Review of the Configuration and Transient Stability of Large-scale Renewable Energy Generation through Hybrid DC Transmission

Xinshou Tian, Yongning Chi, Longxue Li, and Hongzhi Liu

***Abstract*—Based on the complementary advantages of Line Commutated Converter (LCC) and Modular Multilevel Converter (MMC) in power grid applications, there are two types of hybrid DC system topologies: one is the parallel connection of LCC converter stations and MMC converter stations, and the other is the series connection of LCC and MMC converter stations within a single station. The hybrid DC transmission system faces broad application prospects and development potential in large-scale clean energy integration across regions and the construction of a new power system dominated by new energy sources in China. This paper first analyzes the system forms and topological characteristics of hybrid DC transmission, introducing the forms and topological characteristics of converter-level hybrid DC transmission systems and system-level hybrid DC transmission systems. Next, it analyzes the operating characteristics of LCC and MMC inverter-level hybrid DC transmission systems, provides insights into the transient stability of hybrid DC transmission systems, and typical fault ride-through control strategies. Finally, it summarizes the networking characteristics of the LCC-MMC series within the converter station hybrid DC transmission system, studies the transient characteristics and fault ride-through control strategies under different fault types for the LCC-MMC series in the receiving-end converter station, and investigates the transient characteristics and fault ride-through control strategies under different fault types for the LCC-MMC series in the sending-end converter station.**

***Index Terms*—Hybrid DC transmission, Transient stability, Configuration, Control system.**

I. INTRODUCTION

UNDER the "dual carbon" strategic goal, the proposal of a new type of power system dominated by renewable sources has greatly promoted the rapid development of China's renewable energy industry. Among them, wind power and photovoltaic power, after more than a decade of development and practice, have achieved large-scale grid-connected applications. By the end of 2023, China's cumulative grid-connected installed capacity of photovoltaic power reached 609.49 million kilowatts, and the installed capacity of wind power reached 441.34 million kilowatts. The two account for 36% of the total installed capacity of China's electricity, rapidly transitioning towards the main energy form, with renewable energy development still mainly focused on centralized development. As over 70% of China's energy consumption is concentrated in the eastern and central regions, connecting these large-scale renewable energy bases and load centers requires high-capacity long-distance transmission, with transmission distances exceeding 1000 km. To accomplish the aforementioned transmission tasks, the use of ultra-high voltage direct current transmission technology is almost the only feasible technical means.

Conventional HVDC transmission technology based on grid commutated inverter (LCC-HVDC) uses thyristors as the commutation elements, featuring advantages of high transmission capacity, technological maturity, low construction costs, and operational losses. It can quickly eliminate DC-side faults by forcing the inverters on both sides into the inverter state through forced commutation. However, it has a strong dependence on the AC system, requiring grid voltage for commutation and consuming a large amount of reactive power [1]-[2], which cannot meet the demand for weak synchronous support for large-scale renewable energy integration and transmission. Voltage source converter-based high-voltage direct current transmission (MMC-HVDC) technology has advantages such as independent operation without relying on the AC grid and providing voltage support to passive networks. It has been applied in offshore wind power island transmission. However, compared to LCC-HVDC with the same capacity and voltage level, MMC-HVDC has disadvantages such as high construction costs, high operational losses, and lack of DC fault ride-through capability [3]-[4], making it unsuitable for the transmission of tens of millions of kilowatts of power from large-scale renewable energy bases.

In order to combine the advantages of LCC-HVDC and MMC-HVDC, scholars from various fields have conducted extensive research on the LCC-MMC hybrid DC transmission

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system in recent years. This technology simultaneously uses both ends or multiple ends of a DC transmission system and, by adopting different hybrid structures, connects LCC and MMC in series and parallel to form a new type of hybrid DC transmission system. In the hybrid cascaded DC transmission system, LCC can not only reduce construction and operating costs but also utilize the forced commutation capability and unidirectional conduction of thyristors to provide DC fault handling capability. MMC can decouple control reactive power to support AC voltage, providing stable AC voltage sources for renewable energy stations on the rectifier side and suppressing commutation failures of LCC on the inverter side. Due to the unique technical advantages of the hybrid DC transmission system, it has tremendous potential to meet the economic and technical requirements for large-scale renewable energy transmission. It has received wide attention from academia and industry, and there have been some engineering applications, such as the "Kunliulong" DC project [5] and the "Baihetan-Jiangsu" DC project [6]. The new hybrid DC transmission technology integrates the advantages of LCC-HVDC and MMC-HVDC, further improving the efficiency and reliability of long-distance high-power transmission, and has become an important development direction in DC transmission [7].

In order to review the current research status of transient stability and control of large-scale renewable energy transmitted through hybrid DC systems, and to summarize the challenges faced and the advantages and disadvantages of crossover control technologies under different types of faults for various hybrid DC topology forms. This paper first analyzes the system configuration and topological characteristics of different hybrid DC transmission. Secondly, it studies the characteristics of the LCC and MMC inverter-level hybrid DC transmission system and its transient stability, which include Operating characteristics and transient stability of hybrid DC transmission system. Thirdly, it investigates the transient stability of the LCC and MMC hybrid DC transmission system within the converter station and provides corresponding fault ride-through control strategies which include hybrid DC transmission system with LCC-MMC series in receiving end converter station or in sending end converter station.

II. System Configuration and Topological Characteristics of Hybrid DC Transmission

LCC-HVDC is characterized by the inability to supply power to passive networks, high reactive compensation requirements, weak reactive power control capability, commutation failures, high voltage and capacity levels, and low losses. MMC-HVDC, on the other hand, features the ability to supply power to passive networks, lower reactive compensation requirements, strong reactive power control capability, no commutation failures, relatively lower voltage and capacity levels, and higher losses. The hybrid DC transmission system can leverage the respective advantages of LCC and MMC, weaken the interaction between AC and DC, ensure safe and stable operation, and construct a coordinated hybrid DC transmission system. The hybrid DC transmission system combines MMC and LCC in different ways to form various transmission topology structures. Depending on the different forms of hybridization between LCC and MMC, the topology structure of the hybrid DC transmission system can be divided into two categories: inverter-level hybrid DC transmission system and system-level hybrid DC transmission system.

