Survey of Technologies of Line Commutated Converter Based High Voltage Direct Current Transmission in China

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***Abstract*—This paper reviews the applications of line commutated converter based high voltage direct current transmission (LCC-HVDC) technologies in China, with a special focus on UHVDC technology developed in the last 10 years. The paper examines six specific aspects of areas—voltage increase, capacity upgrade, reliability improvement, engineering design innovation, equipment and materials innovation, and the R&D of next step. Subsequent advances in LCC-HVDC technologies in recent years are also discussed.**

***Index Terms*—±800 kV, electromagnetic environment, main circuit, UHVDC.**

I. INTRODUCTION

SINCE the construction of the first ±500 kV HVDC project (Gezhouba–Shanghai), research and development and corresponding engineering practices in China have advanced considerably over the past 20 years. In particular, since 2004, a series of technologies and equipment has been in development centering on aspects of the ±800 kV UHVDC [1], [2]. Many technological breakthroughs have been realized in this area resulting in verifiable high reliability, as well as significant social and economic benefits from the implementation of LCC-HVDC technology. In sum, advances in HVDC technology have greatly expanded its application around the world.

Currently, more than 20 LCC-HVDC projects have been put into operation in China. Among these, State Grid Corporation of China (SGCC) was responsible for conducting 18 HVDC projects, including four ±800 kV HVDC projects, of which two reached the maximum capacity of 8000 MW; ten were ±400 kV to ±660 kV DC projects; and five were back-to-back (BTB) projects. The total transmission capacity is currently at 58,260 MW, with approximately 17,000 km of transmission lines, presently accounting for about 40% of global capacity, while ranking first in the world. In addition, SGCC has made innovative strides in research and continuous improvement of HVDC technology development, with a goal to reduce transmission losses, enhance engineering security, and achieve economic savings. Globally, other study/project practices on very long distance, very large capacity LCC-HVDCs have also been conducted in India and Brazil. This paper presented the technical breakthroughs for ±800 kV UHVDC projects of SGCC.

The content is organized into six sections dealing with voltage increase, capacity upgrade, reliability improvement, engineering design innovation, equipment and materials innovation, and the R&D of next step.

II. INNOVATIONS IN VOLTAGE INCREASE

In the past ten years, the DC voltage was increased from ±500 kV to ±660 kV and ±800 kV in China by R&D and demonstration project construction. Economic transmission distance was boosted to the 2000 km level [1].

To solve the challenge of voltage increase, it is necessary to study issues in overvoltage suppression, electromagnetic environment, and external insulation, as well as the testing capabilities for dealing with voltage increase.

A. Overvoltage Suppression

The UHVDC system overvoltage level directly decides the air gap of converter station/transmission line and and insulation level of equipment.

In 2002, the technical report entitled, “HVDC Converter Stations over ±600 kV” in the CIGRE technical brochure (No. 215), made recommendations for insulation levels of ±800 kV, 5000 MW with a two series connected 12-pulse converter system. The recommended value of high-voltage converters is shown in Table I.

TABLE I
EXPECTED INSULATION LEVEL OF ±800 KV DC HIGH-VOLT CONVERTER STATION (DC BUS)

LIWL (kV)	SIWL (kV)	
1,990	1,891	CIGRE
1,800	1,600	Optimization

However, high over voltage means a large air gap and difficulties in equipment manufacture. Some research and development thus is necessary to reduce these problems. For example, as a result of average distribution of smoothing reactor on the pole/neutral line and the configuration of the surge arrester in the middle of two converters, the HV area over voltage level is inhibited significantly [3], [4].

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In Table I, it can be seen that the SIWL and LIWL of valve side of the high voltage converter transformer and DC pole bus were reduced to 1600 kV and 1800 kV [3], representing a decrease of 15% and 10%, respectively, when compared with the CIGRE results.

In addition, the UHVDC transmission line is long and the its over-voltage is high in the middle range of 100–200 km. Based on this, the DC line segmented insulation coordination was employed.

B. Electromagnetic Environment Index

Currently, the maximum synthetic electric field strength limit under the DC transmission line worldwide is 25–40 kV/m. In China, the limit is 30 kV/m under ±800 kV DC transmission lines. The DC line audible noise limit is 40–45 dB (A). In China, the ±800 kV DC transmission line audible noise limit is 45 dB (A). These are consistent with international standards.

