<tr>
<td>12-pulse bridge (91)</td>
<td>1320</td>
<td>998</td>
<td>32.3</td>
</tr>
<tr>
<td>Upper 6-pulse bridge (72)</td>
<td>1815</td>
<td>1276</td>
<td>42.2</td>
</tr>
<tr>
<td>Down 6-pulse bridge (71)</td>
<td>880</td>
<td>665</td>
<td>32.3</td>
</tr>
<tr>
<td>Y-winding terminals of high-voltage end (52)</td>
<td>2255</td>
<td>1470</td>
<td>53.4</td>
</tr>
<tr>
<td>D-winding terminals of high-voltage end (62)</td>
<td>1870</td>
<td>1168</td>
<td>60.1</td>
</tr>
<tr>
<td>Y-winding terminals of low-voltage end (51)</td>
<td>1375</td>
<td>809</td>
<td>70.0</td>
</tr>
<tr>
<td>D-winding terminals of low-voltage end (61)</td>
<td>1100</td>
<td>632</td>
<td>74.1</td>
</tr>
</tbody>
</table>

The total flashover rates including shielding failure rate and back flashover rate are better not over 0.1times/(100 km·a).

The insulation coordination of the ±1100 kV Changji-Guquan UHVDC project, and will act as a reference for future UHV projects.
3 External insulation characteristics

3.1 Air gap

With the increase in voltage levels, the external insulation characteristics become saturated. If enlarging the insulation size of the equipment in proportion to that of ±800 kV projects, the difficulty and cost in equipment development and project design will greatly increase. Considering the electric performance and economy of the ±1100 kV UHVDC project, the project team has carried out a great deal of research and experiments on the air gaps of the project.

Switching impulse discharging tests were carried out on the full scale ±1100 kV tower head, and the 50% switching impulse flashover characteristics were achieved, as shown in Fig. 3. According to DL/T 436-2005, Technical guidelines for HVDC transmission lines, the calculation formula of 50% positive switching impulse flashover voltage of the air gap from lines to the ground is shown as

\[
U_{50} = U_{m} \times k_1 \times k_2 \times (1 - 2\sigma_S) \times k_3
\]

where \( U_{50} \) is the 50% switching impulse flashover voltage, kV; \( U_{m} \) is the maximum operating voltage, kV; \( k_1 \) and \( k_2 \) are the air density and temperature correction factor of the gap flashover voltage under switching impulse voltages; \( k_3 \) is the switching overvoltage multiple; \( \sigma_S \) is the variation coefficient of the air gaps’ flashover voltages under switching overvoltage, which is set at 5%.

The highest overvoltage level of the Changji-Guquan ±1100 kV transmission line appears at the midpoint of the line, the highest value is 1762 kV, or 1.57 p.u. (1 p.u. = 1122 kV). Considering that the V-shaped insulator string is applied on the line, \( U_{50} \) is calculated by \( \sigma_S \). According to the switching impulse flashover characteristic curve shown in Fig. 3, the minimum air gap distances of the ±1100 kV DC transmission line at an altitude of 3000 m and below are calculated, and the results are shown in Table 4.

Experiments are carried out on typical air gaps aimed at valve halls and DC fields at various voltage levels. The experiments mainly focus on the flashover characteristics from the large-size fitting electrodes to the surrounding grounding bodies. The flashover characteristic curves of typical air gaps, such as shielding electrodes and grading rings with different sizes to the ground, and to the wall and the ground, are achieved. The diameter of the maximum sphere reaches 2.0 m, the maximum grading ring has an outside diameter of 3.8 m, and a pipe diameter of 800 mm. Fig. 4 is the flashover picture of the air gap between a 2 m diameter sphere and the ground. Fig. 5 illustrates 50% switching impulse flashover voltage curves of the rod-plane gap. When the gap distance is 3–8 m, the gap factor of the gap flashover voltage from a 2 m diameter sphere to the plane is 2.39–1.64. The gap factor decreases with the increase of the gap distance.