Pole-to-pole mixed DC transmission systems [8] can achieve black start and passive operation, maximizing the advantages of both DC transmission systems, and are applied in weak AC systems. The mixed doubly-fed/multi-fed DC transmission system [9], similar to the pole-to-pole mixed DC transmission system, utilizes MMC-HVDC to provide dynamic reactive support for the receiving end AC system, stabilize the voltage of the connected AC bus, and reduce the probability of LCC-HVDC commutation failures. This type of hybrid DC transmission system structure can also achieve black start and passive operation. An end-to-end hybrid DC transmission system can be used for offshore wind power grid connection [10], but the transmission capacity is limited by the MMC equipment level, which can not meet the needs of large-scale renewable energy bases onshore. A layered access-mixed cascaded wind power DC transmission system [11]-[12] fully leverages the technical advantages of conventional DC transmission and flexible DC transmission, ensuring transmission stability while meeting the flexible access of wind power bases and considering economic factors. Multi-terminal hybrid DC transmission systems [13] inherit the advantages of LCC and MMC and have broad development prospects in cases where flow reversal is not required at the LCC station. In conclusion, several typical important LCC and MMC inverter-level hybrid DC transmission system topological structures can be obtained [14], as shown in Fig. 1. Fig. 1(a) shows the topological of hybrid DC transmission with one end MMC and another end LCC. Fig. 1(b) shows the topological of hybrid DC transmission with one pole LCC and another pole MMC. Fig. 1(c) shows the topological of hybrid multi terminal DC transmission, and there can be different structures in multi terminal. Fig. 1(d) shows the topological of hybrid dual (Multi) input DC transmission, where multiple types of DC transmission systems converge simultaneously at one end. The hybrid DC transmission systems, including pole-to-pole mixed DC transmission systems, mixed dual- or multi-fed DC transmission systems, end-to-end hybrid DC transmission systems, layered access-hybrid cascaded wind power DC transmission systems, and multi-terminal hybrid DC transmission systems. These systems utilize hybrid DC transmission technologies to improve transmission stability and meet energy transmission requirements in different environments and contexts, presenting broad prospects for application.

After considering factors such as the ability to self-clear DC line faults, providing support voltage to the sending end AC grid, and not causing significant commutation failure impacts when faults occur in the receiving end AC grid, the

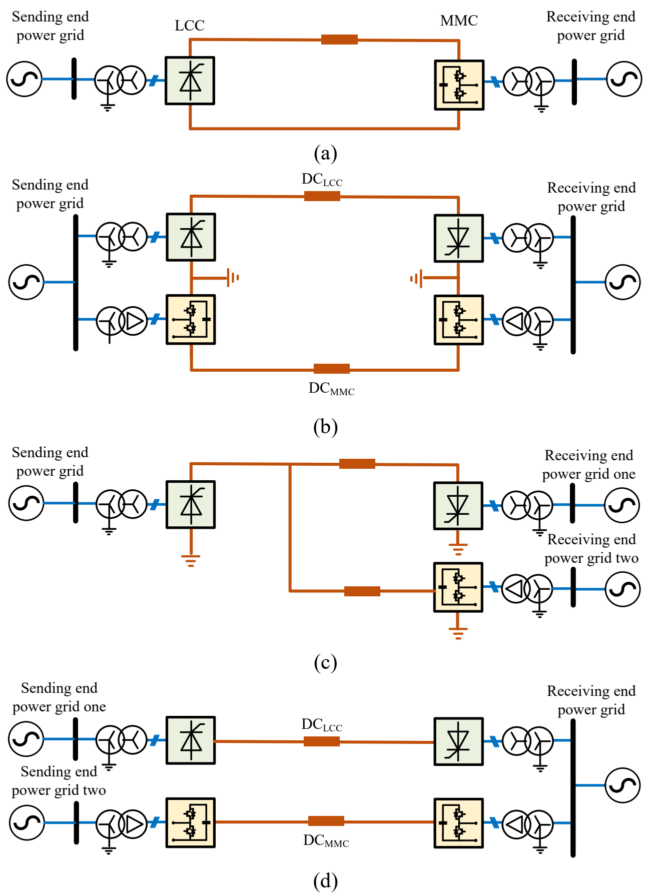

Fig. 1. Typical LCC and MMC inverter-level hybrid DC transmission system topological structures. (a) Hybrid DC transmission with one end MMC and one end LCC. (b) Hybrid DC transmission with one pole LCC and one pole MMC. (c) Hybrid multi terminal DC transmission. (d) Hybrid dual (Multi) input DC transmission.

previously studied LCC-MMC series hybrid DC transmission topology [15] has potential application value. The LCC-MMC series forms the inverter side of the DC transmission system [16], where the series MMC is controlled to enhance the voltage support capability of the AC grid connected to the inverter side, thereby improving the resistance to LCC commutation failures, making it suitable for weak AC systems. A hybrid DC transmission system composed of parallel LCC and MMC is proposed [17]-[18], allowing LCC to be applied in weak AC systems, while the parallel MMC can generate reactive power to enhance the stability of the converter station bus voltage, increase the system's power transmission capacity, and improve system dynamic performance. Additionally, a series-parallel converter hybrid DC transmission system combining the advantages of series and parallel converter hybrid DC transmission systems [19]-[20] is presented.

The basic structure of the LCC-MMC series hybrid DC transmission system is shown in Fig. 2. It can have a series structure of LCC and MMC only at the receiving end, or at the sending end, or both at the sending and receiving ends, but commutation failure issues still exist at the receiving end. MMC typically uses half-bridge submodules to improve cost-effectiveness. Fig. 2(a) shows the topological of hybrid DC transmission with LCC-MMC series only at receiving end. Fig. 2(a) shows the topological of hybrid DC transmission with LCC-MMC series only at sending end. Fig. 2(a) shows the topological of hybrid DC transmission with LCC-MMC series at dual terminal. The LCC-MMC series hybrid DC transmission topology, considering factors such as self-clearing capability of DC line faults, provision of voltage support to the sending-side AC grid, and minimal impact on commutation failures in the receiving-side AC grid during faults. Previous studies have shown that by controlling the series VSC to enhance the voltage support capability of the inverter-side AC grid, the resilience against LCC commutation failures can be improved, making it suitable for weak AC systems. Additionally, the hybrid DC transmission system composed of parallel LCC and VSC enhances power transmission capacity, improves system dynamic performance, and enables LCC application in weak AC systems.