To meet the limits of electromagnetic environment above and radio interference, 6 or more bundled conductors have to be used based on the following measurements:

1) section of sub-conductor;
2) distance between pole conductors;
3) height of the pole conductors.

In addition, the surface condition of the conductor and fittings need to be designed and handled properly. The pole conductor distance is 22/20 m depending on different projects and conductors, the corresponding height is 18/21 m for non-residential and residential neighborhoods area, respectively [4].

The following are some research findings:

1) In residential areas, replacing the nominal electric field limit with the synthetic electric field limit could lead to more scientific and rational evaluation of the electromagnetic environment, and facilitate environmental monitoring and assessment.
2) The ground synthetic electric field increases with altitude. Under these conditions, the height of the pole-conductor has to be lifted by about 6% per 1000 m.
3) From the measurements of DC lines in operation and testing of the UHVDC testing line, it was found that in the winter dry environment of northern area, the ground synthetic electric field of negative pole line when there are many particles in air.

The ±800 kV DC line and converter station electromagnetic environment limits presented by SGCC have been accepted by China's power industry standard and written into the IEC technical report, "Electromagnetic environment of UHVDC transmission line limits" (IEC/TR 62681). The results have been widely used in ±800 kV UHVDC.

C. External Insulation

UHVDC external insulation is challenging due to the high voltage level, heavy pollution, and high altitude areas along the transmission lines. Previous research only focused on the short string of insulators. Studies for external insulation features of long string insulators and post insulators were lacking in the initial stages of research and development of UHVDC.

China Electric Power Research Institute has carried out an artificial contamination test for the first time on large size insulators. The maximum length of the suspension insulators was 15.6 m, and the maximum height of the post insulators was 12 m. These tests solved the pressure stability and fog uniformity problems in large spaces. The following results were obtained:

1) the flashover performance of DC disc insulators, post insulators, and composite insulators in short size and full-size conditions, respectively;
2) the flashover performance of 300 kN large-tonnage insulators;
3) various types of string insulators altitude correction factors;
4) innovative test methods for weak hydrophobicity of composite insulation surface;
5) the flashover performance of V composite insulator strings and composite post insulators on hydrophilic surfaces and weakly hydrophobic surfaces.

These test results provide a direct and accurate design basis, and improves the economy while guaranteeing design reliability of external insulation [5]–[8].

D. Test Capability

The UHVDC transmission system operates under a complicated environment, which is difficult to simulate accurately. All the existing well-known test stations in the world are not capable of testing or researching UHVDC. Therefore, it was necessary to improve the test capabilities and innovative test technology at the start of the research and development phase of the UHVDC.

A world-class UHVDC test base and a high-altitude test base has been constructed in Beijing and Tibet respectively.

All the electrical design of those test bases were done by China Electric Power Research Institute. In addition, those test bases are equipped with 100% local equipment with complete intellectual property rights.

The UHVDC test base has made 52 major technological innovations [9], [10], including:

1) technical specifications for 7200 kV impulse voltage generator;
2) weakly damped capacitive voltage divider;
3) test methods for DC tests;
4) combined switching/lightning impulse voltage test of air gaps;
5) icing and de-icing test under constant voltage;
6) simulation test of superimposed AC/DC electromagnetic environment impact.

The test base also has set 15 records, including:

1) a double-circuit transmission line with the highest test voltage level and maximum length;
2) the widest adjustment range of configurations and electrical parameters;

3) the largest multifunctional AC/DC pollution and environment test room that can simulate pollution, icing, rain, and low ambient pressure conditions.

Today, testing of UHVDC voltage up to ±1100 kV has been achieved.

The Tibet high-altitude test base is the only high voltage test laboratory over 4000 m altitude around the world. With this test base as the basis, subsequent tests in the range of 4300 m altitude have also been performed and a number of important original results have been achieved, including:

1) air gap discharge characteristics;
2) insulator pollution flashover characteristics;
3) transmission line corona characteristics;
4) electromagnetic environment.

Almost 100 key scientific research projects have been initiated in the UHVDC test base and the high-altitude base, including the "973 program" of Ministry of Science and Technology, Major Program of National Natural Science Foundation of China, National Key Technology Research and Development Program, and the projects sponsored by the SGCC. The achievements from these R&D projects have contributed greatly to support the UHVDC project design and construction.