3.2 Pollution characteristic

Owing to the electrostatic aspiration effect of DC electric fields, the pollution problems of DC projects are much more serious than those of AC ones. The transmission distance of the ±1100 kV project is longer and the geographical conditions along the project...
are complex and diverse. Therefore, the contamination depositing characteristics of the ±1100 kV equipment are more complex than those of ±800 kV equipment. Through the statistical analysis of test results obtained from DC transmission lines in service, we draw the conclusion that the average DC non-soluble deposit density is six times of the average equivalent salt deposit density. Based on the design and operational experience on DC projects, we generally divide the geographic conditions into four pollution levels (very light, light, medium, and heavy polluted areas) based on the equivalent salt density. The thresholds are 0.05, 0.08, and 0.15 mg/cm². Through pollution tests and field observation, the different pollution level areas along the transmission line are determined. According to the pollution investigation and analysis, we drew the conclusion that there is no ‘very light’ pollution levels area along the ±1100 kV transmission line, and the percentages of light, medium, and heavy areas to the whole line are 11.4, 50.7, and 37.9%, respectively. The pollution flashover characteristics and altitude correction relations of large-tonnage DC insulators with different shed shapes and mechanical strengths were obtained by pollution flashover tests under different atmospheric pressures. Based on pollution withstand voltage methods, the differential correction was conducted for uneven pollution distribution on upper and lower surfaces according to different rainfalls as well as the contamination depositing conditions in southern and northern areas. The differentiation insulation design for the ±1100 kV project was proposed as shown in Table 5.

4 Electromagnetic environment control

Compared with ±800 kV DC transmission projects, the ±1100 kV UHVDC transmission projects have thicker wire, and the bundle number increases from six to eight. Some technical problems, including audible noise and radio interference prediction methods of 8-bundle conductors, and prediction of total electric field on the ground when ±1100 and ±800 kV DC transmission lines are in the same corridor, are coming with these changes. All these issues need to be overcome. Based on the premise that the key electromagnetic environment parameters meet the environmental protection requirements, to ensure the designs of lines and converter stations economical and reliable is one of the main technical challenges that ±1100 kV DC transmission technology faces.

4.1 Electromagnetic environment limits

In the process of developing the electromagnetic environment control of ±800 kV HVDC projects, it is proposed that the nominal electric field limit of ±500 kV lines be replaced by the total electric field limit to make the construction of UHVDC projects comply with inhabitation environment regulations and meet the environment protection requirements. The electromagnetic environmental limit of ±1100 kV DC transmission projects should be the same as those of ±800 and ±500 kV projects. According to international electromagnetic standards, combined with the actual geographical environment in China, the limits of electric field, ion flow density, magnetic field, radio interference, and audible noise of ±1100 kV DC transmission lines were presented, as shown in Table 6.

Table 6 shows that all the electromagnetic environment limits are the same as those of ±800 kV DC projects. A large number of theoretical studies [48–51] and experimental results show that, for ±1100 kV projects, when the conductors of transmission lines are 8 × 1250 mm², the pole-pole spacing is 26 m, and the height of pole lines to the ground is 25 m, the indicators can meet the requirement of international electromagnetic standards.

4.2 Audible noise and radio interference control of transmission lines

Owing to the high voltage levels, the electromagnetic environmental problems of ±1100 kV UHVDC projects have gained more attention than those of ±800 kV projects [52]. To ensure that the audible noise and radio interference do not exceed the limit, we need to focus on the control of the electric field strength on the line surface. In particular, the pole-pole spacing and the cross-section of sub-conductors play an important role in the control of electric field strength. To solve this problem, many experimental studies have been carried out in corona cages and high-voltage transmission test line segments. As a result, an audible noise prediction method of UHVDC lines is proposed for multi-bundle large-section lines [53]. Combined with audible noise and radio interference limits, 8 × 1250 mm² conductors are adopted in ±1100 kV UHVDC lines, and the pole-pole spacing should be 26 m. To meet the requirements of audible noise and radio interference control of the Changji-Guquan ±1100 kV DC transmission project, the altitude correction method proposed for predicting audible noise, radio interference, and corona loss of ±500 kV DC lines is also applied for the ±1100 kV project. This was obtained by carrying out corona effect tests of ±500 kV lines at high and low altitudes [54, 55]. Therefore, the audible noise and radio interference control are realised for high-altitude areas along the Changji-Guquan demonstration project.

4.3 Control of total electric field and ion flow density along lines

Owing to the long transmission distance, UHVDC transmission lines will inevitably be parallel with other transmission lines. On the other hand, in order to improve the transmission capacity of the unit power transmission corridor, there may be some designs in which multiple circuits of DC lines or AC and DC lines share the same power transmission corridor.

