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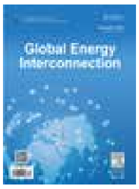

Full-length article

Recent developments in HVDC transmission systems to support renewable energy integration

Zhou Li[1], Ruopei Zhan[1], Yazhou Li[1], Yan He[1], Jinming Hou[2], Xiaoling Zhao[2], Xiao-Ping Zhang[3]

1. Southeast University, Nanjing 210096, P. R. China
2. Global Energy Interconnection Development and Cooperation Organization, Beijing 100031, P. R. China
3. University of Birmingham, Birmingham, B15 2TT, U. K.

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Abstract: The demands for massive renewable energy integration, passive network power supply, and global energy interconnection have all gradually increased, posing new challenges for high voltage direct current (HVDC) power transmission systems, including more complex topology and increased diversity of bipolar HVDC transmission. This study proposes that these two factors have led to new requirements for HVDC control strategies. Moreover, due to the diverse applications of HVDC transmission technology, each station in the system has different requirements. Furthermore, the topology of the AC-DC converter is being continuously developed, revealing a trend towards hybrid converter stations.

Keywords: Direct current transmission system, Topology, Control strategy, AC-DC converter.

1 Introduction

Currently, the demand for both massive renewable energy integration and passive network power supply is steadily rising. In addition, global energy interconnection has become increasingly popular. As an important solution, high voltage direct current (HVDC) transmission systems can provide favorable access to distributed renewable energy and passive networks. It can also easily achieve asynchronous grid interconnection. Hence, the requirements for HVDC transmission systems are increasing, prompting the need for multi-terminal HVDC (MTDC) transmission systems [1-4], whose main task is to design corresponding control strategies for power distribution according to the requirements of each terminal. Thus, in recent years, an increasing number of studies have researched the control strategies of these systems, such as master-slave control, DC voltage droop control, etc. [5, 6]. However, due to the topological complexity of HVDC transmission systems and the different requirements for AC systems at each terminal, the control strategies are more complex and diverse [7-9]; therefore, further research is required. The line requirements of the HVDC transmission system are likewise experiencing ongoing development. Because of this, the transmission power of each line is required to have independent controllability. Each DC line of

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✉ Zhou Li
lizhou@seu.edu.cn

Ruopei Zhan
zrp_seu@126.com

Yazhou Li
liyazhou93@126.com

Yan He
heyan2603630@126.com

Jinming Hou
jinming-hou@geidco.org

Xiaoling Zhao
xiaoling-zhao@geidco.org

Xiao-Ping Zhang
X.P.Zhang@bham.ac.uk

a true bipolar DC transmission system can operate independently, as opposed to the conventional pseudo bipolar DC transmission system. In addition, the AC-DC converter has a more flexible control strategy. Due to the applications of bipolar and monopolar DC transmission systems, it is necessary to consider hybrid DC transmission systems in future development directions [10].

Currently, the two basic technologies employed in HVDC transmission systems are as follows: HVDC based on voltage sourced converters HVDC (VSC-HVDC) and HDVC based on line commutated converters (LCC-HVDC). Compared with AC transmission technology, LCC-HVDC technology has many advantages, such as lower line costs, fewer losses, no capacitive effects, and no synchronization problems. Also, it exhibits a longer transmission distance, larger transmission capacity, and higher stability. However, the LCC-HVDC converter requires a large number of reactive power compensation devices; when the power flow is reversed, the voltage polarity of LCC must be changed. Thus, it is difficult to construct a MTDC transmission for LCC. In terms of the distinction between LCC-HVDC and VSC-HVDC technologies, the VSC-HVDC equipment occupies a smaller floor area and has a more compact structure because it does not require reactive power compensation. In addition, the LCC-HVDC system is at risk of commutation failure, while no such risk exists for the VSC-HVDC system because of insulated-gate bipolar transistor (IGBT) technology. However, the current VSC-HVDC transmission system also has disadvantages of high costs, large operation losses, and comparatively low capacity. In addition, a substantial gap still exists in VSC-HVDC transmission [11-13]. According to the characteristics of both HVDC transmission technologies, the converters in HVDC transmission networks have developed multiple systems, so the structure of the converter station should be designed according to the specific situation.

This study therefore proposes topology for a future MTDC grid (Fig. 1) and analyzes the recent control strategy trends of HVDC transmission systems. This paper is divided into six sections: section 2 illustrates the topological diversification of bipolar HVDC transmission systems; section 3 presents the complex topology and control strategies of the developed MTDC transmission system; section 4 discusses the diverse applications of the HVDC transmission system; section 5 describes AC-DC converter diversification in the HVDC transmission system, and section 6 presents the conclusions.