III. INNOVATIONS IN DC CURRENT/CAPACITY INCREASE

Increasing sections of line conductors is an effective and efficient option to solve line corona and electromagnetic environment issues when DC voltage increases. The larger section of line conductors allows the spaces for larger DC current. The increased size of equipment for insulation and electromagnetic issues also provides a natural margin for further expansion of the DC current and transmission capacity. An economic analysis showed that by increasing the DC current based on increased DC voltage, the transmission capacity and efficiency of corridor utilization could be significantly improved with very limited project cost increase [11]. Based on this fact, the ±800 kV HVDC transmission capacity rose from 6400 MW to 7200 MW and 8000 MW, which achieved more power transmission, and higher economic effectiveness and efficiency under the same transmission corridor.

Benefiting from the enhancement of voltage and capacity, the unit capacity length investment was thus reduced from RMB 216/(100 kW·km) to RMB 156/(100 kW·km).

A. Security and Stability of DC Infeed

Due to the large capacity of the DC feed, power flow transferring caused by DC blocking poses a serious challenge to power angle stability, voltage stability, and frequency stability control [4], [12]. A comprehensive analysis of the security and stability characteristics were carried out through the large-scale UHV AC and DC hybrid transmission system simulation, and a generator/power grid/DC multi-coordinated optimal control strategy was also proposed. In addition, the AC/DC power grid security and stability control system was established. This system is able to coordinate multi-DC fast power modulations, as well as AC systems and power source support. The proposed method and system have solved the important issue of the impact of sending/receiving AC grid caused by the failures of bulk capacity DC system.

B. Delivery of Renewable Energy

By conducting a study on wind and thermal power proportion at the DC sending side and the DC operation mode, the reasonable proportion of wind/thermal and leading phase operation mode of thermal power units were determined. The relationship between UHVDC and the wind generator was studied, and it became clear that the wind generator off the grid caused by overvoltage was the most important issue at the sending side. Also, it was determined that the DC line fault restart, the commutation failure of the inverter side, and the bipolar block were all critical failures of the wind power generators.

C. Standards of Equivalent Disturbing Current

Equivalent disturbing current value (I_{eq}) is an indicator to measure the impact of DC transmission lines on the audio telephone line. In the past, in China, an equivalent disturbing current was required to be no more than 500 mA under DC bipole operation and 1000 mA under DC monopole operation during the starting phases of HVDC project practices. The study of the first ±800 kV UHVDC project showed that equivalent disturbing current could be not more than 3000 mA and 6000 mA in normal bipolar mode and normal monopole mode, respectively [13] due to the extensive use of fiber-optic communications. This result simplified the DC filter design, and reasonably reduced the anti-interference costs of the audio communication system.

IV. INNOVATIONS IN RELIABILITY

Improvements in voltage and current mean larger capacity, adding to the reliability of the HVDC project. The study of topology of converters, DC system control and protection, and ice melting technology were introduced in this part.

A. Layout of Two 12-pulse Converter Series Connected Topology and Reliability Index

In the first ±800 kV demonstration projects, a comparison was made among three main circuit schemes, namely, one single converter on each pole scheme, two converters connected in a series scheme, and two converters connected in parallel scheme. Taking equipment design and transportation limitations into account, the project adopted the two converters in series connection on each pole scheme. Further, the voltage distribution schemes between the two converters were compared for technical and economic aspects. The 400 kV + 400 kV scheme was seen to have comparative advantages in terms of insulation level, equipment manufacturing and transportation, converter station comprehensive cost, operational flexibility, and the DC fault's impact on the AC system. As a result, it was determined to use the 400 kV + 400 kV solution on ±800 kV UHVDC. This main circuit scheme has become a typical UHVDC system case, as shown in Fig. 1.

The reliability and availability indicators [2], [4], [14] required in the specification of UHVDC projects and actual operational data from 2011 to 2013 are shown, as in Table II.

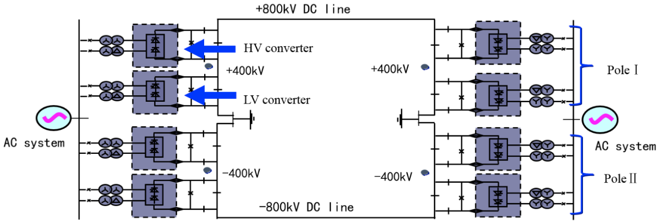

Fig. 1. The topology of UHVDC main circuit.