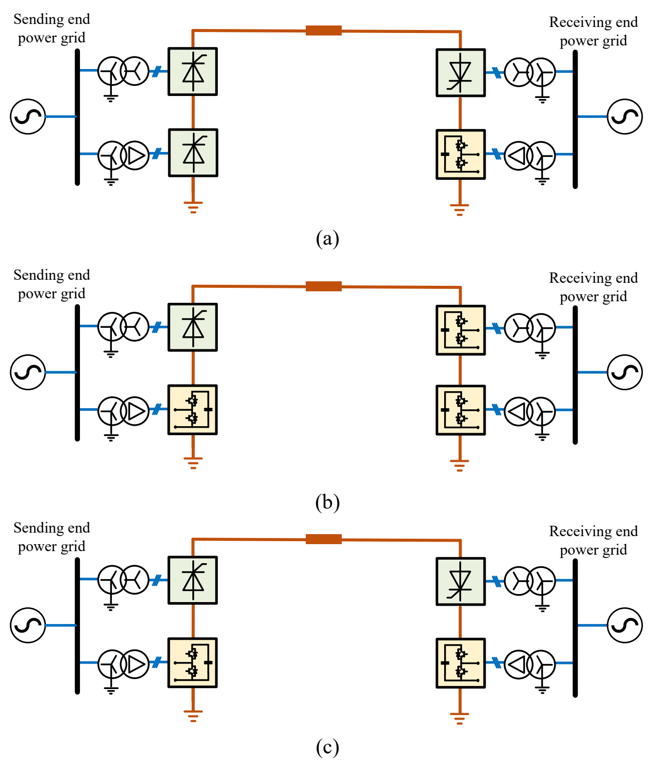

Fig. 2. LCC-MMC series within the converter station hybrid DC transmission system topological structures. (a) Hybrid DC transmission with LCC-MMC series at receiving end. (b) Hybrid DC transmission with LCC-MMC series at sending end. (c) Hybrid DC transmission with LCC-MMC series at dual terminal.

III. LCC AND MMC INVERTER-LEVEL HYBRID DC TRANSMISSION SYSTEM AND TRANSIENT STABILITY

A. Operating Characteristics of Hybrid DC Transmission System

Hybrid DC transmission with one end MMC and one end LCC has the following characteristics: 1) There is no need for the DC system to have the function of reversing DC flow. 2) Compared to traditional DC systems, the inverter station of the hybrid system does not experience commutation failures, thus avoiding the issue of commutation failures that commonly occur at conventional DC drop points. 3) Unlike conventional MMC DC transmission systems, a large power diode valve group can be configured at the DC output of the inverter station in the hybrid system, allowing for the clearance of DC line faults. Additionally, due to the need for voltage polarity changes to achieve flow reversal in LCC converter stations and current direction changes in conventional half-bridge MMC converter stations, the LCC-MMC hybrid dual-end DC transmission system faces challenges in achieving flow reversal without shutdown, requiring polarity switch operations through bipolar connections and appropriate polarity switch actions after the converter is shut down to achieve power reversal [21]-[23]. Therefore, a hybrid DC transmission system based on full Bridge Sub-Module (FBSM) MMC has been proposed to achieve non-shutdown flow reversal [24]-[27].

Hybrid DC transmission with one end MMC and one end LCC is suitable for DC fault self-clearing capability in high-capacity overhead line transmission. The submodule structure mainly consists of full-bridge sub-module (FBSM) and clamp-double sub-module (CDSM) [28]. These two submodules use more power devices such as IGBT, increasing the operational losses and construction costs of the DC system, making it less economical compared to the other two topological structures. To reduce the number of full-bridge sub-modules and improve the economic viability of this structure, a hybrid MMC using a combination of full-bridge sub-modules and half-bridge sub-modules at the receiving end has been proposed [29]-[30].

In cases where AC transmission networks need to be interconnected through DC, multiple DC lines need to be constructed, leading to increased construction and operational costs. Multi-terminal DC transmission becomes a solution for integrating renewable sources, providing cross-regional power supply, and supplying power to passive power grids. Multi-terminal hybrid DC transmission significantly expands the functionality of DC transmission, allowing energy transfer to weak AC systems, island regions, serving as an access network for small-scale distributed energy sources, effectively addressing power supply issues from energy centers to AC transmission systems [31]. Multi-terminal DC transmission technology consists of multiple converter stations connected directly to DC transmission lines, with different converter station DC buses connected to the same DC network. Based on the structure of the DC network, multi-terminal DC transmission technology can be classified into parallel, series, and hybrid types [32]. Multi-terminal DC transmission systems can simultaneously connect to multiple AC grids, delivering power to multiple AC grids, effectively solving issues related to multiple power sources and multiple load points. Compared to multiple point-to-point lines, multi-terminal DC transmission systems can fully utilize DC transmission lines, reducing line costs and offering significant advantages in terms of power supply reliability, economic viability, and control flexibility [33].

In cases where LCC converter stations and MMC converter stations exist on the same AC bus or on AC buses with close electrical distances, they form an LCC-MMC hybrid multi-infeed DC transmission system. Compared to multi-infeed systems composed solely of traditional DC, this system has two advantages: 1) MMC converter stations can flexibly control reactive power, to some extent improving the voltage and reactive power characteristics of the multi-infeed HVDC system. 2) The infeed of MMC converter stations can effectively regulate AC bus voltage stability, significantly enhancing the fault recovery capability of the DC transmission system.

In hybrid DC transmission systems, the existing LCC control methods can mainly be divided into predictive extinction angle control and measured extinction angle control strategies. Taking the Cigre_Benchmak model as an example, the control method used is based on measured extinction angle for the inverter-side extinction angle control, and direct current control for the rectifier-side direct current, with the overall control structure shown in Fig. 3. At the pole control level, under normal conditions, the inverter side adopts fixed γ angle control, and the rectifier side adopts current control. When fluctuations in the voltage at the sending and receiving ends cause changes in the DC voltage, the DC voltage enters the VDCOL (low-voltage current limit module) to provide a reference current (rectifier side).