Fig. 6 shows the results of the transverse distribution of the total electric field on the ground when ±1100 kV DC lines and ±800 kV DC lines are assembled in parallel. It can be seen from Fig. 6 that the transverse distributions of the total electric field on the ground in different line arrangement are different, which is mainly reflected in the maximum value of the total electric field on the ground and its occurrence position. Therefore, in the engineering design, the pole line height should be determined based on different line arrangements to meet the requirements for the total electric field limit on the ground.

Table 5 Insulation design for ±1100 kV DC lines according to different pollution levels

<table>
<thead>
<tr>
<th>Pollution level</th>
<th>Numbers of insulators (550 kN, 635 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>light</td>
<td>74–88</td>
</tr>
<tr>
<td>middle</td>
<td>92–102</td>
</tr>
<tr>
<td>heavy</td>
<td>102–116</td>
</tr>
</tbody>
</table>

Different rainfall of different areas are considered while determining the numbers of insulators.

Table 6 Limited value of ±1100 kV DC transmission lines

<table>
<thead>
<tr>
<th>Beneath the line</th>
<th>Buildings</th>
<th>Total electric field on the ground, kV/m</th>
<th>Ion flow density on the ground, nA/m²</th>
<th>Magnetic field, mT</th>
<th>Audible noise, dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Buildings (day)</td>
<td>Building s (night)</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>10</td>
<td>55</td>
<td>45</td>
<td>58</td>
</tr>
</tbody>
</table>

Application scope of the radio interference limit is 0.5 MHz, the projection of positive polarity line is 20 m from the bottom of the line, measured when the weather is clear.
5 Key equipment

5.1 Converter transformer

Some technical challenges to include local temperature rises in restricted spaces, combined action of DC and AC voltages, severe distortion of electric field, partial discharge, magnetic vibration, noise reduction, and transportation difficulties must be addressed in developing ±1100 kV converter transformers [57]. Following successful development and manufacturing of ±800 kV converter transformers, researchers have conducted much research on ±1100 kV converter transformers [58-62]. Research indicates that the optimised arrangement sequence of UHV converter transformers can make it easier to implement the vertical outlet line at the end of grid side. The optimised arrangement sequence from inside to outside is core, regulating windings, grid-side windings, and valve-side windings. The insulation level of bushing at the valve side is more than that of windings in ±1100 kV converter transformers. The multiple of lightning and switching impulse is 1.05, while that of DC withstand, power-frequency withstand, and polarity reverse voltage is 1.15 [61]. The design of valve-side windings can be obtained by simulation results. Adopting special structure design, parallel units, and on-site installation can effectively reduce the size of converter transformers [58, 62].

Based on previous studies, single-phase, double-winding, and oil-immersed transformers are applied in the Changji-Guquan UHVDC project. Changji converter transformers are on-load tap-changer transformers with its grid-side neutral point directly grounding. They have forced oil-circulated cooling systems. The grid-side voltage of the Changji converter station is 750 kV. The ±1100 kV project at the Guquan converter station is hierarchically connected to 1000 and 500 kV AC grids. The structure of converter transformers, connected with 1000 and 750 kV AC grids, is core, regulating windings, grid-side windings, and valve-side windings from inside to outside. The structure of converter transformers, connected with a 500 kV AC grid, is core, valve-side windings, grid-side windings, and regulating windings from inside to outside. Fig. 7 illustrates the ±1100 kV UHV converter transformer. The capacity of the Changji and Guquan converter transformers are 607.5 and 587.1 MVA, respectively. Table 7 shows the parameters of ±1100 kV converter transformer in the Changji converter station.

5.2 Converter valves

Converter valves are key equipment in HVDC transmission systems realising the conversion between AC and DC power energy. Some technical difficulties need to be overcome in developing ±1100 kV converter valves which include the uniform distribution of broadband voltage on multi-level series thyristor modules, the insulation shielding design near saturation impulse parameters, the ion flow density will generally meet the requirements of being <100 nA/m².

Field measurement results from UHVDC converter stations show in order to control the ground total electric field below 30 kV/m, the ground total electric field generated by the tubular busbar should be lower than the ground total electric field limit of the converter station. This is because there are many charged structures and equipment in converter stations, and they are much more complex. When comparing the field measurement results of the ground total electric field in UHVDC converter stations to the calculated results of the single tubular busbar generated ground total electric field, it is determined that in order to control the ground total electric field in a wide range of the converter station <30 kV/m, the single tubular busbar generated ground total electric field should be controlled in 20–25 kV/m. According to the above principles in determining the electric field limits, as well as the results of full-scale model experiments and simulation analysis carried out by China Electric Power Research Institute, for ±1100 kV converter stations in low-altitude areas, the field ground total electric field can be controlled <30 kV/m if Φ400 tubular busbars are adopted and their heights range is 17.2–21 m.