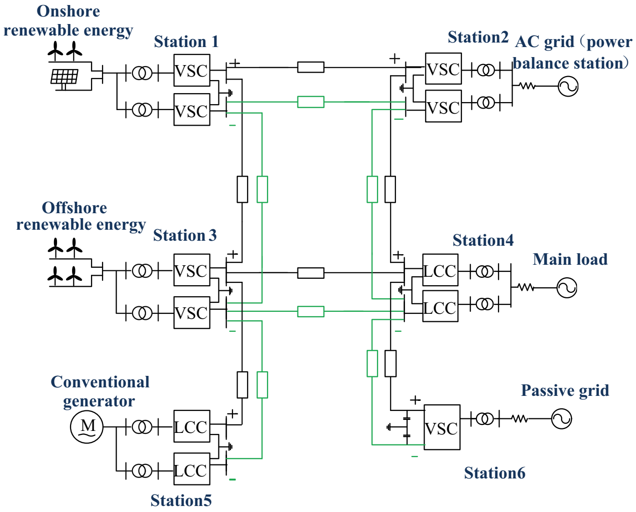

Fig. 1 Schematic of MTDC topology

2 Topological diversification of bipolar MTDC transmission systems

2.1 Pseudo bipolar HVDC transmission system

Both VSC and LCC can be adopted in the construction of bipolar HVDC transmission systems, whereas bipolar MTDC systems are typically based on the development of bipolar VSC-HVDC technology. Thus, we predominantly discuss bipolar VSC-HVDC transmission systems. The two most common connection modes are pseudo bipolar connections and true bipolar connections. Specifically, the HVDC cables of a pseudo bipolar HVDC transmission system are connected to a converter. Especially, the traditional 2-level or 3-level VSC is grounded through a capacitor as shown in Fig.2, while the MMC VSC does not have to be grounded through a capacitor. In the pseudo bipolar HVDC transmission system, and the earth point is set between the positive and negative lines of the converter, with no direct current flowing through the ground point but returning through the negative cable (Fig. 2). When one of the DC cables fails, the two cables cannot operate normally [14, 15].

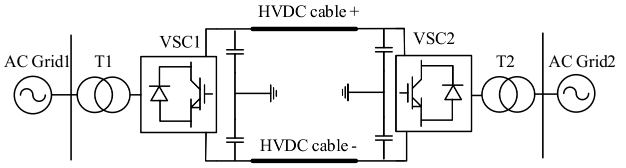

Fig. 2 Pseudo bipolar VSC-HVDC transmission

2.2 True bipolar HVDC transmission system

In the true bipolar HVDC transmission system, each direct current DC cable is connected to an independent converter. As shown in Fig. 3, the earth point of the true bipolar HVDC system is set at a single point in each station. In contrast to the pseudo bipolar VSC-HVDC, it exhibits independent control for the positive and negative poles and has the following features [16-19]:

(1) Independent operation of the positive-pole and negative-pole networks. This structure enables the system to operate under both a symmetric true bipolar mode and an asymmetric mode where the current flowing through the positive pole network is not equal to that through the negative pole network. Furthermore, as the system can operate in asymmetric mode, the positive and negative pole networks can be controlled separately, enabling an active power shifting strategy.

(2) Higher reliability of power supply. The true bipolar VSC-MTDC has two independent converters at its DC terminal for the positive-pole and negative-pole networks. When a fault occurs or regular maintenance is processed on the DC side of a single pole, only the default pole is affected, while the other pole can continue to operate normally. These features enhance HVDC system reliability.

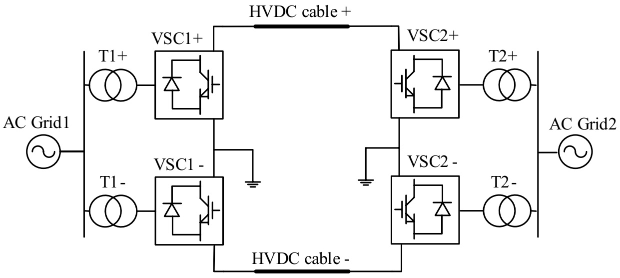

Fig. 3 True bipolar VSC-HVDC transmission system

When the pseudo and true bipolar HVDC transmission systems are combined, a hybrid bipolar HVDC system topology emerges, as illustrated in Fig. 4 [20]. However, for large-scale renewable power integration via MTDC transmission systems, more research is required on the control strategy and topology of the bipolar MTDC transmission system.

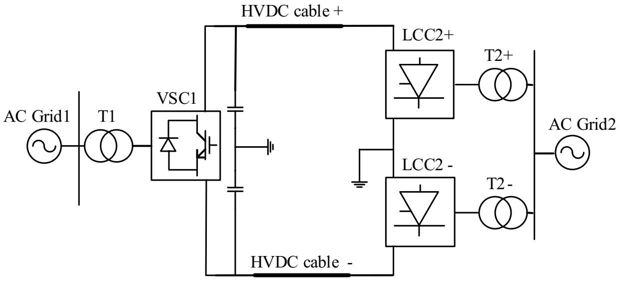

Fig. 4 Hybrid bipolar HVDC transmission system

3 Complicated topologies and coordinated control strategies in HVDC transmission systems

3.1 Development of MTDC transmission systems

Currently, most DC systems are point-to-point terminal DC transmission systems. These systems are used to transport the energy produced by wind farms or traditional thermal power plants to the major AC network [21]. In recent years, a few multi-terminal DC transmission systems have begun operating. By adopting the coordinated control strategy, the HVDC system integrates the requirements of each terminal, maintaining voltage stability, ensuring accurate distribution of power flow, and ultimately achieving flexible and controllable power transmission for the MTDC system. However, with the greater number of terminals and diversification of interconnected AC systems, the system-level control strategy of the DC systems has also become more complicated.

3.2 Topologies of the MTDC transmission system

(1) Radial-network MTDC system

In terms of the MTDC transmission system, there are mainly three kinds of topology: radial-network HVDC system, circular-network HVDC systems, and meshed HVDC systems [22].

The radial-network MTDC transmission system uses the power balance station as the radiation center to stabilize the voltage. This center controls the power to each radiation branch. Fig. 5 demonstrates a radial-network four-terminal HVDC transmission system; if the voltage of the central station in this system is stable, the voltage change of an individual DC wire only affects the DC voltage of the station at the end of the wire, with all others remaining stable. This control strategy is simple, but the power of the entire system cannot be transmitted when the central station fails.