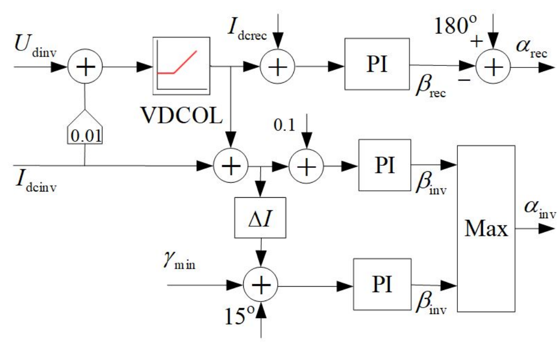

Fig. 3. LCC control strategy structure.

where, U_{dinv} is the DC voltage of inverter side LCC, I_{dcinv} is the DC current of inverter side LCC, $\gamma_{\min}$ is the minimum turn off angle, I_{dcrec} is the DC current of rectification side LCC, α_{rec} is the firing angle of rectification side LCC, α_{inv} is the firing angle of inverter side LCC.

The main control objectives of the MMC system are the active and reactive power on the AC side (or the DC bus voltage), generally achieved by controlling the AC-side current. Depending on the different control objectives, the MMC control can be divided into the following categories: 1) Control of external voltage and/or current. 2) Control of internal current. 3) Control of average capacitor voltage. 4) Control of capacitor voltage balance. Fig. 4 shows a detailed control block diagram, which can be divided into valve control level and pole control level. The former mainly includes submodule capacitor voltage balancing algorithm and valve control pulse triggering, while the latter includes external loop control, internal current loop, and circulating current suppression modules. The control system consists of 6 main modules, namely: PLL and DQ conversion, DC voltage and active power control, AC voltage and reactive power control, main current control, and switch control. The DC voltage and active power controller generates the active current (d-axis) required by the current controller to control the active power or DC voltage, depending on the operation mode of the converter station. If DC voltage control is adopted, a PI controller is needed; if active power control is adopted, the d-axis current is calculated directly from the measured grid voltage.

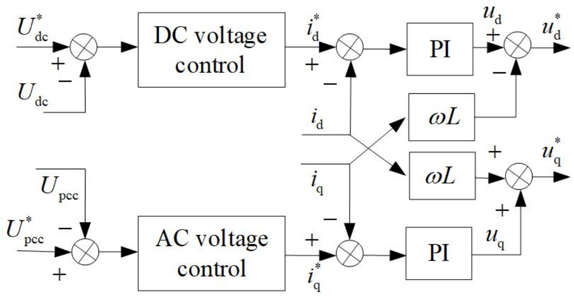

Fig. 4. Control framework of MMC system.

where, U_{dc}^* is the DC voltage reference value, U_{dc} is the DC voltage, U_{pcc}^* is the parallel point voltage reference value, U_{pcc} is the parallel point voltage, i_d^* is the d-axis current reference value, i_d^* is the d-axis current, i_q^* is the q-axis current reference value, i_q^* is the q-axis current, u_d^* is the d-axis control command, u_q^* is the q-axis control command.

Taking the example of an end-to-end hybrid DC system composed of LCC at the sending end and MMC at the receiving end, the control method is more flexible due to the active power decoupling characteristics of MMC. Fig. 5 presents several typical LCC-MMC control methods, including LCC fixed direct current + MMC fixed voltage or voltage droop, and LCC fixed direct current or droop + MMC fixed direct current forms shown in Fig. 5.

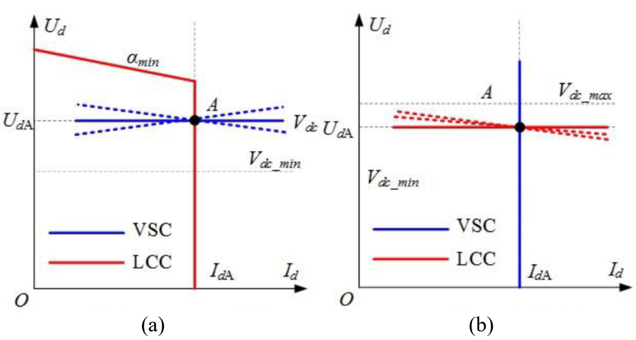

Fig. 5. Control framework of MMC system. (a) LCC fixed current + MMC fixed voltage. (b) LCC fixed voltage + MMC fixed current.

B. *Transient Stability of Hybrid DC Transmission System*

In the hybrid DC transmission system with LCC and MMC inverters-level, both LCC and MMC converters are involved. The fault process time scale of the LCC converter is relatively large and controllable, while that of the MMC converter is relatively small with strong non-linear characteristics. The mutual coupling between different types of converters will make the system fault characteristics more complex.

For single-ended conventional DC LCC systems, scholars have improved the switching function model of LCC based on the consideration of different commutation angles of the converter and the variation of conduction timing [34], enhancing the model accuracy and applicability. Based on this, a switching function model for the AC side asymmetrical faults of the converter is proposed [35]. Furthermore, by combining the fault response characteristics of the DC system, an equivalent model that interfaces directly with the AC system is established, which is also applicable for fault analysis and harmonic calculation of AC/DC systems [36]. A high-voltage DC transmission system harmonic analysis method for dealing with AC grid faults is proposed by combining the AC system equivalent harmonic network. The issue of fault current calculation during AC grid faults on the inverter side with high DC power injection is addressed, taking into account the impact of secondary harmonic currents on the converter switching function and the steady-state response of the control system [37]. The DC transmission systems based on LCC mostly use converter intrinsic control (adjusting trigger angle/locking converter) to clear line faults [38]. During normal operation, the DC control system maintains stable power transmission on the line; in case of a fault, the DC control system immediately adjusts the converter control mode to suppress the development of adverse events. When the DC control system can not prevent the fault from spreading or detects a severe power system fault, the DC protection action will shut down the system. In summary, the DC protection system adopts different fault clearing schemes according to the type of fault. Common strategies include: switching to backup control and protection systems, excluding control and protection system intrinsic faults, converter phase shifting, bypassing, locking trigger pulses, pole isolation, tripping AC circuit breakers; circuit breaker failure protection action, locking AC circuit breakers; reducing converter power; pole balancing, etc.