4.4 Electric field control of converter station

The ±1100 kV converter stations have higher voltage levels than ±800 kV stations. The electromagnetic environmental effect caused by line corona discharge is more serious. In particular, the strength of the ground total electric field in the converter station is directly related to the occupational health of the operation and maintenance staff and must be properly handled. According to the design and operational experience of ±800 kV converter stations, the type selection and height of the tubular busbar should be paid more attention in order to control the strength of the ground total electric field in converter stations.

At present, there is no limit on the total electric field of ±1100 kV converter stations at home and abroad. The total electric field limit is determined by the perception of the human body when exposed to the total electric field. Therefore, the total electric field and ion flow density limit of the ±1100 kV converter station can be determined by referencing the relevant standards of ±800 kV converter stations which has been accepted; the ground total electric field strength does not exceed 30 kV/m [56]. Within these

Fig. 6 Total electric field on the ground level with the separation distance between ±1100 and ±800 kV lines being 70 m

Fig. 7 Diagram of the ±1100 kV UHV converter transformer
voltage, and the development of some key parts such as thyristors and saturation reactors.

Therefore, by optimising the size and the shielding system construct of valve towers, the distribution of distributed capacitors between converter valves and the ground is improved, and the mutual capacitance among valve thyristors is enhanced. Thus, the voltage inside the valves, under the steep impulse voltage of 1200 kV/μs, can be evenly distributed. At the same time, a shielding structure with a C-shape top is proposed. Therefore, the surface electric field strength is decreased and the air gap necessary for valve tower external insulation is reduced. The proper insulation coordination of ±1100 kV converter valves is achieved. As for developing and manufacturing key components, the 6-inch 8.5 kV/5500 A thyristor was developed and manufactured by optimising the design of the terminal of chip mesa and the gate-cathode and coordinating the on-state and turn-off characteristic. By optimising the electrical parameters of saturated reactors and applying novel technology in manufacturing iron cores with very thin silicon-steel sheets, the iron loss can be reduced by 20% and the operating hot-spot temperature can be lower than 70°C with the saturated reactors keeping their original structure size unchanged. The low thermal-resistance heat sink with frontal spacer and rear denser staggered fin mini-channel arrangement is developed to realise effective cooling of high-power thyristors.

The ±1100 kV/5500 A UHVDC converter valve tower has been successfully developed and manufactured. It adopted a double-valve structure with suspension and air insulation as its insulation mode. Each converter valve contains ten valve modules in series. The performance parameters of converter valves are shown in Table 8 and a picture of the valve is shown in Fig. 8.

5.3 Smoothing reactors

The main function of the UHVDC smoothing reactor is restricting the AC component in DC side of the converter valves [63]. In combination with the DC filter, the smoothing reactor can also filter the AC component at the DC side and restrain fault currents. Therefore, it is a key piece of equipment in the UHVDC project. To reduce the cost of production and transportation, UHVDC smoothing reactors are always dry type. Major design considerations include insulation coordination, temperature rise control, noise control, seismic design, anticorona, and lightning protection measures, which are brought about by the voltage level increases. A 150 mH inductance should be connected in series to the pole bus in the Changji-Guquan ±1100 kV UHVDC demonstration project. Owing to the limitations of manufacturing level and transportation conditions, the 150 mH inductance is composed of 2 ±1100 kV dry-type smoothing reactors in the series; each of them is 75 mH.

According to the results of lightning impulse tests on simulation coils and the insulation characteristic of epoxy resin encapsulating material, when the surface electric field of ±1100 kV dry-type smoothing reactors is 3.6 kV/cm, there will be no flashover on the winding surface. Therefore, while the lightning impulse voltage is 1380 kV, the drying arc distance of the winding surface should not be <3.84 m. Under normal operating conditions of ±1100 kV dry-type smoothing reactors, the geometric mean of harmonic voltages between terminals is 41 kV. Based on test results in fog chambers, the drying arc distance of the windings surface, under long-term steady voltage, should not be <3.20 m. Overall, considering the above factors and transportation limitation, the recommendation drying arc distance of ±1100 kV dry-type smoothing reactors is 3.87 m.

The main parameters of ±1100 kV smoothing reactors are given in Table 9.

