文章编号：0258-8013 (2009) 22-0076-07 中图分类号：TM 723 文献标志码：A 学科分类号：470·40

±1 000 kV特高压直流输电技术研发思路

刘泽洪，高理迎，余军，张进

(国家电网公司，北京市 西城区 100031)

R & D Ideas of ±1 000 kV UHVDC Transmission Technology

LIU Ze-hong, GAO Li-ying, YU Jun, ZHANG Jin

(State Grid Corporation of China, Xicheng District, Beijing 100031, China)

ABSTRACT: ±1 000 kV ultra high voltage direct current (UHVDC) transmission technology can realize the optimal allocation of energy resources over a large area, and is suitable for the extra long-distance and super-capacity electrical power transmission. In this paper, the research and development (R&D) thought and plan of ±1 000 kV UHVDC transmission technology are presented. They are organized into five parts. In the first part, the necessity to carry out ±1 000 kV UHVDC projects and the necessity to conduct the corresponding R&D are analyzed. In part two, the system adaptability of ±1 000 kV UHVDC transmission is discussed, and the key points of researches are presented. Part three analyzes the technical feasibility of the transmission line and apparatus in converter stations. The key technical difficulties and R&D roadmap are discussed. In part four, a new thought to analyze economic advantages of ±1 000 kV UHVDC transmission technology from the perspective of converter station cost, transmission line cost and energy price is put forward. Part five introduces the R&D plan of ±1 000 kV UHVDC transmission technology of the State Grid.

KEY WORDS: ±1 000 kV UHVDC; research and development; apparatus; transmission line

摘要：±1 000 kV特高压直流输电技术能够实现大范围内能源优化配置，适合巨型能源基地实现电力超大容量、超远距离外送。提出了±1 000 kV特高压直流输电技术研发思路，共包括 5 个部分：第 1 部分分析指出了±1 000 kV特高压直流输电工程建设的必要性和开展±1 000 kV特高压直流输电技术研究的必要性；第 2 部分研究了±1 000 kV特高压直流输电在各种情况下的系统适应性和研究重点；第 3 部分研究了±1 000 kV特高压直流输电的换流站设备和线路的技术可行性，提出了需要进一步研究的技术难点和研发思路；第 4 部分提出了从换流站造价、线路造价和能源价格方面分析±1 000 kV特高压直流输电技术经济优势的思路；第 5 部分介绍了国家电网公司±1 000 kV特高压直流输电技术研究的计划。

关键词：±1 000 kV 特高压直流；研发；设备；线路

0 INTRODUCTION

Currently, Xiangjiaba-Shanghai ±800 kV UHVDC pilot project is going smoothly. Studies on the key technology have achieved breakthrough. The key kinds of equipment including converter transformer have been developed successfully, and entered mass manufacturing phase. Based on a great amount of tests and calculations, the key parameters of the transmission line have been determined and realized in the design, which means the feasibility of ±800 kV UHVDC transmission has been technically proved. The monopole is expected to be put into operation in March 2010.

Due to the inverse distribution between energy resources and economic development in China, the optimal allocation of the energy resource over a large area is objectively necessary [1-2]. As for hydro-power, thirteen huge bases have been scheduled with about 215 GW installed capacity. Among them, the exploitable capacity of Tibet reaches up to about 110 GW. As for thermal power, many large coal bases have possessed the basic conditions for exploitation. Except for the local consumption, the prospective power output scale can reach 200 GW. Among them, the estimated capacity of thermal power plants in Sinkiang is 50 GW, and most will be delivered to load centers in east China.

The distance from the huge energy bases in Tibet and Sinkiang to load centers exceeds 2 700 km. In case of ±800 kV UHVDC technology, the transmission loss will exceed 10% according to the investigation [2], which is not the optimal solution. Given this distance, ±1 000 kV UHVDC transmission is an effective solution for electric power delivery, and lays a solid foundation for the development of huge energy resource bases. Meanwhile, the more power can be transmitted with limited line corridors, which means high use efficiency of land resource. It is in line with the call for building a resource-conserving and environmentally-friendly society in China.

