Research on Coordination Control Strategy of LCC-MMC Hybrid HVDC Transmission System under Fault

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Abstract. High voltage direct current based on modular multilevel converter (MMC-HVDC) has a good application prospect in engineering, but it is expensive and cannot handle DC faults and other disadvantages. So it is still not suitable for long-distance transmission. To solve these problems, this paper designs multi-terminal hybrid DC transmission system with a line commutated converter based on the rectifier side (LCC) and a modular multilevel converter based on the inverter side (MMC). Besides, for the asymmetric fault on the AC side of the system, the minimum trigger angle control strategy based on the rectifier side LCC and the maximum modulation ratio control strategy based on the inverter side MMC are proposed to improve the DC system transmission power and reduce the possibility of power transmission interruption. Finally, a model of hybrid DC transmission is built in PSCAD/EMTDC, the proposed strategy is verified its effectiveness.

1. Introduction
High voltage DC power transmission system is developing, the straight technology of line commutating converters has developed very mature. Although the LCC composed of thyristors has merits of large transmission capacity, less investment, and inclusive operating technology, it still cannot absorb the disadvantages of its large absorption reactive power and commutation failed. Flexible DC transmission system does not have the possibility of commutation failure, and can supply power to weak AC systems, large cities with dense loads, isolated loads and passive systems. Therefore, the hybrid DC transmission system combining the merits of conventional DC transmission and flexible DC transmission have wider applications\cite{1-7}.

In [8], the author propose a new hybrid transmission system based on LCC-MMC topology, and designed a steady state control strategy and start-up control strategy; the problem of commutation failure of traditional DC transmission and voltage source DC The transmission system is unable to clear DC line faults and other problems in [9]. A new type of current source hybrid DC transmission system is proposed, its steady-state mathematical model is derived, and its controller and control strategy are designed. In [10], a horizontal comparison and simulation study of three proposed microsecond-level MMC electromagnetic transient mathematical models is conducted, and the practicability of the simplified electromagnetic transient average model in severe AC and DC transients has been verified, and its applicable scenarios and use methods have been analyzed. In [11],...
the basic control strategy of HVDC transmission system with hybrid system of LCC-MMC is researched. Two feasible DC fault ride-through control strategies are introduced, including blocking processing and non-blocking fault ride-through. However, no control method is proposed for AC-side faults. In [12], the characteristics of LCC and MMC in start-up control are studied, the start-stop scheme and fixed operation of multi-terminal LCC-MMC hybrid HVDC transmission system are proposed, and the feasibility of rapid start-up is proposed. Simulation results show that the scheme is feasible. In [13], the author proposes an improved C-MMC topology on the inverter side and an alternate constant pressure control strategy using casting bypass, but the ac fault control on the inverter side is not described; The MMC converter topology based on the clamped dual submodules is studied in[14], and the author realizes the DC blocking characteristics according to the normal and blocking working modes of the submodules, but this seed module will generate large steady-state operating losses, and the use of a large number of semiconductor devices is uneconomical.

In this paper, this paper takes three-terminal hybrid HVDC power transmission system with LCC as the transmitting terminal and MMC in parallel as the receiving terminal. Secondly, it analyzes the problems of DC power transmission drop or interruption. Then, a coordinated control strategy based on the minimum triggering angle control of the rectifier station and the maximum modulation ratio control of the inverter station is designed as the fault protection strategy of hybrid DC transmission system. Finally, the hybrid DC transmission system simulation model is built in PSCAD/EMTDC to verify the effectiveness of the proposed coordination strategy.

2. System Structure and Mathematical Model

2.1. System Structure

The topology of three terminals hybrid DC transmission system is shown in figure 1. The rectifier station is a 12-pulse line commutation converter station where two 6-pulse converter units are connected in series on the DC side. The AC-phase voltages of the two 6-pulse units are out of phase and the center point of DC side is grounded. Half-bridge modular multilevel converter(HB-MMC) is designed in structure, the converter transformer adopts the star-angle connection method, and the valve side is grounded through a large resistance.

![Figure 1. Topology of LCC-MMC hybrid DC transmission system.](image)

2.2. System Mathematical Model

The output voltage of the 12-pulse LCC rectifier station is:

\[
U_{dc1} = 2.7U_1 \cos \alpha - \frac{6}{\pi} \chi_{s1}I_{dc1}
\]

According to Kirchhoff current law, the k \((k = a, b, c)\) phase current can be expressed as: \(i_k = i_{ph} + i_{ph'}\).