TABLE II
RELIABILITY AND AVAILABILITY DATA OF THE FIRST ±800 KV UHVDC PROJECT (XIANGJIABA–SHANGHAI)

Indicator	Special Value	Actual Performance		
		2011	2012	2013
Forced energy unavailability (FEU) (%)	≤ 0.5	–	–	–
Scheduled energy unavailability (SEU)(%)	≤ 1	0.077	0.038	0.01
Average forced outage rate of converters (times/year)	≤ 2	0	0.25	0.25
Monopole Forced Outage Rate (per pole) (times/year)	≤ 2	0	0	0
Bipolar Forced Outage Rate (times/year)	≤ 0.05	0	0	0

All data are average values.

1) The interface standards of different technical solutions have been proposed, which overcome the obstacle of different interfaces for different equipment supplies, thereby creating conditions for the use of domestic equipment.
2) The ±800 kV DC arrester parameters, configuration schemes, and insulation coordination design are proposed for the first time. The equipment's insulation level requirement can be reasonably determined, and its investment can be controlled under assurance of safety and reliability.
3) The UHVDC main circuit is configured with two 12-pulse converters connected in series with a by-pass circuit breaker and disconnectors; the DC yard is arranged symmetrically by pole. Smoothing reactors are arranged by average on pole bus and neutral bus, with a triple-tuned DC filter.

B. Real Time DC Protection

Typically, only one redundant configuration of DC protection is used. In order to improve the operational reliability of the DC system in the UHVDC project, and additional two redundant systems were implemented in the DC protection system, from the measuring coil and measuring circuit to the main CPU protection. This means that three completely redundant systems are running in parallel. The protection output uses “two out of three” tripping logics [15], [16]. The output decision logic device is configured redundantly according to the valve group and pole, with redundant power supply. Operating experience has proved that “two out of three” is an effective way to improve the reliability of DC protection.

C. DC Online Melting Ice Technology

To prevent the damage caused by snow and freezing precipitation in southern China on the DC transmission line, the UHVDC project added melting ice circuit wiring in DC yards. In the melting ice mode, by adjusting the connection, the high voltage converter could be operated in parallel with another pole's low voltage converter to get twice the rated current (8000 A) [17], [18] to melt the ice. In the implementation process, there is no need to add current capacity on any equipment, but rather simply set up a temporary jumper to change the connection.

V. INNOVATIONS IN ENGINEERING

A. Common Ground Electrode and Step Voltage Standard for Ground Electrode

Multiple sharing of ground electrodes for HVDCs can reduce the occupancy of electrode site resources [19]. Multiple UHVDC projects that share ground electrodes means larger current and a bigger polar ring.

During the study/design of common ground electrode, a step voltage test with different characteristics was conducted on 1028 individuals to verify the old limits, and the conclusions revealed a step voltage limit for the human body. According to the research result, an optimized shared ground electrode was designed at the sending side in the area of the lower branch of Jinsha River for multi UHVDC converter station, which saved more than RMB 50 million in two UHVDC projects.

B. A Complete 3D Valve Hall Design

The 3D valve hall design is more intuitive and accurate than the traditional 2D design. It enables the air gap between related equipment to be checked conveniently and accurately, thus fundamentally eliminating the possibility of discharges inside the valve hall. Also, the electrical installation and construction drawings of the valve hall can be distilled by obtaining sectional drawings directly from the 3D models. Therefore, the design work is reduced to the greatest extent and accuracy of various plane and sectional drawings are ensured.

C. AC Filter Yard Arranged in “⊞” Shape

To reduce the land occupation of reactive power compensation part of the converter stations, the AC filter yard is arranged in “⊞” shape.

Here, the AC filters and shunt capacitors in each bank are placed at either side of the bus. With this arrangement scheme, the land of reactive power compensation area of a converter station can be saved by 7300 m^2 [1]. Moreover, by modifying the conventional “⊞” arrangement, the space below the filter buses can be fully utilized when coupled with the use of vertical break dis-connectors, making employment of either odd or even number of reactive power compensation sub-banks possible. This can further save land occupation by 15% [1] and reduce the length of gas-insulated buses.

D. HELVA Technology

HELVA technology, which is an advanced geographic measurement system employing aerial photography and GPS technology, provides 3D models, orthophotos, digital terrain models, and digital maps obtained by processing aerial photos, field control position data, and annotation data. Using HELVA technology, we can get the latest features and topography both accurately and vividly. The benefits include:

1) accurately and efficiently carrying out distance measuring;
2) route optimization and tower optimization;
3) greatly reducing survey and design efforts;
4) improving survey and design quality;
5) savings on project investment.