According to the plan of the State Grid, the rated current and capacity of ±1 000 kV UHVDC transmission will be 4 500~5 000 A and 9.5~10 GW respectively. Reliability is of great importance to stability of the power grid, which requires deep and detailed study of system adaptability and countermeasures [3].

The ±1 000 kV UHVDC transmission project is featured by the highest voltage, largest capacity and longest distance, and is a new height of power transmission technology. The engineering design and equipment development are of great challenges. Furthermore, no existing experience in the world can be used for reference. According to the experience of ±800 kV UHVDC construction, the requirements of high-voltage equipment, such as ±1 000 kV converter transformer and bushing, will certainly reach the utmost limitation of the electrical equipment and material capability. To reduce the difficulties of equipment development, it is necessary to optimize the overall technology solution considering various requirements. Moreover, key technical difficulties can be solved by prototype development. On the other hand, the electromagnetic environment and external insulation have a big impact on the cost of the project. It is important to utilize open thinking and innovative design to lower the cost.

1 SYSTEM ADAPTABILITY OF THE ±1 000 kV UHVDC TRANSMISSION PROJECT

1.1 The Hydro-power Sending End

Because of the huge capacity of the ±1 000 kV UHVDC transmission, the fault will cause vast power shifting and power shortage in receiving system. It is necessary to study the reliability of the UHVDC transmission and its impact on the stability of the sending-end power grid with the hydro-power and thermal-power generation units, and the stability of the receiving-end power grid, which will provide the countermeasures for security and stability issues.

The hydro-power delivery is a typical application of the (U)HVDC transmission technology, and most (U)HVDC transmission lines are constructed for it. It has mature and reliable operation experience. For ±1 000 kV UHVDC, the increased capacity is the key point of system study, and will be evaluated under the following scenarios: single/multi converter fault, AC system fault, critical operation (island operation) and the weak connection of sending end with main grid, and so on.

1）Converter failure.

In ±1 000 kV UHVDC, each pole will be composed of two or three converters. That means that the most common fault is single converter blocking, which will result in power shifting. For this condition, a lot of experience has been accumulated during the construction and operation of ±500 kV, ±800 kV HVDC projects. Firstly, the sending-end power grid should place emphasis on the converter failure and strengthen the power grid stability in the planning stage. Secondly, the modulation capability of the remaining part of the UHVDC system can be fully utilized to limit the large scale power shifting, as well as the security/stability control activities. The target is to reduce the frequent generator tripping and water spilling as much as possible when security and stability of sending-end power grid can be guaranteed.

2）Critical operation (Island operation).

When the connection between the sending-end power grid and the main grid breaks off, the island operation will appear. During its establishment, the surplus reactive power may cause the temporary over-voltage. For frequency stability, the coordination between the DC system and generator units is essential under the stable island operation, which requires the employment of frequency control in the DC system. Moreover, the fast linkage control between the DC system and generators is also required when faults occur. Based on flexible control and operation of UHVDC's multi-converter, the redundancy control can be used to mitigate the impact of fault and prevent it from expanding. During the previous UHVDC construction, the study of island operation has been conducted, and a lot of results have been achieved [4]. For ±1 000 kV UHVDC, the DC system control and generator tripping strategy for island forming, stable operation and fault condition should be studied according to the structure of the sending-end power grid and enhanced UHVDC capacity.

3）Sending-end power grid connecting and the coordination control of multi-UHVDC system.

In the planning, the electricity of huge energy resource bases will be delivered by multi-UHVDC transmission lines. The connecting of the sending-end power grid of various UHVDC systems is favorable to the stability of power grid due to the mutual power support. When the one UHVDC trips, the potential capability of fast modulation and overload can be exploited to absorb the shifted power within the limitation of tie-lines between sending-end power grids. This is coordination control of multi-UHVDC system. It can balance the power over a larger range and enhance the power grid stability. Along with the quick development of UHVDC project, the practical study of coordination control needs to be performed based on the theory results.

For the weak connection between the sending-end power grid and the main grid, great attention should be paid to the stability of tie-lines, for which modulation capability of the UHVDC can be considered.