According to Kirchhoff voltage law, the upper arm and lower arm of a phase unit can be expressed respectively:

\[i_{ph} = I_{dc1} \sin \alpha; i_{ph'} = I_{dc1} \cos \alpha\]
In the formula, “2L” is the inductance of bridge arm reactance; “2R” is the equivalent resistance of bridge arm. Add equations (2) and (3) and divide by 2 to get the mathematical model of the inverter station:

\[
\begin{align*}
\frac{u_k - (u_{pk}/2)}{u_k - (u_{nk}/2)} = 2L \frac{di_{pk}}{dt} + 2Ri_{pk} \\
\end{align*}
\]

(2)

(3)

The voltage difference between upper arm and lower arm is:

\[ u_{differ} = \frac{1}{2} (u_{nk} - u_{pk}) \]

(5)

Then the transmission voltage modulation ratio “m” of MMC is calculated from the fundamental amplitude of the voltage difference between upper arm and lower arm divided by \[ U_{dc2}/2 \], which can be expressed by equation(6):

\[ m = \frac{U_{diff}}{U_{dc2}/2} \]

(6)

The DC current between converter stations can be expressed as:

\[ I_{dc1} = \frac{U_{dc1} - U_{dc2}}{R_{d1} + R_{d2}} \]

(7)

\[ I_{dc3} = \frac{U_{dc1} - U_{dc3}}{R_{d1} + R_{d3}} \]

\[ I_{dc1} = I_{dc2} + I_{dc3} \]

In the above equations, \( X_{r} = \alpha L \) is expressed as equivalent commutation reactance; \( \alpha \) is expressed as the trigger angle; \( u_{pk} \) and \( u_{nk} \) are the capacitor voltages of the k-phase upper arm and lower arm; \( u_k \) is K-th phase voltage on the valve side; R and L are half of the resistance and half of the reactance inductance of the bridge arm; \( U_{diff} \) is the amplitude of the fundamental phase voltage; \( I_{dc1} \) is the rectified DC current; \( I_{dc2} \) and \( I_{dc3} \) are the DC currents of the MMC connected in parallel on the inverter side.

3. Control Protection Strategies

3.1. Basic Control Strategy

The basic control strategy of the hybrid HVDC transmission system is that the LCC rectifier station uses constant DC voltage control and minimum trigger angle control; one terminal of the MMC inverter station at both terminals in parallel uses constant DC voltage control and maximum modulation ratio control, another terminal uses constant active power control. During normal operation, the basic control strategy of the system is that the LCC rectifier station uses constant DC voltage control, and the MMC inverter station uses constant DC voltage control and constant active power control. The control block diagrams of converter station at both ends are shown in Figure 2 and Figure 3.
3.2. Minimum Trigger Angle Control
When the AC voltage drops at the LCC converter station, or the DC voltage of the LCC rectifier station is greater than reference value of DC voltage in steady state operation, or the DC voltage value of the MMC side is greater than the DC voltage of the LCC steady state operation, the minimum will start trigger angle control to reduce the trigger angle, and decrease trigger angle $\alpha$ to compensate the DC voltage drop. Two series of 6-pulsation converters in a 12-pulsation converter share a set of trigger angle instructions $\alpha_{ord}$. The minimum trigger angle module is shown in Figure 4.

3.3. Maximum Modulation Ratio Control Strategy
When an AC asymmetric fault appear in the AC system of the MMC station, the DC voltage of the MMC station is proportional to its connected AC side voltage. When the rectifier station occurs an AC fault, DC voltage of the inverter MMC is always controlled at the rated reference value, DC voltage of the inverter station remains unchanged. Therefore, when an asymmetric fault appear in the AC system, by reducing the DC voltage on the inverter side, the active power transmission of the system can be guaranteed. Based on the basic control strategy, the maximum modulation ratio control strategy is added to the constant DC voltage inverter station to control the asymmetrical faults of the AC grid in the system. The block diagram of the maximum modulation ratio control strategy is shown in Figure 5.
According to equation (4), under the premise that the valve-side voltage \( u_k \) on the inverter side does not change, the modulation voltage \( v_k \) of the current closed-loop control does not change, and the average of fundamental peak of the three-phase modulation voltage remains unchanged. Therefore, according to the equation (6), it's inversely proportional between the modulation ratio "m" and the DC voltage \( U_{dc} \). The half-bridge type sub-module MMC usually takes the modulation ratio rating of 0.85, and the maximum is normally 1 during normal operation.