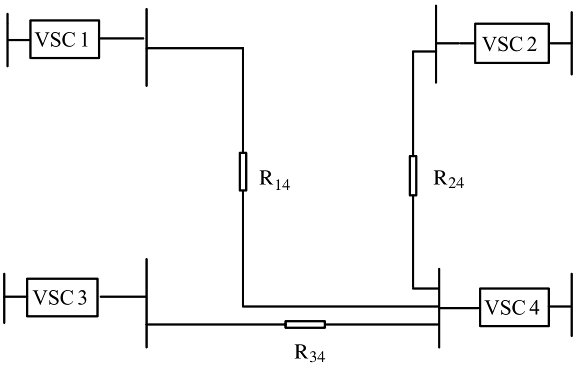

Fig. 5 Topology of a radial-network MTDC system

(2) Circular-network MTDC system

The circular-network MTDC transmission system connects the stations in a ring shape (e.g. Fig. 6). In this system, if the DC power of a converter station is adjusted at one terminal, it will inevitably affect the DC voltage of other stations in the system, thus affecting the power transmission of other stations. It is difficult to independently modify the DC voltage and power of a single station. Therefore, although the power system of the circular-network MTDC transmission system has strong stability, voltage control is complex [23].

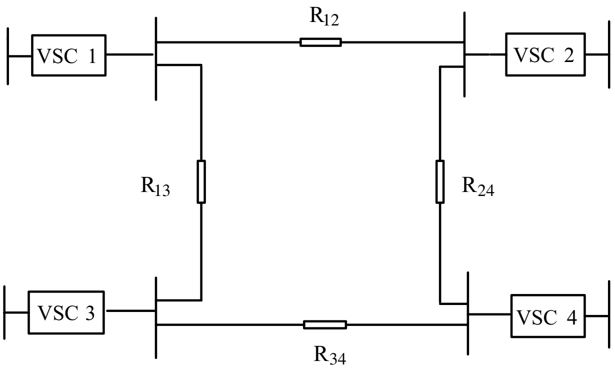

Fig. 6 Topology of a circular-network four-terminal MTDC system

(3) Meshed MTDC system

In a meshed MTDC transmission system (e.g. Fig. 7), both a circular-network structure and other branches act to improve the transmission power capability and stability of the DC system. At present, there has been minimal research on meshed MTDC systems and no corresponding practical engineering. However, with increasing demand for grid-connected equipment, the construction of meshed MTDC transmission systems will become a necessity in the future [24].

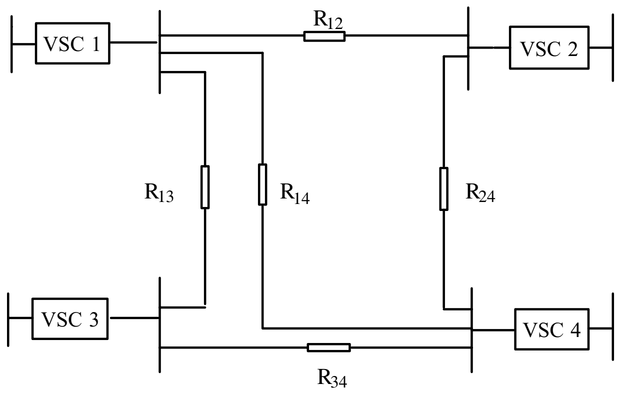

Fig. 7 Topology of a meshed four terminal MTDC system

3.3 Coordinated control strategies in MTDC transmission systems

(1) Conventional coordinated control strategies

Traditional multi-terminal DC system-level control strategies predominantly include master-slave control, DC voltage margin control, and DC voltage droop control. In master-slave control, the master station maintains the DC voltage, while the slave station sets the DC power; thus, the master station undertakes the task of power balance. In addition, the DC voltage margin control adds the concept of margin to the master-slave control. When the DC voltage of the master station exceeds the limit or exits the operation and the DC voltage of the slave station exceeds the voltage margin, the master and slave station perform the conversion of control tasks together to maintain stability of the DC voltage [5].

In systems that either adopt master-slave control or

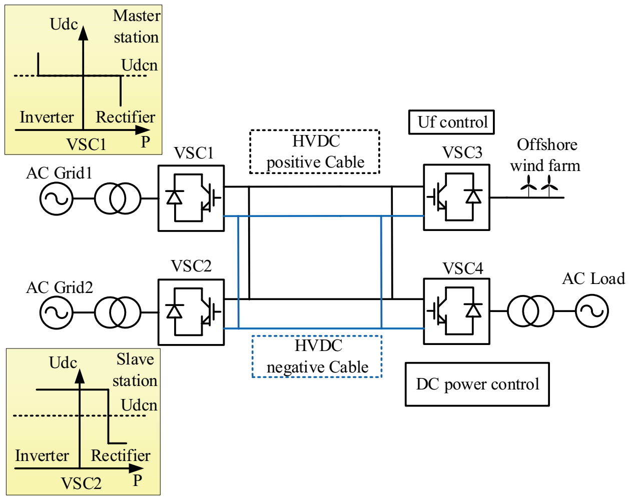

Fig. 8 Master-slave control strategy

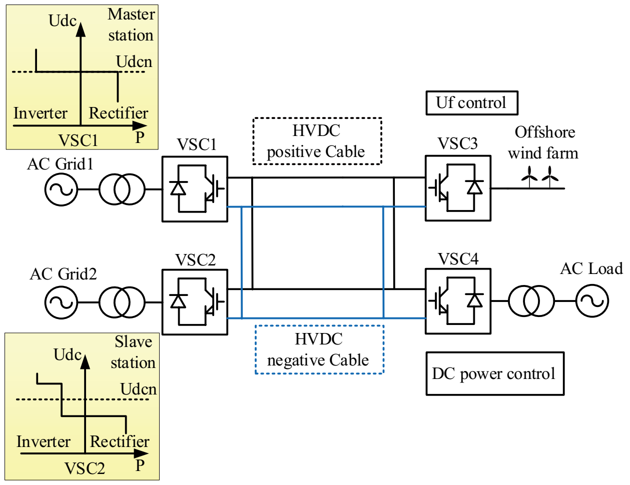

Fig. 9 DC voltage margin control strategy

the DC voltage margin control strategy, there is only one individual station in the power circulation at any time. This leads to the problem of insufficient dynamic adjustment capability for the DC system transmission power. As a result, power fluctuations of the DC system is likely to cause significant voltage fluctuations. Hence, DC voltage has poor dynamic stability.