For single-ended MMC flexible DC transmission system fault research, there are currently mainly three aspects of related research: DC fault simulation analysis, theoretical research, and influencing factors. The fault process of MMC bipolar short-circuit is divided into two stages: pre-locking and post-locking, and equivalent models of the converter faults in each stage are provided [39]-[40]. In-depth analysis of the transient characteristics of the converter's DC side is conducted [41]. Dynamic responses of single-phase grounded faults under different grounding methods are simulated and analyzed [42]-[43]. The mechanism of overvoltage generation in single-phase grounded faults is revealed by analyzing the electrical stress of the converter bridge arms [44]. For line faults, the relationship between fault characteristics and converter station control modes is clarified by analyzing the changes in electrical quantities on the system's DC side during master-slave control and droop control. During sending-end AC faults, full-bridge submodule type and full-half-bridge hybrid type MMCs can actively reduce DC voltage to maintain power transmission; however, clamp dual submodule type MMCs lack the ability to reduce voltage and may experience power transmission interruptions [45]. During receiving-end AC faults, several submodule type MMCs can maintain a certain power transmission capability. Full-bridge submodule type and full-half-bridge hybrid type MMCs can actively reduce DC voltage to suppress submodule capacitor overvoltage, while clamp dual submodule type MMCs still face submodule capacitor overvoltage issues.

A significant amount of research has been conducted on the DC line protection principles of hybrid DC transmission systems. The main protection configuration schemes for different line faults in multi-terminal hybrid DC transmission systems are preliminarily discussed [46]. An improved method for identifying transient current polarity and fault area based on transient current polarity and current energy in flexible DC grid protection is proposed [47]. Directional series protection and current differential protection are applied to multi-terminal hybrid DC systems and verified through simulations [48]. Protection schemes based on longitudinal impedance, transient power polarity, and instantaneous energy of voltage fault components are compared with traditional traveling wave protection. In conclusion, the current fault clearing methods mainly include: 1) Fault clearing schemes based on AC circuit breakers. After a DC line fault occurs, to protect the converter and DC system equipment, the protection system sends a trip signal to the AC side circuit breaker to disconnect the AC and DC systems to prevent short-circuit current from flowing into the fault point on the AC side; after the DC side line fault current decays to zero, the fault line is cut off using a DC switch to isolate the DC fault [49]. 2) Fault clearing schemes based on DC circuit breakers. Currently, DC circuit breakers have been applied in high-voltage DC transmission, medium and low-voltage DC distribution networks, renewable energy grid connection, rail transportation, and marine applications. Depending on the application scenario, DC circuit breakers can be designed based on different technical solutions to meet the requirements of compactness and low cost while ensuring breaking performance [50]. According to different topologies, existing practical DC circuit breakers are mainly divided into three categories: mechanical DC circuit breakers [51], solid-state DC circuit breakers, and hybrid DC circuit breakers [52]-[53]. 3) Fault clearing schemes based on submodule converters. The protection technology based on fault self-clearing submodule topology of the converter prevents continuous discharge of internal energy storage units by locking the converter or changing its control mode, cuts off the AC system short-circuit current input, and isolates the fault line through components such as mechanical switches in the DC line. According to different mechanisms for suppressing fault currents, typical submodule converters with fault self-clearing capabilities can be divided into three categories. The first type utilizes the capacitor charging effect of the full-bridge submodule to absorb some energy in the fault loop, while providing reverse voltage to suppress fault current, such as CDSM, series connected double sub modules (SDSM) topology, etc [54]. The second type uses the bypass effect to disconnect the DC side circuit and the AC side circuit of the converter, thereby cutting off the path for AC side fault current input to achieve the purpose of suppressing fault current [55]. The third type is the self-blocking submodule topology designed by directly cutting off the bridge arm current with a switch circuit, such as the self-blocking submodule topology designed in reference [56]. The control logic of an improved inverter-side AC fault ride-through control strategy is shown in Fig. 6 [57]. During steady-state operation, the fault detection mode is 0, and it switches to mode 1 when a fault occurs in the receiving-end AC system. The full bridge sub-module hybrid modular multilevel converter (FHMMC) can actively reduce the DC voltage and operate under low voltage or even negative voltage conditions. After the fault is cleared, the fault detection mode switches back to 0, the DC voltage reference value of the FHMMC is restored, and the DC voltage of the FHMMC is quickly controlled back to its steady-state value to restore the active power entering the DC system. Throughout the three different stages before, during, and after the fault in the receiving-end AC system, the rectifier-side LCC always maintains a fixed direct current control mode.

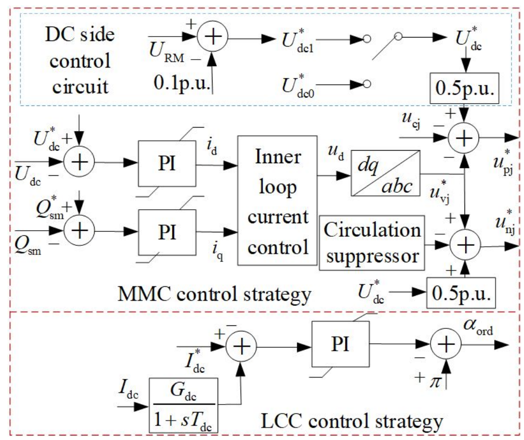

Fig. 6. Fault ride-through control strategy of.hybrid DC transmission.

where, Q^*_{sm} is the reactive power reference value, Q_{sm} is the reactive power.

IV. LCC-MMC Series within the Converter Station Hybrid DC Transmission System and Transient Stability

For the various topological structures of the hybrid DC transmission system formed by the series connection of LCC and MMC within the converter station, when considering the transient stability of the new hybrid DC system and its fault crossing strategy, such structures can be classified as the receiving-end converter station adopting a series structure of LCC and MMC, and the sending-end converter station adopting a series structure of LCC and MMC.

A. Transient Stability of Hybrid DC Transmission System with LCC-MMC Series in Receiving End Converter Station

For the LCC-MMC series hybrid DC transmission system, when only the receiving end adopts a series structure of LCC and MMC, the sending end needs to be connected to a strong AC system composed of thermal power and hydropower [58]-

[59], such as in the southwest region of China. There are many forms of the series connection structure of the receiving-end LCC and MMC, with typical structures such as those shown in Fig. 7, including standalone MMC structure, dual MMC parallel hierarchical structure, and triple MMC parallel hierarchical structure.