1.2 The Thermal-power Sending End

For the thermal-power generation unit, the tripping and recovery is much more costly and time consuming. So there are more requirements for the strong sending-end power grid. For the weak connection between the sending-end power grid and the main grid, strain control of the UHVDC system is not a critical issue because of the fast modulation capability when the generator or AC system fails. But the DC system failure is quite serious because of the power shifting and possible consequent failure. So much more careful study is necessary. To avoid the weak sending-end power grid, the reasonable time sequence of construction of the sending-end power grid and UHVDC should be scheduled. Meanwhile, the multi-UHVDC coordination control should be studied to absorb the power shifting if all conditions permit. In addition, because HVDC can not provide damping, the sub-synchronous oscillation (SSO) is likely to happen when the connection between the sending-end power grid and the main grid is weak and most transmission power of the UHVDC system comes from the neighboring steam turbo-generator, which has been proved by experience and academic analysis. Therefore, it should be avoided strictly [3].

1.3 Receiving-end Power Grid

Because of the huge capacity of ±1 000 kV UHVDC, it must feed into strong receiving-end power grid. That means, the developments of ±1 000 kV UHVDC must be in line with the scale and the time sequence of the AC grid. For the parallel connection of AC and DC, the AC power grid must be strong enough to absorb certain shifted power to reduce the generator tripping and the load loss in the receiving-end power grid. For the multi-infeed UHVDC system, it is expected that the coupling of various (U)HVDC is not strong, and the reactive power should be configured reasonably to avoid the cascading failure in the planning stage. On the other hand, the fast modulation of (U)HVDC should be fully utilized to provide the effective measures for the security and stability control of the receiving-end power grid. Furthermore, the mechanism of the AC-DC hybrid large power grid needs to be studied deeply and turned into practical security and stability control measures and fault recovery strategy. In addition, it should be noted that the UHVDC feeding into strong 1 000 kV UHVAC power grid directly is hard to be realized in short term because the development of converter transformer is too difficult even though it is good for the system stability.

1.4 Reliability

Because each pole of ±1 000 kV UHVDC will adopt 2 or 3 series connected 12-plus converters, the single pole and double pole blocking caused by equipment failure will be equal to or lower than those of ±800 kV UHVDC. Consequently, the forced energy unavailability will be reduced also. According to the experience of the HVDC project under operation, the equipment failure, especially the control and protection failure, is main constrain of reliability improvements [5]. For ±1 000 kV UHVDC, not only the reliability of single equipment should be improved, but also the impact of single equipment failure on the whole UHVDC system should also be mitigated, which need to be reflected in the control and protection system.

2 TECHNICAL FEASIBILITY OF THE ±1 000 kV UHVDC TRANSMISSION PROJECT

2.1 Transmission Line

2.1.1 Electromagnetic Environment

Among the limitation of the transmission line, the composed electric field strength and the ion current density affect the height of the DC line. The audible noise and radio interference affect the bund type of the line [6]. The pilot study shows that several types line can satisfy the electromagnetic environment requirements, including 6×1 120 mm^2, 8×800 mm^2, 8×900 mm^2 and 8×1 000 mm^2. However, due to the length of ±1 000 kV UHVDC transmission line, the total investment is very large. Besides electromagnetic environment, the requirements of tower load and insulation need to be considered to optimize the transmission line design to reduce the cost. Based on preliminary studies, bund of 6 sub-conductors seems still suitable for installation of ±1 000 kV lines.

2.1.2 Air Gap of the Transmission Line in High-altitude Areas

As for the southwest (Yunnan and Sichuan) and Tibet hydro-power delivery, transmission lines will pass through high-altitude areas. After the high altitude amendment, length of the line insulator string, controlled by the switching over-voltage, and the air gap may be enlarged greatly, which means a significant increase of the transmission line cost. The new technology application, such as line surge arrester, should be studied to decrease the switching over-voltage. Employing the advanced experiment condition [6], the insulation and the cost of the line can be further optimized.