Moreover, the DC voltage droop control strategy utilizes the linear relationship between DC voltage and active power. Specifically, multiple stations can assume the functions of power balance and voltage stability, which also helps achieve good voltage dynamic characteristics. However, the DC voltage droop control essentially compromises power transmission accuracy in exchange for DC voltage dynamic control stability. Therefore, it has a problem of lower transmission power accuracy under steady state conditions [6, 25].

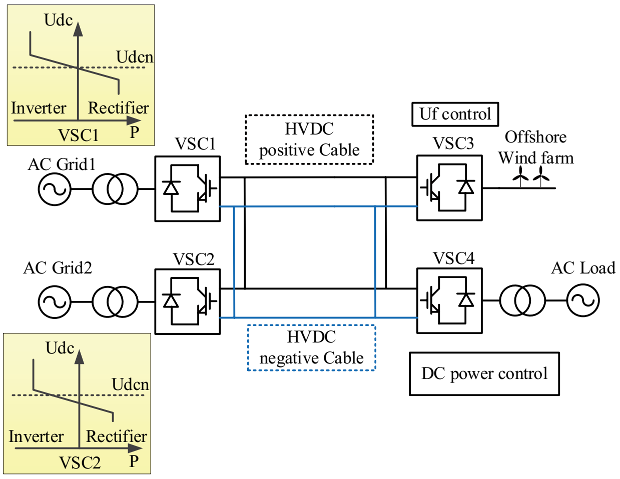

Fig. 10 DC voltage droop control strategy

In general, the control stability of the VSC-MTDC, especially DC voltage stability, will face new challenges due to the increasing demand for renewable energy integration and more complex topology [26, 27]. Meanwhile, a number of deficiencies in mainstream coordinative control strategies have drawn concern. Master-slave control maintains the accuracy of power control but exhibits poor dynamic stability of the DC voltage. On the contrary, the DC voltage droop control strategy compromises the accuracy of transmitted power to achieve good dynamic stability of the DC voltage. As traditional control strategies cannot adapt to complex MTDC network requirements, a novel coordinated control strategy is a major issue for future research.

(2) Novel coordinated control strategies

Presently, studies concerning the control strategies of multi-terminal HVDC transmission systems mainly focus on the VSC-HVDC transmission system, and most commonly on the DC voltage droop control strategy. A previous study [28] proposed a generalized voltage droop control strategy. This station level control strategy can be switched in three ways: active power control, DC voltage control, and DC voltage droop control, which can improve power distribution capabilities and increase flexibility. In [29], a new coordination control strategy for VSC-MTDC was proposed: a master-auxiliary control strategy that combines the advantages of the DC voltage margin and DC voltage droop control strategy. This strategy helps achieve a stable DC voltage through the control parameters of each station. It can also ensure power distribution capabilities while suppressing high power fluctuations. In [30], a strategy is proposed that adjusts the voltage droop characteristics of each terminal by an optimal power flow calculation in order to achieve the ideal active power allocation in the MTDC system. However, a major limitation of this strategy is that the power flow calculation cannot be applied when the MTDC system becomes complicated. In contrast, Reference [31] suggested using a DC chopper for power flow control in a flexible DC transmission network and proposed an improved voltage droop control strategy; however, this strategy leads to increased costs.

Another study [32] proposed a novel DC voltage control strategy, based on the assumption that each VSC station should be given a specific DC voltage in a complex DC network rather than having a system with only one station responsible for the power balance. A DC power flow calculation (optimal power flow theory) determines the VSC DC voltage, which ensures N-1 safety. In [33], a time-optimal control strategy was proposed based on Lyapunov Theory to improve the power distribution speed in the MTDC system; it can immediately adjust the power and improve the transient stability when a fault occurs.

4 Diverse applications of HVDC technology

4.1 Renewable energy integration and passive grid power supply

It is estimated that, by 2030, Chinese wind and solar power facilities will undergo large-scale development. Large-scale centralized development and long-distance transmission have become the dominant modes of renewable energy use; however, compared to hydropower and coal-fired power generation, wind and solar power are characterized by intermittentness, volatility, randomness, and non-storability, resulting in clear off-peak generation. Thus, it is predicted that large-scale access will result in significant challenges to the national grid [34, 35].

VSC-HVDC transmission technology provides a solution for renewable energy integration and passive network power supply, combining the advantages of active and reactive independent control, no reactive power compensation, and no risk of commutation failure. In terms of passive networks, the VSC-HVDC system can be employed directly for power supply. Moreover, LCC stations can be used as a centralized power transmission terminal and VSC stations can be used at the passive network terminal in a multi-terminal hybrid HVDC system [36, 37]. As for renewable energy integration, the cost of integration using VSC-HVDC is lower than that using a traditional AC system in long-distance transmission. Renewable energy integration based on VSC-HVDC can improve new energy consumption, reduce dependence on AC systems, and boast a short oscillation time and fast recovery under false conditions [38].