The maximum modulation ratio module calculates the average of fundamental peak voltage through the three-phase modulation voltage \( v_k \), and then uses equation (6) to calculate the real-time modulation ratio \( m \). The deviation between the real-time modulation ratio \( m \) and the modulation ratio reference value \( m_{ref} \) enters the PI controller, and the deviation \( \Delta U_{dc_{ref}} \) of the DC voltage reference value is output. This module reduces the DC voltage of the constant voltage station by modifying the DC voltage reference value.

Because AC fault will cause the DC current to contain a double frequency component, and its value is greater than the protection setting value, therefore, 100Hz DC current component is selected as the enable signal for whether the maximum modulation ratio is enabled. The fast Fourier transform of the MMC positive and negative currents is used to filter the 100Hz components, and after a time delay, the enable signal is output. The protection principle of 100Hz DC current component is:

\[
\begin{align*}
& I_{dc_b_{100Hz}} > I_{setP} \quad \text{or} \quad I_{dc_n_{100Hz}} > I_{setN} \\
& I_{setP} = k_1 I_{dc_b_{N}} + k_2 I_{dc_b} \\
& I_{setN} = k_1 I_{dc_n_{N}} + k_2 I_{dc_n}
\end{align*}
\]

(8)

In the formula, \( I_{dc_b_{100Hz}} \) and \( I_{dc_n_{100Hz}} \) are 100Hz components of the extracted DC current, \( I_{dc_b} \) and \( I_{dc_n} \) are positive DC rated current and actual current value, \( I_{dc_b} \) and \( I_{dc_n} \) are negative DC rated current and actual current value, \( k_1 \) and \( k_2 \) are protection coefficients.

4. Simulation Verification

The simulation model of the HVDC power transmission system shown in Figure 1 is built in PSCAD-EMTDC.

Table 1. Main parameters.

|                       | Rectifier station LCC | Inverter station 1 MMC1 | Inverter station 2 MMC2 |
|-----------------------|-----------------------|-------------------------|-------------------------|
| AC side rated voltage/kV | 525                  | 525                     | 525                     |
| Rated DC voltage/kV    | 320                   | 320                     | 320                     |
| Converter station structure | 12 pulse converter | HB-submodule | HB-submodule |
| Bridge arm reactance/mH | -                    | 100                     | 100                     |
| Bridge capacitor/µF    | -                     | 10000                   | 10000                   |
4.1. AC fault Simulation on the Rectifier Side
The single-phase-to-ground fault is set in phase A of the AC side of the rectifier station. The fault is set to start from 3 seconds and last 1 second. The LCC station’s trigger angle drops to minimum limit angle 5°. The MMC station control switches to maximum modulation ratio control. The simulation diagrams are shown in Figure 6.

The DC side of the MMC port can detect that the DC current caused by the fault contains a double frequency component, so the MMC also immediately turns to maximum modulation ratio control. Under the influence of the strategy, the inverter-side voltage converter station corrects the voltage switching process is smooth, there is no risk of overcurrent and overvoltage inside the SM, and the DC reference value through maximum modulation ratio control module, and controls the inverter-side DC power. Besides, the maximum modulation ratio module helps the hybrid DC transmission system voltage drop on the rectifier station is also reduced, effectively improving the transmission of active power. The MMC station causes sub-module capacitors to charge, so the voltage on DC side rises. The simulation diagrams are shown in Figure 6.

4.2. AC fault Simulation on the Inverter Side
The two-phase short-circuit ground fault is set between phase B and C of the MMC station. The fault is set to start from 3 seconds and last one second. Since the DC side of the constant voltage station MMC1 cannot detect the negative sequence components generated, the control strategy will not change. The simulation diagrams are shown in Figure 7.

The amplitude of the AC voltage drops under fault, and active power output decreases. Because the negative sequence current caused by AC fault will not flow into the DC side. At this time, the MMC port cannot detect the double frequency component, so the control strategy will not switch. It can be known from the simulation results that the imbalance between the input power and the output power of MMC station causes causes sub-module capacitors to charge, so the voltage on DC side rises. The capacitors discharge after fault, the voltage decreases, and system resumes normal operation.

5. Conclusion
This paper designs three-terminal hybrid HVDC power transmission system of LCC-MMC, and
studies active power transmission drop caused by the asymmetric fault. Based on the existing AC side fault ride-through control strategies, a coordinated protection control strategy for the hybrid system is proposed. The minimum trigger angle of LCC and the maximum modulation ratio of MMC are adjusted for the real-time, so that the active power can still ensure effective transmission during a fault, and prevent power transmission interruption.

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