2.2 Converter Station

2.2.1 Main Circuit

Each pole of ±1 000 kV UHVDC may adopt 2 or 3 series connected converters. The potential allocation of the voltage includes 500 kV+500 kV, 333 kV+333 kV+333 kV and 400 kV+400 kV+200 kV, and so on. For the 2 converters scheme, two high-end converter transformers in parallel is also a possible topology. There are many factors that affect the main circuit. Among them, the development and the transportation of high-end converter transformer has the utmost impact [5]. The main circuit design has to consider the difficulty of converter transformer development, and the size of the converter transformer is decided by transportation condition, the site location, etc. More converters mean more apparatus, large footprint and complex control and protection, which result in high cost. But the size of the equipments is reduced, and the operating flexibility is improved. Furthermore, the reliability and energy availability is improved under the same single converter failure rate, as well as the DC system failure’s impact on AC system. For fewer converters, the result is opposite. Meanwhile, the number of converters and the voltage allocation has a big impact on the over-voltage level and insulation level of equipments, which decide the difficulties of the equipment development to a large extent.

2.2.2 Over-voltage Protection of the Converter Station

In ±800 kV XJB-Shanghai UHVDC converter station, the configuration of surge arrester reduces the over-voltage level effectively. For ±1 000 kV UHVDC, the over-voltage level of high-end equipments, including converter transformer, valve, smoothing reactor, and so on, is the key issues. Based on the topology of main circuit, the surge arrester configuration of key position, such as the top of the valve, the valve side of converter transformer and smoothing reactor, must be researched in detail [7], which will benefit the developments of the equipments.

2.2.3 The Equipment Development

1）±1 000 kV high-end converter transformer.

The oil-paper insulation system in the converter transformer has to withstand the stable AC and DC combined electric field and temporary electric field under polarity reversal condition and during impulse strikes. Various factors, including temperature, micro water and ageing of the materials, will affect the resistance of materials as well as the distribution of DC electric filed. The insulation design is very difficult, especially the key components, such as valve side lead system and bushing, etc. Meanwhile, the size of the converter transformer is limited by the transportation condition, which brings more difficulties. Besides the difficulty reduction from main circuit design, the basic research of the converter transformer's insulation mechanism should be launched. The prototype development is also necessary considering the key technical difficulties.

2）Valve.

Due to the mature voltage distribution technique of thyristor levels, the valve's DC voltage withstanding capability can be improved by adding more series connected thyristor levels. But the enhanced DC voltage will affect the selection of air gap in the high-end valve hall and the shielding method of the valve tower, which are decisive factors of the footprint of the valve hall. According to the arrangement of valve hall, the theoretical study and withstanding voltage test of various air gaps under different altitude need to be preformed to provide the data for valve hall design.

3）Wall Bushing.

Dry type capacitor core plus composite insulation jacket (filling gas) is a proven solution for internal and external insulation. For ±1 000 kV DC wall bushing, the core has two types-whole wrapping and jointing of two short parts. The former one requires high level manufacture technique and facilities. The latter one needs high level design, especially the design of jointing place of flange. The enlarged size of composite insulation jacket only can be done by stronger processing equipment. Meanwhile, the weigh of ±1 000 kV DC wall bushing is heavier and demands stronger mechanical strength. Due to the difficulties of development, a prototype is necessary to find and solve all the technical problems.

4）DC yard equipment including bypass breaker and disconnecting switch.

The external insulation of the equipment is solved by the support DC insulator. The rise of the height requires more mechanic strength and stability. The insulation and mechanic performance of driving parts should be noted. But no insurmountable technical obstacles exist.

5）The DC support insulator.

Due to the voltage enhancement, the height of insulator is further improved, which makes the structure stability more difficult to achieve. There are two ways to decrease the height by creep distance reduction [5]. The first one is to decrease the dirty level. The second one is to adopt the composite insulator or the compositing porcelain insulator. Because of the accumulated abundant experience of external insulation and first class test conditions in China, the ±1 000 kV DC insulator is not a critical issue. However, the cost should be considered.

6）DC voltage divider.