4.2 Regional power interconnection

It is common knowledge that global clean energy resources are unevenly distributed, and wind power and solar power generation are random and intermittent. Thus, to achieve large-scale development and efficient utilization of clean energy, it is necessary to build a clean, energy-centered, globally-configured energy network [1]. Compared with traditional AC transmission, HVDC transmission has many advantages for interconnection of the power grid. Firstly, during long-distance transmission, it reduces the risk of synchronous operation problems that often occur in the AC transmission system, thus increasing the short-circuit capacity in AC transmission. Also, asynchronous operation is beneficial for the respective scheduling and operation of the grid. Secondly, it can reduce the impact of the grids Interconnection in the event of an accident. Thirdly, due to technological advancements, the price of thyristor equipment has reduced and reliability has increased. Consequently, the direct current transmission method is often the preferable choice [39].

At present, research on the interconnection of DC systems in regional power grids is typically limited to the conception stage. One previous study [40] proposed the idea of HVDC transmission between China and Arabia to achieve energy interconnection. Taking Kashgar, a city in western Xinjiang, as the starting point, and using ultra-HVDC (UHVDC) of 800 kV, the line delivers electricity to Sukur, Pakistan, achieving energy interconnection. Another study [41] reported that successful application of HVDC and FACTS technologies in Northern Europe, China, India, and the United States would provide valuable experience and advice for building the super grid. Moreover, Ref. [42] suggested that political risks and the international situation will influence transmission costs and built a quantitative assessment model for power interconnection. It is also advisable that, in order to achieve a future energy Internet, traditional DC, flexible DC technology, and multi-terminal DC technology must be developed in unison [39].

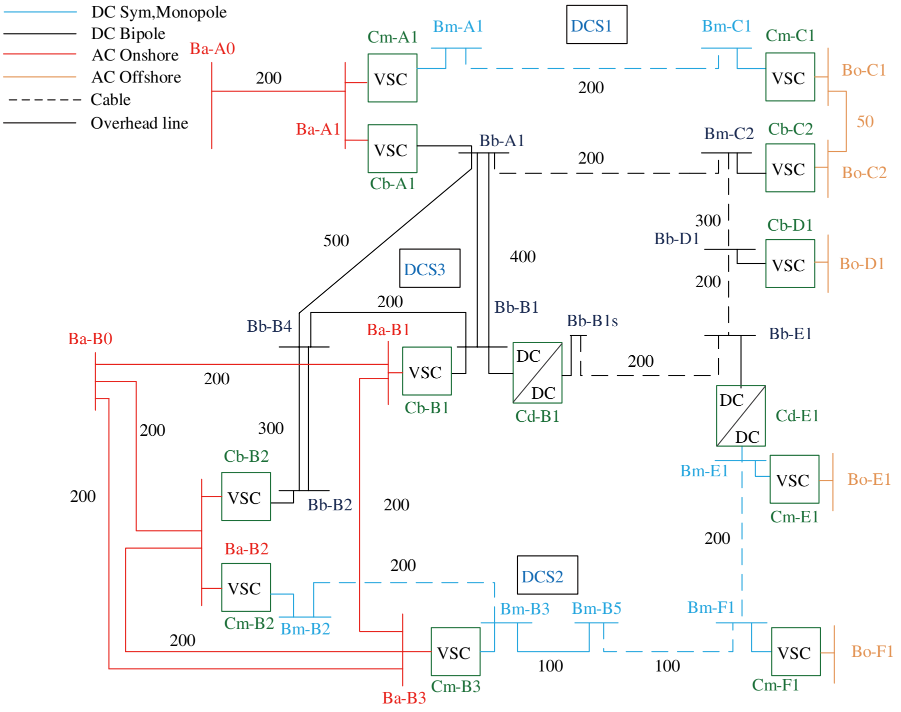

Fig. 11 The CIGRE B4 DC grid test system

Substantial previous research has evaluated the interconnection of DC grids. For example, one study proposed the DC grid test system shown in Fig. 11 [43], where all line lengths are given in kilometers, three lines represents an AC line circuit and two lines represents a DC line circuit. Onshore AC busses are denoted “Ba”, offshore AC busses are “Bo”, monopolar DC busses are “Bm”, bipolar DC busses are “Bb”, monopolar AC-DC converter stations are “Cm”, bipolar AC-DC converter stations are “Cb”, and DC-DC converter stations are “Cd”. This system provides a common reference for research into DC grids.

4.3 DC distribution

The existing global distribution network structure can no longer meet user requirements for energy conservation and environmental protection, power supply reliability, power quality, and quality service. This is due to distributed generation access, changes in household appliance electricity modes, the popularity of electric vehicles, and the increase of controllable load. These requirements will lead to a gradual change in the shape of the traditional distribution network. Employing the DC power distribution network instead of the AC power distribution network brings advantages in terms of controllability, reconfigurability, and transmission capacity. It also has the ability to reduce power loss and operating costs, maintain high reliability, and exhibits no AC stability problems. It can improve user side power quality and reduce line loss and the use of inverters. This provides a pathway for renewable energy to enter the grid and help protect the environment in a more flexible way. Therefore, along with its mature electronic power technology, DC power distribution is predictable [44].

As a MTDC transmission technology in the field of power distribution, DC distribution networks are affected by the development of DC transmission technology. Compared to DC transmission networks, DC distribution networks have more new energy access points and energy storage equipment on the load side. Moreover, there are more converters in a DC distribution network and a certain spatial distance exists between the VSCs. The network parameters cannot be ignored, and DC distribution systems are characterized by stability. The topology of this type of network is predominantly star-connected topology [44].

