Research on Hybrid Cascaded Multi-terminal HVDC Transmission and Its Dynamic Model Test

Zhan Rong-rong¹, Liu Long-hao¹, Dou Qiong-zhu², Zhang Lei*, Bai Lei-cheng²

¹State Key Laboratory of Power Grid Safety and Energy Conservation (China Electric Power Research Institute)
²XJ Group Corporation
1050638316@qq.com

Abstract. Hybrid cascaded multi-terminal DC transmission topology scheme adopts LCC converter at the rectification side, inverter side uses high-end LCC converters in series with low-end multiple VSC converters. This topology solution can make full use of the advantages of LCC and VSC technology. As a new generation of HVDC transmission technology, hybrid cascade multiterminal still has many key technologies to be broken. Through the development of hybrid cascade multiterminal HVDC dynamic simulation test system, the start-up, shutdown, high and low valves switching-back and DC fault self-cleaning of hybrid cascade multiterminal HVDC transmission are studied and tested. It provides technical support for the engineering application of hybrid cascade multi-terminal HVDC transmission technology.

1. Introduction
In order to further leverage the technical advantages of LCC-HVDC and VSC-HVDC and realize the complementary, and improve the technical economy of DC transmission systems, hybrid DC transmission technology has become a hotspot in the field of DC transmission. Hybrid DC transmission system can take advantage of VSC-HVDC without commutation failure, flexible control, low cost and low loss of LCC-HVDC, and further expand the application range of flexible DC transmission technology[1]. At present, hybrid cascaded multi terminal DC transmission technology has not been applied in engineering and is still in the research stage. By building a hybrid cascade multi-terminal dynamic mold test system, Experimental research is conducted on a number of key technologies such as hybrid cascade multi-terminal start, high and low valve group switching, dc fault ride-through, to provide technical support for the engineering application of hybrid cascade multi-terminal DC transmission technology.

2. Hybrid cascaded multi-terminal DC transmission topology
The typical topology of hybrid cascade multi terminal DC transmission is shown in Figure 1. It can be seen from the figure that LCC converter is used at the rectifier side to form high and low valve groups in series, LCC and VSC converter are used at the inverter side in series, LCC converter is used at the high-end valve group at the inverter side, multiple VSC converters are used at the low-end valve group in parallel, and mature MMC topology is used at the VSC converter.
Hybrid cascade multi-terminal DC transmission has the following technical characteristics:

1. The inverter-side converter can independently control active and reactive power.
2. During DC fault, the inverter-side LCC clears the DC fault current by forcing the negative potential provided by the phase shift.
3. In the case of serious AC fault on the rectifier side, the inverter station LCC can reduce the DC voltage and run to the backup DC current control state to avoid DC current interruption.

3. Design of hybrid cascade multi terminal dynamic model system

In order to study the key technologies of hybrid cascaded multi terminal DC transmission, a hybrid cascaded multi terminal dynamic model test system is built [2]. The hybrid cascaded multi terminal dynamic model test system adopts a single pole topology structure. The rectifier side is composed of LCC1 and LCC2 in series, and LCC1 and LCC2 adopt 12 For the pulsating thyristor converter valve, LCC3 at the high-end valve group at the inverter side adopts 12 pulsating thyristor converter, and the low-end valve group is composed of two MMC converters in parallel [3]. In order to realize the research on the on / off strategy of the high and low valve groups, the DC side of the hybrid cascade multi terminal dynamic model test system is equipped with a DC switch to realize the on / off function of the high and low valve groups. The main wiring diagram of the hybrid cascade multi terminal dynamic model test system is shown in Figure 2.

3.1. operation mode of hybrid cascade multi terminal DC transmission

The main operation modes of hybrid cascade multi terminal DC transmission as follows:

1) The inverter side VSC converter operates in STATCOM mode;
2) Under the operation mode of full voltage, LCC1 and LCC2 at the rectifier side are under constant DC current control, LCC3 at the high end of inverter side is under constant DC voltage control, and VSC at the low end is under constant DC voltage control at one end. In addition, the active power at both ends is under constant active power control, and the power is evenly distributed between the VSC;
3) It has two half pressure operation modes, LCC-LCC and LCC-VSC.
3.2. enable / disenable function of high / low valve group
In order to verify the on / off function of high and low valve groups of hybrid cascade DC transmission, the on / off function of high and low valve groups is designed in the hybrid cascade DC transmission electric model test system, and the main wiring diagram of high and low valve groups of hybrid cascade is shown in Figure 3.