It is composed of series connected modules which are resistors and capacitors in parallel, and is always put in the composite insulator. The voltage measurements capability can be improved by increasing the modules [8].

2.2.4 The Layout of Converter Station

Because of the big footprint and investment of converter station, the design optimization of the whole layout is one of essentials in engineering design, which is decided by the main circuit, site condition, the direction of AC lines and the type of distribution equipment, etc. Among them, the layout of converter transformer and valve hall is most important and will determine the structure of the converter station. The final target of the layout optimization is to reduce the footprint. The other requirements, such as the security of equipment, the noise, the maintenance, and so on, are the limitation factors. The layout of the DC yard needs to consider the external insulation, and the AC yard design should coordinate with the DC yard. The noise issue is the emphasis of AC and DC filter layout. At the same time, the shield measures of the site should be studied to satisfy the stricter and stricter noise reduction requirement. In general, the layout of converter is the key point for 3 converters topology. If the parallel high-end converter transformer is employed, the lead layout in high-end valve is the key point.

3 ECONOMIC ADVANTAGES OF THE ±1 000 kV UHVDC TRANSMISSION SCHEME

3.1 The Investment Analysis of the Transmission Line

The extra low loss and extra huge capacity of ±1 000 kV UHVDC provide the economic and reliable solution for the long distance power delivery of huge energy resource bases [2]. The preliminary study shows that the economic advantage of ±1 000 kV UHVDC is obvious when the transmission distance exceeds 2 500 km [2].

According to the annual cost approach, the influencing factors of investment include line, tower, construction and the cost of transmission loss. Compared with the ±800 kV UHVDC transmission line, the economy of the ±1 000 kV UHVDC transmission line is better due to the loss reduction for long distance power delivery. However, the enhancement of the DC voltage influences the electromagnetic environment, the air gap of the tower, the type and length of insulation string. Among them, the electromagnetic environment further influences the type of the line and the air gap of the tower. So many factors may result in the large increase of the transmission line investment. Therefore, the optimization and innovation is crucial to reduce the transmission line investment.

3.2 The Investment Analysis of the Converter Station

Preliminary study shows that the investment per kW of ±1 000 kV UHVDC converter station is almost the same with that of ±800 kV UHVDC. Among them, the investment of high-end converter transformer, wall bushing and support insulator increases. The air gap decided by insulation and electromagnetic environment is also improved, which results in the increasing of footprint. The accurate investment should be analyzed based on the practical technology solution.

3.3 Comparison With Other Technologies

According to the annual cost approach, the economic distance of the ±800 kV and ±1 000 kV UHVDC transmission are shown in Fig. 1 [2].

From Fig. 1, it can be seen that the annual cost of ±1 000 kV UHVDC transmission will be lower than that of ±800 kV UHVDC transmission when the distance exceeds 2 500 km, and the advantage is more obvious for longer distance. The result of Fig. 1 is the comparison based on academic calculation of a single project. For the large-scale power delivery, the comparison between UHVDC groups is also necessary.

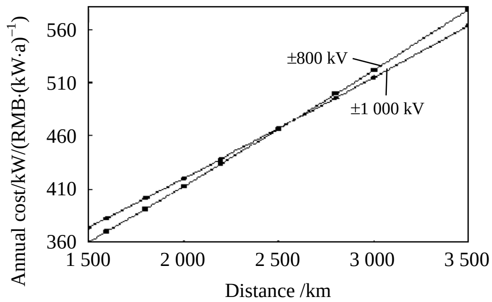

图 1 ±800 kV 与±1 000 kV 的年费用等价输电距离比较

Fig. 1 Economic distance of ±800 kV and ±1 000 kV UHVDC transmission based on annual cost approach

4 CONCLUSIONS AND PROSPECT

In general, ±1 000 kV UHVDC technology can realize the optimization of energy allocation over a very large area with excellent economy, less footprint and environment impact. State Grid has launched a lot of research projects based on Jinshajiang power delivery project, and achieved preliminary results. Now, State Grid plans to establish ±1 000 kV UHVDC workgroup and start the further research in three aspects.