Today, this technology has been adopted for about 95% of transmission lines at 330 kV and above projects in China. Such completely digitized technology allows for whole-process optimization of transmission lines design, ranging from route selection, planning and design of towers, to tower positioning. Now, the HELAV technology is being used in transmission lines with a total length of more than 150,000 km, leading to a reduction of 4140 km, and savings of more than RMB 6 billion.

E. F-type Tower

The vertical installation of two-pole conductors on F-type tower means that corridor width could be narrowed to the greatest extent. This means there will be reduced demolition of residential dwellings and factories. Thanks to continuous improvement, F-type straight-line towers can now be designed with a three-degree turning angle and can be directly connected to conventional straight line towers, which allows for more flexible and convenient applications. By uniformly arranging the jumper brackets on one side of the tower body, it is possible that the shielding angle of the earth wire with respect to conductors and jumpers is less than 0°.

It is a well-known fact that finding routes in Shanghai and Jiangsu region is challenging. By employing F-type towers in these regions, however, the distance between two neighboring UHVDC transmission lines is reduced to 60 m. Regardless of the additional weight of the towers in the range of 360 tons, as well as additional construction costs of tower bodies of about RMB 3.9 million, approximately, 3000 m^2 area of houses, one cement plant, and one wharf have avoided demolition, which means an investment reduction of RMB 30 million in the existing UHVDC projects.

VI. INNOVATION IN EQUIPMENT AND MATERIALS MANUFACTURING

A. Technical Parameters of Main UHVDC Equipment

Detailed technical parameters of the main UHVDC equipment are listed in Table III. The localization rate of the equipment reached 68.52%/84%, depending on the projects. In the meantime, the localization rate of ±500 kV DC equipment reached 100%. The locally manufactured equipment such as converter valves, control and protection and DC insulators were also exported abroad.

TABLE III
COMPARISON OF MAIN PARAMETERS BETWEEN UHVDC AND CONVENTIONAL DC EQUIPMENT

Designation	800 kV DC Projects	500 kV DC Projects
Thyristor	Size: 6 inches	Size: 5 inches
	Blocking voltage: 8,500 V	Blocking voltage: 7,200 V
	DC current: 5,000 A	DC current: 3,000 A
	Surge current: 51 kA	Surge current: 36 kA
	Thermal resistance: 3.0 K/kW	Thermal resistance: 4.2 K/kW
Converter Valve	Air-insulated suspended double valve structure;	Air-insulated suspended quadruple/double valve structure;
	Rated voltage: ±800 kV;	Rated voltage: ±500 kV;
	Rated current: 5,000 A;	Rated current: 3,000 A;
	6-inch thyristors selected	5-inch thyristors selected
Converter Transformer	Rated capacity: 321–402 MVA;	Rated capacity: 297.6 MVA;
	Rated voltage: ±800 kV;	Rated voltage: ±500 kV;
	Rated impedance: 18%	Rated impedance: 16.7%
Smoothing Reactor	Dry core type reactor;	Oil-immersed type transformer
	Rated voltage: ±800 kV;	Rated voltage: ±500 kV;
	Rated current: 5,000 A;	Rated current: 3,000 A;
DC Control and Protection	±800 kV DC control and protection system	±500 kV DC control and protection system
	DCC800, PCS-9550 or DSP3000 platform used	Mach2, PCS9500 or DSP2000 used platform used

B. Research and Development of Key Components of Equipment

Through project construction and equipment development, China has established the capability of self-manufacturing of key components, such as silicon steel sheets of 0.27 mm/100 mW, special DC insulating oil, valve-side outlet devices, complex special-shaped and molded insulation parts for converter transformers, and 6-inch thyristors for converter valves. Multi-physics field simulation platforms for testing converter transformers/converter valves in electrical, thermal, magnetic, and mechanical environments have also been developed. Additionally, physics platforms for insulation temperature rise test of converter transformers and operating test platforms for converter valves have also been established.