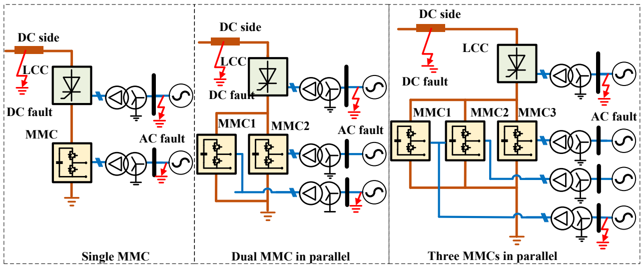

Fig. 7. Typical LCC-MMC series within the receiving-end converter station.

In the event of a DC fault, relying on the unidirectional conductivity of the high-voltage valve group LCC at the receiving end, the MMC will not contribute short-circuit current to the fault point, thus saving expensive high-voltage DC circuit breakers and improving economic efficiency. The traditional fault crossing strategy involves the rectifier-side LCC adopting phase-shifting control strategy, adjusting the firing angle to operate in the inverter mode, thereby quickly releasing the energy stored in the DC line to suppress the fault current. The MMC station locks the converter valve submodule and cuts off the AC fault current fed into the system through the submodule capacitor's reverse DC potential, without the need for MMC locking. For the topology of the receiving end adopting a hybrid structure of LCC and multiple MMCs, [60] analyzes the system's DC fault response characteristics and proposes corresponding recovery control strategies to suppress the problem of power backflow between MMC parallel groups during faults and large current fluctuations during system recovery. For the topology with a DC transmission line between the high-voltage LCC at the receiving end and the low-voltage MMC, [61] proposes an adaptive reclosing method for the DC transmission circuit breaker based on the voltage at both ends of the DC circuit breaker to quickly isolate the DC line fault between the high-voltage LCC and the low-voltage MMC valve groups. Although this topology is generally feasible in technical implementation, it increases the probability of DC faults, thereby reducing the system's operational reliability, while introducing additional DC transmission lines and DC circuit breakers will increase construction costs. The control strategy for dealing with DC faults is shown in Fig. 8. Under normal conditions, the command value for the inverter station's LCC backup current control is set to be one current margin lower than the rectifier station's fixed current control, typically 0.1 p.u. to prevent instability in the system caused by simultaneous action of the fixed current control of both LCCs. In the event of a DC fault, relying on the unidirectional conductivity of thyristors, the MMC does not feed short-circuit current to the fault point, causing the DC current from the fault point to the entrance of the inverter station's LCC to rapidly decrease to zero, prompting the inverter station's LCC control system to reduce α1 to the minimum limit. During the DC fault, the MMC does not need to be blocked, and its DC voltage can be maintained near the rated value, allowing the inverter station's LCC to withstand a reverse voltage equal to the MMC's DC voltage.

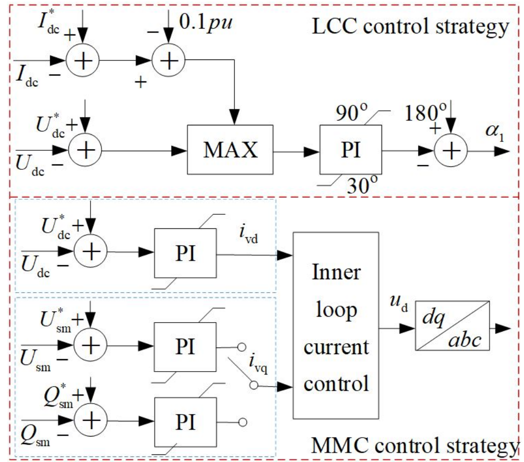

Fig. 8. Typical LCC-MMC series within the receiving-end converter station.

In the case of AC faults at the sending end that are not severe, the voltage reduction capability of the high-voltage valve group LCC at the receiving end can maintain power transmission. When the fault is severe, the half-bridge submodule type MMC lacks voltage reduction capability and will still experience intermittent DC current and interrupted power transmission [62]. When a near-end AC system fault causes a drop in the AC bus voltage, hindering MMC power transmission, due to communication and signal triggering delays, LCC can not respond quickly, resulting in a large amount of surplus power at the receiving end, forcing the submodule capacitor to charge excessively and causing severe overvoltage, even leading to device damage. For the LCC-MMC series hybrid DC transmission system, an AC system fault at the receiving end not only causes MMC overvoltage but also leads to phase failure of the receiving-end LCC and results in DC overcurrent. To suppress overvoltage of the MMC submodule capacitor at the receiving end, MMC dynamic reactive power compensation can be utilized to enhance the voltage support capability of the receiving-end grid, thereby improving the LCC's ability to withstand phase failures; even if the LCC experiences phase failure, the low-voltage valve group MMC can maintain a portion of the DC voltage, enabling the DC system to continue transmitting power to the AC system, thereby reducing the impact on the AC system, but the issue of submodule capacitor overvoltage exists [63]. [64] proposes a voltage-power coordinated control strategy and a low-voltage current limiting control strategy based on changes in the receiving-end AC voltage. The two most severe faults causing MMC submodule capacitor overvoltage and designs a large-capacity controllable self-recovery energy dissipation device for practical engineering. [65] proposes a protection strategy for unbalanced current in the converter arm and a step-by-step locking strategy for the converter. [66] compares and analyzes the principles and fault crossing characteristics of three overvoltage suppression methods: controllable surge arrester [63], DC chopper resistor [67], and leakage thyristor [68]. To suppress transient overcurrent at the receiving end MMC, [69] analyzes the mechanism of phase failure of LCC due to AC faults at the receiving end and resulting DC overcurrent, and proposes an overcurrent suppression strategy based on fuzzy clustering and identification. [70] proposes two solutions: series connection of diodes on the DC side of MMC or series connection of resistors on the bypass switch. [71] introduces a fault current limiter to limit the DC overcurrent caused by LCC phase failure and prevent MMC from locking due to overcurrent. In addition, [72] presents a MMC reactive power control method that can effectively reduce the probability of subsequent phase failures of LCC and improve the transient characteristics during system faults and recovery processes.