1）To study and work out the overall technology solution of the ±1 000 kV UHVDC transmission system.

Considering the requirement of reliability, economy and environment, the study includes the main circuit type, main circuit parameter, reactive power configuration, the coordination of over-voltage and insulation, heavy goods transportation, and so on. The results will provide the parameters for equipment development. During the study, the iteration between the overall technical solution and equipment development will be made, and repeated optimization and adjustment of the technical plan will be conducted until the most optimal and feasible technical solution is achieved.

2）Key equipment development.

Based on parameters defined by the overall technical solution, the key equipments will be developed, including ±1 000 kV UHVDC high-end converter transformer, wall bushing and DC yard equipments, and so on. The insulation characteristics of the high-end valve also need to be studied to provide the data for valve hall design.

3）Key technology study.

The key technologies include the following: the technology and economy analysis of the transmission line, corona discharge of converter station equipments and transmission lines, electromagnetic environment, discharge characteristics of the air gap and high altitude correction, characteristics of external insulation under filthy pollution, lighting protection and the parallel AC lines influence on DC line system, etc. The key technology study is the foundation of engineering design, which can reduce the investment by optimization.

Finally, the conceptual design of ±1 000 kV UHVDC will be achieved based on the above results, which will solve the technical obstacles, define the technical principles and make the technical preparation for construction of projects.

REFERENCES

[1] 刘振亚．特高压电网[M]．北京：中国经济出版社，2005：28-33．

[2] 刘振亚，舒印彪、张文亮，等．直流输电系统电压等级序列研究[J]．中国电机工程学报，2008，28(10)：1-8．
Liu Zhenya，Shu Yinbiao，Zhang Wenliang，et al．Study on voltage class series for HVDC transmission system[J]．Proceedings of the CSEE，2008，28(10)：1-8(in Chinese)．

[3] 张文亮，周孝信，郭剑波，等．±1 000 kV特高压直流在我国电网应用的可行性研究[J]．中国电机工程学报，2007，27(28)：1-7．
Zhang Wenliang，Zhou Xiaoxin，Guo Jianbo，et al．Feasibility of ±1 000 kV ultra HVDC in the power grid of China[J]．Proceedings of the CSEE，2007，27(28)：1-7(in Chinese)．

[4] 刘振亚．特高压直流输电技术成果专辑(2006 版)[M]．北京：中国电力出版社，2006：484-491．

[5] 舒印彪，刘泽洪，高理迎，等．±800 kV 6400 MW特高压直流输电工程设计[J]．电网技术，2006，30(1)：1-8．
Shu Yinbiao，Liu Zehong，Gao Liying，et al．A preliminary exploration for design of ±800 kV UHVDC project with transmission capacity of 6 400 MW[J]．Power System Technology，2006，30(1)：1-8(in Chinese)．

[6] 张文亮，于永清，李光范，等．特高压直流技术研究[J]．中国电机工程学报，2007，27(22)：1-7．
Zhang Wenliang，Yu Yongqing，Li Guangfan，et al. Researches on UHVDC technology[J]．Proceedings of the CSEE，2007，27(22)：1-7(in Chinese)．

[7] 刘振亚．特高压直流输电技术成果专辑(2007 版)[M]．北京：中国电力出版社，2007：151-192．

[8] Astrom U，Weimers L，Leseale V，et al．Power transmission with HVDC at voltages above 600 kV[C]．2005 IEEE/PES Power Engineering Society Inaugural Conference and Exposition，Durban，South Africa，2005．

刘泽洪

收稿日期：2009-05-20。

作者简介：

刘泽洪(1961—)，男，教授级高级工程师，从事特高压输电工程的建设管理和研究工作，zehong-liu@sgcc.com.cn；

高理迎(1963—)，男，博士，从事特高压直流输电工程的建设管理和研究工作；

余军(1971—)，男，硕士，高级工程师，长期从事电力系统仿真与直流输电工程的研究工作；

张进(1977—)，男，博士，高级工程师，从事电力系统和直流输电的研究工作。

(实习编辑 李婧妍 实习编辑 张辉)