![Main wiring diagram of high and low valves hybrid cascade dynamic simulation system](image)

Fig. 3 Main wiring diagram of high and low valves hybrid cascade dynamic simulation system

4. LCC and VSC converter control principle

4.1. VSC inverter control principle
In the hybrid cascaded multi terminal HVDC system, the control strategy of VSC converter is relatively independent. In most cases, the low-end VSC converter is not affected by the high-end LCC. In normal operation, VSC converter can manually issue command through background to switch between DC voltage control and active power control mode, or between AC voltage control and reactive power control mode [4]. The reactive power controlled by VSC converter can accurately compensate the reactive power absorbed by high-end LCC, so that the reactive power absorbed by converter station from AC system is zero, MMC control of AC bus voltage is conducive to system recovery from AC fault. The control block diagram of VSC converter is shown in Figure 4.

![MMC control block diagram](image)

Figure 4 MMC control block diagram

4.2. control principle of LCC converter
The control and regulation of LCC converter is realized by controlling the trigger angle of LCC converter. The basic control configuration of rectifier side mainly includes the minimum trigger angle control, DC current control, DC voltage control, etc [5-6]. the basic control configuration of inverter side mainly includes the constant turn-off angle control, DC current control, DC voltage control, etc. Typical control block diagrams of LCC controller on rectifier side and LCC controller on inverter side are shown in Fig. 5 and Fig. 6 respectively.
5. Hybrid cascade multi terminal dynamic model system test

The parameters of the hybrid cascade multi terminal dynamic model test system are: DC voltage rating of +4 kV, DC current rating of 10 A, and transmission capacity of 40 kVA. LCC converter system parameters: AC system voltage 0.38kV, converter transformer 0.38kV/0.8kV, capacity 30KVA, smoothing reactor 80mH, VSC converter system parameters: The AC system voltage is 380V, the converter transformer is 0.38kV/1.5kV, the capacity is 30kVA, the single bridge arm is 20 sub modules, the bridge arm reactor is 40mH, the VSC converter DC voltage is 2kV.

5.1. Start control test

The start-up control strategy of hybrid cascade multi terminal DC transmission is to establish DC voltage at the inverter side first, The VSC converter starts first, gradually increases the low-end DC voltage to the rated voltage, and then the high-end LCC at the inverter side unlocks, and the LCC at the rectifier side unlocks. After detecting DC current, LCC at inverter side gradually increases voltage, and LCC at rectifier side increases DC current through trigger angle regulation.
As can be seen from Figures 7 to 9, the inverter-side VSC converter is unlocked first after charging through the soft-start circuit. After unlocking, the DC voltage across the VSC converter reaches the rated value of 2kV, and then the inverter-side high-end LCC converter is unlocked. The trigger control angle is phase-shifted to about 147°. Finally, the rectifier-side LCC converter is unlocked, and the trigger control angle is about 59°.

5.2. **High and low valve group throwback control**

The control strategy of the high and low valve group is: first issue the valve group input command through the background, LCC1, LCC3 begin to transfer the current flowing through the BPS, when the BPS current is zero, the BPS is pulled open, and the DC voltage of the LCC3 converter rises to the rated value is 1pu, the valve group is successfully put into operation; the valve group exit command is issued through the background, the voltage of the LCC1 and LCC3 control ports is 0, the BPS is closed, and the high-end valve group is successfully exited.

5.3. **DC fault ride-through control**

Simulate the DC bus at the inverter-side pole bus outlet (inverter-side 4kV line) with a resistance short-circuit fault and start the fault ride-through function. The rectifier side LCC1 and LCC2 are forced to phase shift to control the DC current to zero. 300ms after the fault occurs, the rectifier side LCC1 and LCC2 cancel the forced phase shift, the current command ramps up to the rated value, and the system resumes normal operation.
6. Conclusion
As a forward-looking technology, the key technology of hybrid cascaded multi-terminal DC transmission is still in the theoretical research stage. There is no application of engineering schemes and lack of experimental verification of key technologies.

The key technologies of hybrid cascaded multi-terminal converter valve start-up, high and low valve group switching, and dc fault ride-through were tested and verified by building a hybrid cascaded multi-terminal dynamic mold test system, which provides technical support for the application of hybrid cascaded multi-terminal DC transmission engineering.

The test results show that the start-up process of the hybrid cascaded multi-terminal DC transmission technology is smooth, and the high-low valve group switch-off and DC fault ride-through technology are consistent with the theory. The test results verify the feasibility of the hybrid cascaded multi-terminal DC transmission.

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