C. Composite Insulators for Lines and Strain Strings

The ±800 kV UHVDC transmission lines use composite insulators for all suspension strings and for some tension strings by trial in areas exposed to light and moderate icing conditions. Composite insulators have excellent pollution flashover, withstanding performance with reduced maintenance need, less insulator weight (about 10% of that of porcelain and glass insulators) and lower loads on towers. In addition, the length of insulator strings can be appropriately reduced, the type and length of jumpers can be simplified and the length of the cross arm of tension towers can be reduced. The composite insulators are less costly than porcelain and glass insulators.

The use of four 550 kN tension composite insulator strings on two towers saved about RMB 241,000 compared with three 550 kN tension disc insulator strings.

D. Application of Large Cross-Section Conductor

Large cross-section conductors generally refer to those having a nominal cross-section of 800 mm^2 and above. With increased voltage levels, the use of larger cross-section conductors is advantageous in reducing losses, controlling the number of conductor bundles and improving the economic and environmental indicators of the line. Based on the 720 mm^2 cross-section conductors used in the Three Gorges HVDC projects, China has successfully developed 900/1000/1250 mm^2 large-section conductors with four-layer stranded and associated fittings and construction machineries [18], [20]. In these projects, the 1250 mm^2 cross-section conductor has increased the conductor conductivity to 61.5% IACS. The concept of crimping loss is proposed and the definition of crimping survival ratio is given. A half-rubber coating pulley technology has been developed to prolong the service life of pulleys. The stringing pulley blocks designed for the large cross-section conductors have less overall weight by 30%–50%. A detachable overhead conductor delivery drum of full-steel corrugated structure is developed, which can address the problem of the conductor swerving during stringing operations and thereby improve the stringing efficiency. In addition, this kind of drum is reusable. A 2* "one pull three" stringing technique has been developed.

For 900 mm^2 large cross-section conductors, one ±800 kV UHVDC project (Jinping–Sunan) consumes 75,000 tons. Given that the quantity of loss hours per year is 3000, one kilometer of line can save 45,000 kWh of electricity each year compared with the traditional 630 mm^2 conductors, which means cost savings of more than RMB 38 million each year. For 1000 mm^2 large cross-section conductors, compared with 630 mm^2 conductors, 42,500 kWh of less loss per kilometer is achieved (Ningdong–Shandong project), which means annual cost saving of nearly RMB 20 million.

E. High-strength Steel, Large-size Angle Steel, and Large-Size High-strength Angle Steel

The high-strength steel used in transmission towers is mainly low alloy and high-strength structural steel with yield strengths of 420 MPa (Q420) or 460 MPa (Q460). The high-strength steel is not only strong but also has impact toughness, and has been used as the main material for towers, accounting for about one-third of of the towers' total weight.

Theoretical and experimental studies have given the compression stability curve and the loaded compression member's stability factor of Q460 high-strength angle steel. Similarly, correction factors of the slenderness ratio under different boundary conditions have also been derived, and the design and prototype test of large-size angle steel towers completed. Compared with the current technology, these towers are more reliable, significantly lighter and less difficult to manufacture and assemble.

Large-size angle steel has been applied in the UHVDC project. It was determined that Q420 and Q460 high-strength steel could reduce the weight of tower by 6%–8% and 5%–12% respectively. Assuming that the high-strength steel material constitutes about one-third of a transmission tower on average, the cost of the tower could be reduced by 2%–6% for Q420 and 2%–8% for Q460, even considering a higher unit price of Q420/460.

Large-size, high-strength angle steels refer to Q420 angle steel with limb widths of 220 mm and 250 mm. Since the hot rolled Q420 angle steel with 200 mm and less limb width has limited carrying capacity in China, the main material of the tower body in UHV/double circuit/multiple circuit transmission line applications has to be made of double- or multiple-splicing angle steels. However, such combined structures are more complicated. It is more difficult and onerous to design, fabricate, and assemble the towers, with more uncertainties, which entail some risks. Instead, large-size angle steels could improve the safety and reliability of towers, lower the tower weight, reduce difficulties in assembly, and improve the efficiency and economy of line construction.

For example, one UHVDC project consumes an average of 250,000 tons of large-size angle steels for towers. Due to the use of large-size angle steels, the weight of towers can be reduced by around 3% and the consumption of steels can be reduced by 7500 tons contributing to an investment reduction of RMB 60 million. In the Jinping–Sunan, Haminan–Zhengzhou and Xiluodu–Zhejiang ±800 kV UHVDC projects, large-size angle steel towers are widely used instead of double/multiple-splicing angle steels. Each project consumes about 70,000 tons of large-size angle steel, reducing tower weight by about 3% and cutting down the project investment of about RMB 90 million. Currently, the research on large-size angle steel with limb width of 300 mm is ongoing.