Currently, the main issue during the fault of the hybrid DC transmission system is surplus power. There are three main methods to address surplus power control during faults. The first method starts with rapid power control from the perspective of new energy islanding, limiting the power injected from the new energy island to the hybrid DC transmission system during faults through control strategies. The second method starts from the perspective of energy dissipation. During faults in the transmission system, surplus power is dissipated using AC or DC energy-dissipating devices, with typical AC-DC energy-consuming devices shown in Fig. 9. Additionally, the use of energy storage-type MMC is also an effective means, with its submodule topology structure shown in Fig. 10. The energy storage device is connected in parallel to both ends of the half-bridge submodule through a bidirectional DC-DC converter. The energy storage device is composed of supercapacitors or lithium battery packs connected in series and parallel, exchanging power through the charging and discharging of submodule capacitors. Compared to the half-bridge submodule, the energy storage submodule only adds two IGBTs, making it more cost-effective. If a fault occurs in the inverter station's LCC AC bus, the power transmission of the MMC is not severely hindered, and the surplus power on the DC side can be absorbed solely by the energy storage device without the need to reduce the DC current command value of the rectifier station's LCC. In the event of a fault on any AC bus on the receiving end, the redundant transmission capability of the MMC and the energy storage device can completely dissipate the surplus power on the DC side.

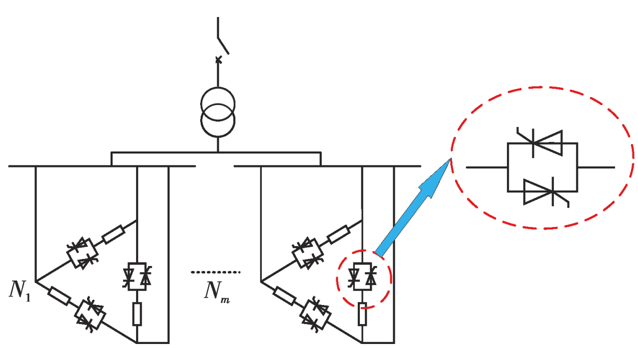

Fig. 9. Typical AC-DC energy-consuming devices.

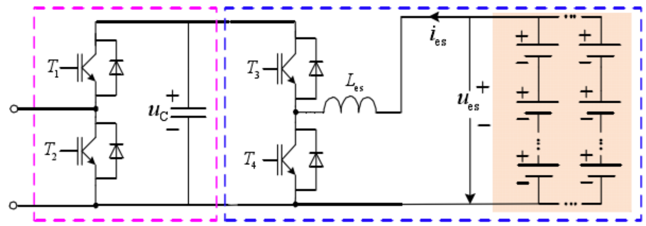

Fig. 10. Submodule topology structure of energy storage-type MMC.

B. Transient Stability of Hybrid DC Transmission System with LCC-MMC Series in Sending End Converter Station

In large-scale clean energy bases with a high proportion of renewable sources such as wind and photovoltaic power, the system strength is insufficient to support reliable phase shifting of LCC, such as in the northwest region of China. Due to the cost and transmission capacity limitations of MMC, using MMC as a large-scale power export solution at the sending end is not economical. Therefore, a topology with a series structure at the sending end is very suitable for such ultra-high-voltage large-scale power export scenarios dominated by renewable sources [73]. This scheme utilizes MMC to provide transient stability active support to the extremely weak sending-end system voltage, to prevent voltage collapse, while also possessing significantly stronger transient active regulation capability than LCC. Furthermore, through appropriate coordinated control, even in the event of a severe AC fault at the sending end, the DC side will not be disconnected. This hybrid DC transmission system faces the following issues that need careful consideration: 1) The voltage support capability of the sending-end pure renewable source generation base needs to consider both normal operating conditions and fault crossing issues when the sending-end AC grid experiences faults. 2) The fault crossing issues when the receiving-end AC grid faults lead to LCC phase failure and obstruction of the receiving-end MMC output power. 3) The self-clearing ability during DC line faults needs to consider the impact of forced phase shifting control of the sending-end LCC on the overvoltage of the sending-end MMC. 4) How to start the sending-end pure renewable source generation base with the LCC-MMC series hybrid DC transmission topology. There are many forms of the series connection structure of the sending-end LCC and MMC, with typical structures such as those shown in Fig. 11, including standalone MMC structure, dual MMC parallel hierarchical structure, and triple MMC parallel hierarchical structure.

In the series connection structure of LCC and MMC at the sending end, the sending-end MMC needs to provide support power to the sending-end AC grid, therefore, grid-forming control must be adopted. Controlling the amplitude and frequency of the AC bus voltage of the rectifier station is an effective means, known as V/f control. V/f control is achieved through dual-loop control, with the specific structure shown in Fig. 12. In addition, to address the issue of DC overvoltage of the MMC under various faults, an AC energy-consuming

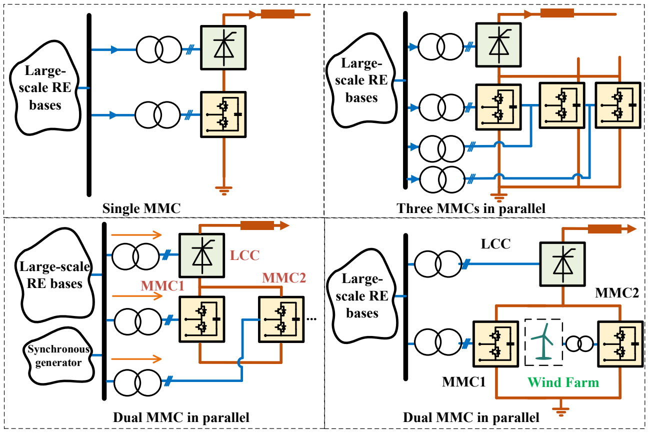

Fig. 11. Typical LCC-MMC series within the sending-end converter station.

device needs to be installed at the rectifier station on the sending end. The input of the AC energy-consuming device is the measured DC voltage values of the sending-end MMC and the receiving-end MMC. The control strategy for the LCC controlling the DC current command value is shown in Fig. 8. The difference between the DC voltage of the sending-end MMC and its command value is taken, and the DC current command value of the sending-end LCC is obtained through a PI controller. If the DC voltage of the sending-end MMC exceeds its command value, the LCC will increase the DC current of the sending end under the action of the controller, thereby increasing the DC power output of the MMC. According to the principle of energy conservation, when the DC power of the MMC exceeds its active power on the AC side, the submodule capacitor will provide the shortfall in power, causing the DC voltage of the MMC to decrease, thereby maintaining the DC voltage of the sending-end MMC at its command value. Typical control structures as shown in Fig. 12.