5.4 Wall bushing

DC wall bushing is the key equipment that connects valve halls and DC fields. Its electrical and mechanical performance is crucial for the safety of the pole [64, 65]. Owing to the non-linearity of material, electrical and mechanical properties, the research and development of ±1100 kV DC wall bushings needs to make breakthroughs on materials, design, and test technology, but not be manufactured by simply size zooming based on the ±800 kV DC wall bushings.
Fig. 9 ±1100 kV DC SF₆ gas insulated wall bushing
(a) Structure scheme, (b) Testing site

Fig. 10 ±1100 kV DC SF₆ composite gas-insulated wall bushing with epoxy core
(a) Structure scheme, (b) Testing site

According to the main insulation structure, ±1100 kV DC wall bushings can be divided into pure SF₆ gas insulation type and epoxy condenser SF₆ gas composite insulation type [66], as shown in Figs. 9 and 10. Considering the different characteristics of these two types of DC wall bushings, the combined effect of the dielectric properties, the space charge, the temperature, and the mechanical stress on the bushings’ performance was researched. The multi-objective optimisation design method, based on multi-physics field including electrical, thermal, and force field, was proposed for ±1100 kV wall bushings. The AC electric field, DC electric field, polarity inversion dynamic electric field, and electro-thermal coupling field were studied under various conditions. A multi-objective optimisation design method of a ±1100 kV DC wall bushing based on multi-physics field calculations such as electric, thermal, and mechanical stress calculations was proposed and applied in bushings’ design. Based on the calculation model, the stress distributions were optimised to realise the structural optimisation including internal and external insulation structure, the current carrying structure, and the mechanical structure. Many challenges, such as super-long conductive rod processing, pouring process of DC epoxy support insulators, manufacturing process of large size epoxy capacitor condenser core, drying, high-vacuum and no gas gap infiltration and solidification, the assembly process, and other key technologies during manufacturing process, were overcome. Test methods that can simulate operating conditions were put forward; the relevant technical standards were determined. The comprehensive test platform for testing the electrical, thermal, and mechanical performance of ±1100 kV UHVDC wall bushings were established. The partial discharge measurement under high DC and AC voltages, temperature rise test, uneven razing test, and other test difficulties were addressed. A test technology system was set up to complete test verification of the bushings. The ±1100 kV pure SF₆ insulated DC wall bushing, with a length of 31 m, was successfully developed and manufactured. The non-defective infiltration and solidification of a super-large epoxy-resin immersed paper capacitor core, with a length of 12 m, diameter of 0.8 m, and weight of 8 t, was successfully completed. Thus, a ±1100 kV SF₆ gas composite insulated wall bushing with a 28 m-long DC epoxy core has also been manufactured. These two types of wall bushings have been tested under the same technical parameters, as given in Table 10.

6 Integration mode of ±1100 kV project into power systems

The transmission capacity of a ±1100 kV project is 12 GW, which is equal to the capacity of four circuits of ±500 kV lines. The ±1100 kV transmission lines can accomplish large-capacity, long-distance, and high-efficiency power transmission. At the same time, the power fluctuations and the impulse to the power grid caused by disturbances on them will be more serious.

At the sending end of ±1100 kV UHVDC demonstration project, some types of renewable energy, such as wind power and photovoltaic, have replaced traditional coal power and become the main component of power export. As a result, on one hand, the short-circuit capacity of converter stations will decrease. DC blocking faults, commutation failures, and AC short-circuit faults near rectifier stations result in overvoltage at the sending grid, leading to the high-voltage outage of renewable power sources, such as wind power and photovoltaic systems. On the other hand, the rotational inertia will decrease. The large amount of unbalanced power caused by DC blocking faults is liable to result in frequency swell that leads to the high-frequency outage of renewable energy sources. To lower the risk of cascading failure resulting from integration of ±1100 kV projects, synchronous condensers should be equipped near converter stations to enhance the capability of the sending end in voltage control. This will also improve the high-frequency and high-voltage withstand standards of renewable energy sources and enhance the anti-reference capability.

As for the receiving end of the ±1100 kV project, the concentrated infeed of large-capacity DC power may easily lead to unbalanced distribution of power flow. The local transmission bottleneck will limit the power receiving capability of the entire AC and DC power grid. On the other hand, the support capability of the power grid will be lowered and the risk of voltage instability under fault impulse may increase. Furthermore, a large amount of power shortage, caused by DC blocking, make the receiving power grid face serious low-frequency problems. To improve the safety of the receiving power grid after the ±1100 kV line integrated, hierarchical integration is adopted to balance power flow distribution, synchronous condensers are equipped in voltage sag areas to support quick voltage recovery, and the power regulation function is optimised to relieve the unbalance power impact.