The current distribution network control strategy is typically designed for DC voltage droop control. A variable slope droop control strategy was proposed that adapts to the low-voltage DC distribution network [46, 47]. This strategy is better than the traditional method due to its dynamic characteristics. The method of segmenting the slope has been applied to engineering, but the tuning complexity is enhanced. Another study [48] proposed an adaptive voltage droop control method for DC distribution networks, which receives the local reference value based on the local voltage and current values of the adjacent converters. This method exhibits improved system dynamics over the traditional method. Meanwhile, the power system stability and the communication requirements between the converters are enhanced. However, it should be noted that current research on DC distribution networks remains in its infancy [45]. The DC distribution network should meet all technical requirements in the power distribution field; therefore, the key technologies of DC distribution such as distribution technology, access conditions, grounding methods, converter stability control, fault identification, and fault isolation should be combined when conducting in-depth research.

Due to the diverse applications of HVDC transmission systems, different converters must be employed in individual systems, which complicates the control strategy. Thus, it is necessary to propose adaptive system control strategies and converter control methods in the future.

5 AC-DC converter development in HVDC transmission systems

5.1 AC-DC converter topology

(1) LCC topology

The LCC uses a thyristor as a switching device. In order to meet the requirements of high voltage, high current, and large capacity, a 12-pulse LCC is typically implemented (Fig. 12). This wiring method minimizes the quantity of equipment at the station and saves costs while maintaining operational reliability [49, 50].

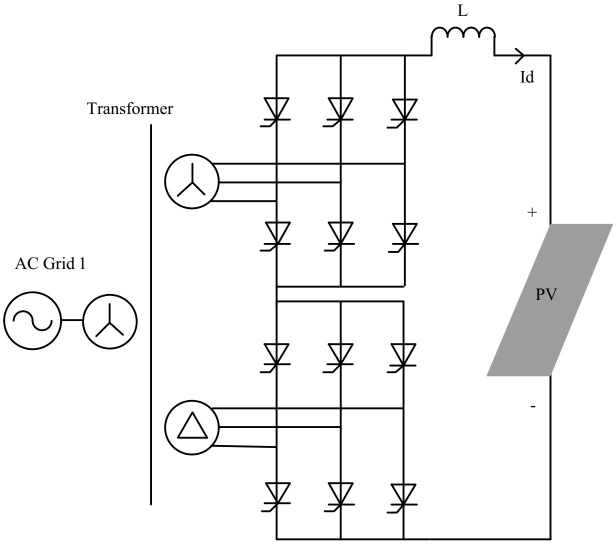

Fig. 12 12-pulse LCC transmission system

Recently, flexible LCCs have used a controllable capacitor to enhance LCC characteristics, resulting in improved harmonic filtering and a significant reduction of the HVDC station footprint. Furthermore, commutation failure can be eliminated with a lower voltage rating and capacitance of the controllable capacitors (compared with traditional LCCs). Fig. 13 illustrates a type of six-pulse flexible LCC topology [51, 52].

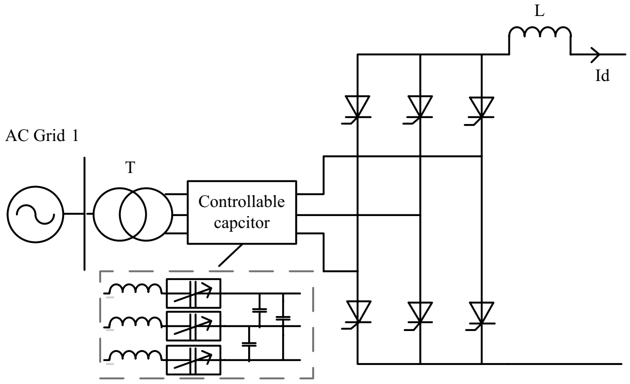

Fig. 13 Topology of a six-pulse flexible LCC

(2)VSC topology

VSC topology predominantly consists of two-level VSC, three-level VSC, and modular multilevel converters. The traditional two- and three-level VSC structure is relatively simple (e.g. Fig. 14). Compared with LCC, conventional VSC has lower voltage levels and limited transmission distances and capacity. The main obstacles to the development of traditional VSC technology include a single IGBT enduring high voltage, difficulty equalizing the voltage of each converter valve in a steady and transient state, high switching frequency, high losses, and high harmonic content of the switching device [53].

Correspondingly, a new generation of VSC technology based on modular multilevel converters has been generated, which solves the specified deficiencies of the traditional VSC system. The hybrid submodule MMC topology is shown in Fig. 15; an example of this is three-phase six-bridge arm construction, which consists of different types of submodules in series. There are four main types of submodule: half bridge submodules (HBSM), full bridge submodules (FBSM), the clamp double SM (CDSM), and the clamp single SM (CSSM) [54, 55] (Fig. 16). In the MMC, uneven voltage caused by the serial press-contact IGBT is mitigated. The requirements for power electronic component consistency are reduced, and the capacity and voltage level of the flexible HVDC transmission system are effectively improved. The switching loss and harmonic content are also reduced due to the modular structure. MMC is therefore very scalable and can achieve redundancy control.