F. Composite Cross Arms

Composite materials have several advantages including lightweight, high strength, corrosion resistance, easy fabrication, and insulation performance, making them ideal materials for transmission tower structures. Although these materials are not economical when used for construction of the entire tower, it is reasonable to use composite materials for key parts of tower that affect the electrical performance (e.g., composite cross arms). In this way, not only the insulation performance of the composite materials, but also the benefits of steel structures including large stiffness and high bearing capacity, are fully utilized.

In recent years, the towers of composite materials have been put into service for a number of transmission lines. In 2011, relying on a 750 kV transmission line project in northwest China, a 750 kV tower with cross arms of composite materials was developed, which reduced corridor width by about 10 m, tower height by 10 m, consumption of tower materials by 10 tons, and foundation cement consumption by 10 m^3. In 2013, research on towers with rotating cross arms of composite materials was conducted leading to further release of longitudinal imbalance tension and reduction in the weight of the tower.

Compared with angle steel towers, the tower with cross arms of composite materials in UHVDC projects has following advantages:

1) cross arm height reduced by 7 m;

2) foundation force decreased by 23%;
3) steel consumption reduced by 28%;
4) tower weight decreased by 19%;
5) foundation concrete volume reduced by 23%;
6) the comprehensive construction cost of tower reduced by about 15%.

VII. FUTURE TECHNOLOGY DEVELOPMENT

Based on the technical achievements described in this paper, the future development and application of UHVDC transmission technology are mainly focused on the following three aspects.

A. Further Upgrading of the DC Voltage Level

For ±1100 kV UHVDC transmission lines, the transmission capacity will reach 12,000 MW, the line loss can be reduced to 1.5% per thousand kilometer, and the economic transmission distance could be up to 5000 km. This could meet the requirements for power delivery over ultra-long distances and for ultra-large capacities [21], such as the thermal and wind power from Xinjiang and the hydropower delivery from Tibet. Technical solutions for addressing external insulation and the electromagnetic environment have been developed, and the main circuit and parameters have been determined [22], [23]. The prototypes of key equipment, such as mockup of converter transformers and wall bushings have been successfully manufactured [24].

The increase of DC voltage and current leads to larger and heavier converter transformers. Because the water transportation is not available on the sending side, it is difficult to transport the converter transformer to the site. An on-site modular assembly technique is required for sending side converter transformers.

B. Further Upgrading of the DC Current/Capacity

The capacity of the ±800 kV UHVDC project with split connection to 500 kV/1000 kV at receiving side will further increase to 10,000 MW, while DC current will increase to 6250 A. The target is to reduce the construction cost of per unit capacity and the utilize efficiency of the corridor. The key of research and development is to further increase the current-carrying capability of equipment, especially valve-side bushings of converter transformers.

C. Further Upgrading of the AC Side Voltage

The sending system of the UHVDC projects is connected to the 750 kV AC grid in the northwest region and the receiving system is connected to 500/1000 kV AC grid [25], [26]. The target is to increase the capability of power collecting and consumption. Currently, feasible solutions have been worked out for DC control and protection technology, AC side 1000 kV low voltage converter transformers and the 1000 kV AC circuit breakers of reactive power compensation banks.

VIII. CONCLUSIONS AND OUTLOOK

On the basis of ±500 kV DC transmission technology, the HVDC transmission voltage level has been upgraded to the UHV level in SGCC, allowing for the advantages of DC transmission with respect to long distance and high capacity. The successful practices of the Xiangjiaba–Shanghai, Jinping–Sunan, Hami–Zhengzhou, and Xiluodu–Zhejiang projects prove the reliability and performance of ±800 kV UHVDC, and greatly push the progress of power transmission and equipment manufacturing technology. These practices also have laid a solid foundation for the development of higher DC voltage and larger capacity transmission technology.

China's demand for energy increases continually. The newly developed energy bases are shifting towards the western and northern regions. UHVDC technology makes it possible to intensively develop various energies in remote areas and transmit to developed area efficiently. It will play an increasingly important role in restructuring the energy supply system and optimizing the allocation of energy resources. It is expected that more than 20 UHVDC lines will be built by 2020 and the relevant technologies will improve continuously in large-scale practical applications.

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