To effectively counter the impact of severe faults due to DC blocking of ±1100 kV projects, wide-area controllable resources should be used both at the sending and receiving ends. The integrated defence system should be constructed featuring multi-resource overall control, multi-area cooperation control, multi-scale coordination, and multi-object combination control.
are as follows: The pollution levels of the areas along the interference can meet the requirements of international and the scheme design has been completed. The research results connected to the valve top. Double ground lines should be the total ground electric field of DC field in a ±1100 kV converter angle is −10°, the ground line can effectively shield the pole lines.

Table 10 Main parameters of ±1100 kV DC wall bushing made in China

<table>
<thead>
<tr>
<th>Test items</th>
<th>Test parameters</th>
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</thead>
<tbody>
<tr>
<td>rated voltage, kV</td>
<td>1100</td>
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<tr>
<td>rated continuous DC current, A</td>
<td>5523</td>
</tr>
<tr>
<td>maximum continuous DC voltage, kV</td>
<td>1122</td>
</tr>
<tr>
<td>1 h power-frequency withstand voltage with partial discharge, kV</td>
<td>1190</td>
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<tr>
<td>2 h DC withstand voltage with partial discharge, kV</td>
<td>1683</td>
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<td>DC polarity reversal voltage, kV</td>
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<td>lighting impulse withstand voltage, kV</td>
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<tr>
<td>switching impulse withstand voltage, kV</td>
<td>2100</td>
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<tr>
<td>EMC test voltage, kV</td>
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<tr>
<td>power-frequency voltage with dissipation factor, capacitance, and partial discharge, kV</td>
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<tr>
<td>cantilever load, N</td>
<td>5000</td>
</tr>
</tbody>
</table>

7 Conclusions

The first ±1100 kV DC transmission project is being constructed and the scheme design has been completed. The research results are as follows:

(i) Compared to ±800 kV converter stations, a high-performance lighting arrester is equipped at the valve side of the converter transformer to further lower the insulation level of the equipment connected to the valve top. Double ground lines should be constructed along the whole transmission line. When the shielding angle is −10°, the ground line can effectively shield the pole lines. The switching voltage margin of equipment in converter stations is 1.15. The maximum overvoltage is at the midpoint of the line, and its value is 1.57 p.u. With lightning arresters, the maximum voltage can be limited below 1.50 p.u.

(ii) The minimum air gap of towers below 3000 m altitude is determined based on test results of switching impulse flashover characteristics. The pollution levels of the areas along the transmission line are determined based on the equivalent salt deposit density. The external insulation is designed differently.

(iii) When 8 × 1250 m² conductors are adopted, the pole-pole spacing is 26 m and the line height is 25 m, the total electric field will be <30 kV/m. The ion flow density, audible noise, and radio interference can meet the requirements of international electromagnetic standards. For ±1100 kV converter stations at low altitude, the tubular busbar is recommended to adopt Φ400, and the height is recommended to be 17.2–21 m. With these parameters, the total ground electric field of DC field in a ±1100 kV converter station can be controlled to below 30 kV/m.

(iv) The 75 mH smoothing reactors and ±1100 kV/5000 A converter valves have been successfully developed and manufactured. The ±1100 kV/5523 A pure SF₆ insulated DC wall bushing and ±1100 kV DC SF₆ gas composite insulated wall bushing with epoxy core have also been developed and applied.

(v) For the ±1100 kV UHVDC demonstration project, to prevent cascading failures at the sending end, which result in high-voltage or high-frequency outages of renewable energy sources, equipping synchronous condensers near converter stations will be considered to improve the anti-interference capability of the sending end power grid. At the receiving end, the demonstration project should be hierarchically integrated into the receiving power grid to balance the power flow. Synchronous condensers should be equipped in voltage sag areas to support quick voltage recovery.

Some technical challenges such as air gap saturation, electromagnetic environment control, multi-physics field, and high rise of local temperature, should be addressed to develop key equipment and accomplish insulation coordination. The transmission distance of the ±1100 kV DC transmission project can reach 1000–5000 km. The development and application of ±1100 kV DC transmission technology can not only promote the energy resource allocation in larger areas, but also advance the development of UHVDC transmission technology around the world and provide important technical measures for optimised international and intercontinental energy allocation.

8 References

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