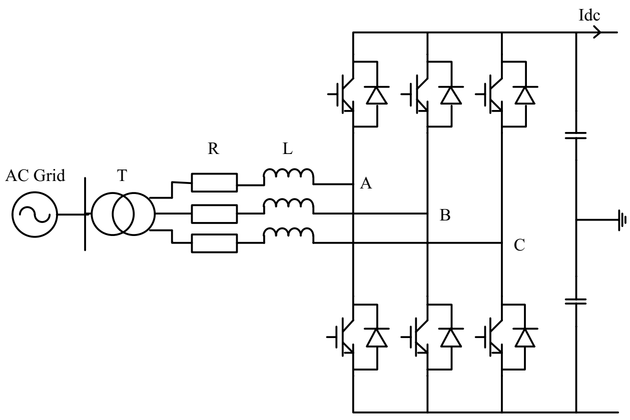

Fig. 14 Topology of a two-level VSC technology

(3) VSC and LCC hybrid converter topology

Hybrid HVDC transmission is undergoing rapid

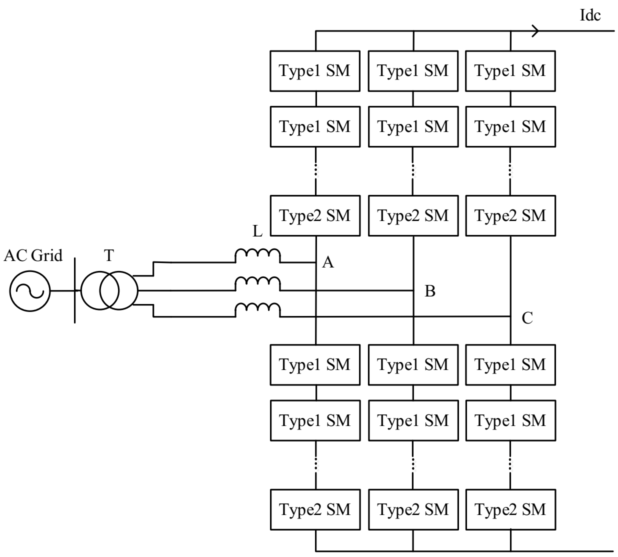

Fig. 15 Topology of a hybrid submodule MMC

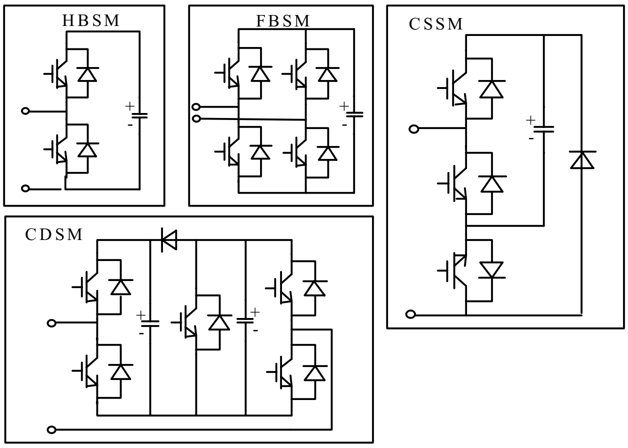

Fig. 16 Topology of four types of submodule

development. Specifically, two projects are in progress in China. One is the Baihetan-Jiangsu ±800 kV hybrid HVDC transmission project in SGCC. The capacity of the converter station is 8000 MW and the transmission distance is approximately 2172 km. The Liangshan converter station in Sichuan adopts LCC technology and the Wuxi converter station in Jiangsu adopts LCC and VSC technology. The other project is the Wudongde-Yunnan ±800 kV hybrid HVDC transmission project, with a transmission capacity of 8000 MW and a total length of 1489 km. The HVDC system of the project contains three terminals. The Kunbei converter station in Yunnan adopts conventional LCC technology, while both the Liubei converter station in Guangxi and the Longmen converter station in Guangdong adopt VSC technology.

A hybrid converter station is composed of three categories: a hybrid multi-terminal station, a hybrid bipolar station, and a hybrid multi-infeed station. Among them, the hybrid multi-terminal station refers to a HVDC system that interconnects the AC system with the LCC and VSC at different terminals. The hybrid multi-terminal HVDC system employs the advantages of both systems: the VSC can efficiently implement branching on the basis of the original line while the LCC is predominantly used for high-power long-distance sending tasks. In addition, the VSC station can serve as a rectifier to distribute power and can provide high-quality electric energy to urban load centers and remote island areas [56, 57]. The hybrid three-terminal HVDC transmission system is shown in Fig. 17 [58].

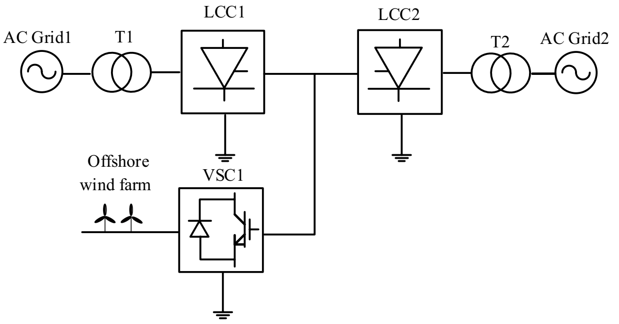

Fig. 17 Hybrid three-terminal HVDC transmission system

The hybrid bipolar HVDC transmission system refers to a system where different poles of the same station use LCC and VSC independently. This type of system uses the VSC-HVDC transmission system's reactive power control capability to reduce dependency on installation of the AC filter at terminals. It can effectively compensate for the reactive power of the AC bus at the receiving terminal, stabilize the AC bus voltage, and reduce the risk of a commutation failure of the LCC. It can also be applied to weak AC systems. The hybrid bipolar DC transmission system is shown in Fig. 18 [59].

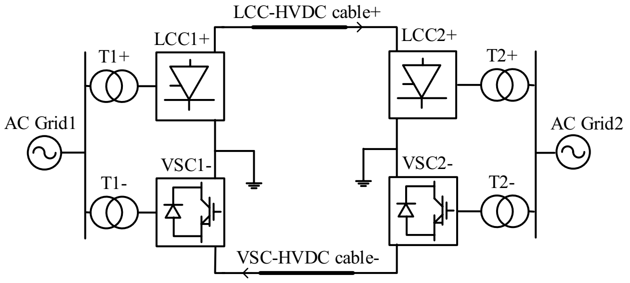

Fig. 18 Hybrid bipolar DC transmission system

In a hybrid multi-infeed DC transmission system, different DC lines are respectively connected by LCC and VSC to the same AC bus. The hybrid DC transmission system uses flexible control of reactive power in the VSC, which can effectively improve the voltage stability of the AC system at the receiving terminal. It can also prevent commutation failures in the other LCCs when the AC bus voltage drops and supply power to the passive network. The hybrid dual-infeed DC transmission system is shown in Fig. 19 [38, 60].