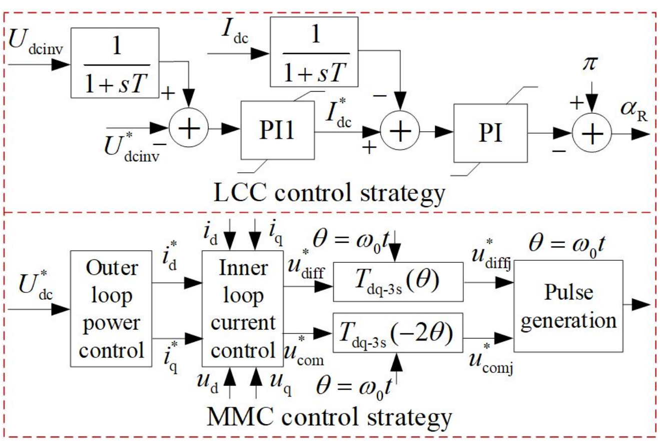

Fig. 12. Typical LCC and MMC control structures.

During DC faults, for topologies where both sending and receiving ends are series structures, the receiving-end MMC does not need to lock, the sending-end LCC enforces phase shifting, and the sending-end MMC needs to lock to block the fault current [74]. For the LCC-diode-half-bridge submodule type MMC hybrid DC transmission system, the unidirectional conductivity of the diode can block the DC fault current, and the MMC does not need to lock. [75] studied the DC fault crossing strategy of a hybrid three-terminal DC transmission system with two receiving ends adopting a diode-half-bridge submodule type MMC structure, where both MMC stations switch to STATCOM mode during the fault, switch back to the pre-fault control mode after the fault is cleared, and calculate the number of series and parallel diodes required for the diode valve stack and the operating losses at steady state. For the LCC-DC fault self-clearing submodule type MMC hybrid DC transmission system, the submodule with self-clearing capability for DC faults locks and provides reverse electromotive force to quickly block the DC fault current in the fault loop. In addition, the full-bridge submodule can output negative voltage during normal operation, with the ability to reduce DC voltage, and can reduce the DC voltage of the full-bridge submodule type and full-half-bridge submodule type MMC to zero or even negative values during DC faults, achieving fault crossing without locking. For the LCC-full-half-bridge submodule type MMC hybrid DC transmission system, [76]-[77] derived the proportion allocation of half-bridge submodule and full-bridge submodule to meet the requirements of fault locking and clearing, low DC voltage over-modulation operation, etc. [78]-[79] proposed an MMC fault crossing strategy based on zero DC voltage control without locking, where the MMC continuously transmits reactive power during faults, while shortening the system recovery time. [80]-[81] compared the fault clearing mechanisms and corresponding DC fault crossing characteristics of three hybrid DC transmission systems: series diode valve group, full-half-bridge submodule type MMC, and LCC-MMC series hybrid type.

In the event of an AC fault at the sending end causing a drop in the AC bus voltage, the sending-end LCC's constant DC current control maintains the DC voltage and current near the rated values by reducing the firing angle. When the firing angle is reduced to a minimum of 5°, the sending-end LCC loses its ability to adjust the firing angle, and its generated DC voltage will be directly proportional to the fault bus voltage of the connected AC system [82]. The half-bridge submodule and clamping dual submodule can not output negative voltage during normal operation and are limited in voltage reduction capability due to voltage modulation ratio constraints, making the voltage reduction capability of these two submodule types of MMC very limited, while the full-bridge submodule and full-half-bridge submodule MMC have strong voltage reduction operation capabilities. As long as the bus voltage of the MMC-connected AC system does not drop to zero, the MMC can maintain power transmission capability, so for topologies where both sending and receiving ends adopt series structures of LCC and MMC, even in the event of a severe AC fault at the sending end, relying on the strong power transmission capabilities of the sending-end MMC and the receiving-end MMC, power transmission can still be maintained without interruption. [74] proposes a two-stage backup current control to maintain power transmission capability of the DC system at the sending end during AC system faults, avoiding intermittent DC current and improving the recovery characteristics of the entire system after the fault is cleared.

V. Conclusion

The LCC-MMC hybrid DC transmission technology simultaneously uses in a two-terminal or multi-terminal DC transmission system and forms a new type of hybrid DC transmission system by serially or in parallel connecting LCC and MMC through different hybrid structures. Due to the unique technical advantages of hybrid DC transmission systems, they have tremendous potential to meet the economic and technical requirements for transmitting large-scale renewable energy sources. This technology has received widespread attention from academia and industry because it can further improve the efficiency and reliability of long-distance high-power transmission, making it an important direction for DC transmission development. Through this study, the following conclusions have been drawn:

1) Hybrid DC transmission systems mix MMC and LCC in different ways to create various transmission topologies. Based on the different forms of hybrid LCC and VSC, the topological structures of hybrid DC transmission systems can be classified into two categories: converter-level hybrid DC transmission systems and system-level hybrid DC transmission systems. By leveraging the respective advantages of LCC and VSC, mitigating the interaction between AC and DC, and ensuring safe and stable operation, a coordinated hybrid DC transmission system can be constructed.

2) In a hybrid cascaded DC transmission system, LCC can not only reduce construction and operating costs but also provide DC fault handling capabilities through forced commutation and the unidirectional conduction of thyristors. MMC can decouple control reactive power to support AC voltage, providing a stable AC voltage source for renewable energy stations on the rectifier side and suppressing commutation failures on the inverter side LCC.

3) There are multiple fault ride-through implementation methods in hybrid DC transmission systems. During faults, surplus power is a major concern, and several surplus power control methods can be employed. Firstly, rapid power control from renewable energy islands can be used to limit the power injected into the flexible DC system during system faults. Secondly, from an energy dissipation perspective, surplus power can be dissipated using AC/DC energy dissipation devices during system faults. Thirdly, by enhancing the energy storage buffer capacity of the converter station during faults and coordinating with a small amount of energy dissipation devices to absorb surplus power. Additionally, using energy storage MMC is also an effective approach.

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