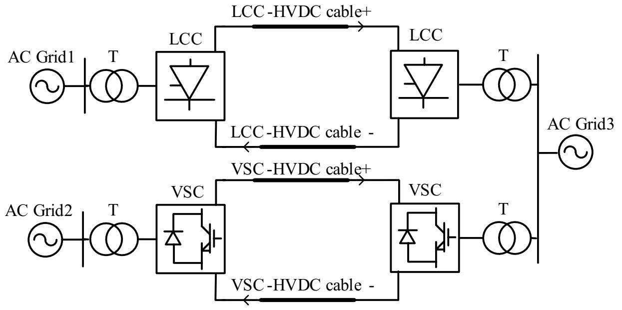

Fig. 19 Hybrid dual-infeed DC transmission system

5.2 Control strategies of AC-DC converters

(1) LCC control strategies

Due to the fact that LCC cannot be reversed in the MTDC system, the control mode of LCC stations can be categorized into two groups: rectification and inverter mode. Rectification mode consists of DC current control and minimum firing angle control whereas inverter mode is composed of DC voltage control, current deviation control, minimum turn-off angle control, and DC current control. It is also notable that low-voltage current limiting control can be applicable in both rectified and inverter modes [61].

(2) VSC control strategies

When the VSC station is interconnected with a strong AC system, independent control of active and reactive power can be achieved mainly through decoupling the dq axis current. Active power can be replaced with its associated physical quantity; e.g., DC voltage or DC current, and reactive power can be measured with its associated physical quantity, which is typically AC voltage. Active and reactive independent control can also limit the current amplitude. When the AC system is in conjunction with VSC, such as renewable energy networks and passive networks, and under weak conditions, VSC acts to stabilize the AC voltage. In these cases, amplitude phase control is adopted, which stabilizes the voltage and phase angle of the AC common coupling point. Thus, the active and reactive power are not controllable [62, 63].

Due to the development of hybrid converters, new controlling strategies combining the advantages of both LCC and VSC control strategies represent a promising future research direction.

6 Conclusions

This study reviews the recent developments in topologies and control strategies for HVDC transmission system and suggests future development trends for the HVDC system. These trends can be summarized as follows:

- With the topological diversification of bipolar HVDC transmission systems, more research is required into their control strategy and topology.
- Due to increasing renewable energy integration and MTDC network topological complexity, traditional control strategies cannot adapt to the more complex MTDC network requirements. Thus, a major research direction will involve proposing novel coordinated control strategies.
- To meet the different demands of HVDC transmission system applications, it is necessary to propose adaptive system control strategies and converter control methods.
- Because of the many different applications of HVDC transmission systems, multiple converters are used in one system to meet the diverse requirements. Therefore, the construction of MTDC transmission systems, which employ different types of converters, is advised. Current hybrid converter technologies cannot meet the demands of future MTDC networks; therefore, further research efforts are vital.

Acknowledgments

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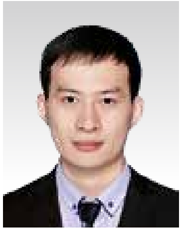
Biographies

Zhou Li received his bachelor and Ph.D. degrees, all in Electrical Engineering, from the School of Electrical Engineering, Southeast University, China, in 2007 and 2014, respectively. He is now a lecturer of the School of Electrical Engineering, Southeast University, China. His research interests include power system operation and control, AC/DC hybrid power transmission, and also renewable energy generation and control.

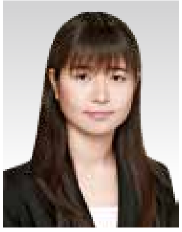
Ruopei Zhan received his bachelor degree in Electrical Engineering from Southeast University, China, in 2018. He is currently pursuing the master degree in Electrical Engineering at Southeast University. His research interest includes the voltage source converter based high direct current.



Yazhou Li received his bachelor degree in Electrical Engineering from Zhengzhou University, China, in 2016. He is currently pursuing the master degree in Electrical Engineering at Southeast University. His research interests include the control and operation of the power system, voltage source converter based high direct current.

Yan He received her bachelor degree in Electrical Engineering from Nanjing University of Science and Technology, China, in 2016. She is currently pursuing the master dgeree in Electrical Engineering at Southeast University. Her research interests include the control and operation of the power system, voltage source converter based high direct current.

Jinming Hou received his bachelor degree at Northeast Electric Power University, China, in 2002. He received his master degree at North China Electric Power University, China, in 2006. He is currently working in Global Energy Interconnection Development and Cooperation Organization in Beijing. His research interest includes power system and automation.



Xiaoling Zhao received her bachelor degree at Wuhan University, China, in 2013. She received her master and Ph. D. degrees at Shanghai Jiao Tong University, China, in 2018. She is working in Global Energy Interconnection Development and Cooperation Organization in Beijing. Her research interests include gas insulation and discharge, power transmission technology.

Xiao-Ping Zhang (M’95, SM’06) is currently a Professor of Electrical Power Systems with the University of Birmingham, U.K., and he is also Director of Smart Grid, Birmingham Energy Institute and the Co-Director of the Birmingham Energy Storage Center. He has co-authored the first and second edition of the monograph Flexible AC Transmission Systems: Modeling and Control, published by Springer in 2006, and 2012. He has co-authored the book “Restructured Electric Power Systems: Analysis of Electricity Markets with Equilibrium Models”, published by IEEE Press/Wiley in 2010.

(Editor Ya Gao)