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Coordinated Control Strategy Research of Multi-terminal Cascaded Hybrid HVDC System

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Abstract. The multi-terminal cascaded hybrid HVDC system is proposed in recent years and it will be put into reality in near future. This paper investigates its control characteristics when MMCs are in master-slave strategy, and the coordinated control improving system stability is also proposed. It is found that the MMC inverter in constant DC voltage control would become a rectifier when fault happens. To solve such problem, the active power reference is immediately adjusted once the fault occurs, such that the DC side operation and AC side voltage stability can both be improved. Nevertheless, the proposed control strategy can also alleviate the large fluctuations in fault recovery process, so that the system can steadily return to original operation point. The simulation results in PSCAD/EMTDC verify the effectiveness of the proposed coordinated control strategy.

1. Introduction

The hybrid high voltage direct current (HVDC) transmission technology combines the advantages of line commutated converters (LCC) and modular multi-level converters (MMC), hence it is proposed in the past years and is expected to play an important role in future long-distance and large-capacity power transmission field [1]-[3].

In order to suppress commutation failure, reference [4]-[6] proposed a hybrid HVDC with LCC at rectifier side and MMC at inverter side, which can completely avoid commutation failure and improve transmission reliability. However, it does not have DC fault ride through ability, and the DC ground fault of overhead transmission line is inevitable, which greatly limits its development [7]-[8]. To solve this problem, unidirectional diodes can be connected in series at the DC outlet of inverter side while it will bring additional loss [9]. In addition, MMC based on full-bridge submodule (FBSM) and clamping dual submodule (CDSM) can be used to suppress fault current [10]-[11]. But a large number of fully controlled power electronic devices are required, and the construction cost is extremely high. Therefore, the cascaded hybrid HVDC with LCC at rectifier side and LCC and MMC in series at inverter side is proposed [12]-[14]. Compared with other hybrid HVDC, the proposed topology only adopts MMCs at the low-end of inverter side, which greatly reduces the construction cost. Due to the single-phase continuity of LCC, there is no fault current at inverter side, so the cascaded hybrid HVDC has excellent DC fault ride through capability without additional loss and cost. Meanwhile, MMCs can improve the voltage stability of AC side and reduce commutation failures of LCC inverters. And even if the commutation failure happens, the hybrid system can still transmit active power due to MMCs. Therefore, the cascaded hybrid HVDC with its unique advantages can be applied to high-voltage and large-capacity overhead line transmission.

Due to the power limitation of MMC inverters, several MMCs are connected in parallel to match the capacity of LCC and improve the transmission capacity of the whole system. The receiving end of this hybrid HVDC can be decentralized and connected to different AC power grid, forming a multi-terminal structure that can meet the power demand of different load centers. Meanwhile, the flexibility and reliability can be highly increased both in the preliminary construction stage and the later operation procedure. Because the control of MMC is very flexible, the control mode of each MMC has different choices and has a variety of combinations. Reference [15] studied the control mode and the form of access to the receiving-end AC system, and analysed the steady-state and fault characteristics, but it did not investigate the corresponding control strategy. Reference [16] proposed a control strategy of the cascaded hybrid HVDC during DC fault, which can alleviate the over-current, but the control strategy is only effective for DC fault. At present, there is few researches on fault characteristics and the corresponding control strategies of the cascaded hybrid HVDC. In particular, MMC in master-slave control may have power reverse transmission when the grounding fault happens, and the current imbalance may occur between parallel-connected MMCs and even lead to overcurrent in serious cases [17]. Therefore, it is of great significance to study control characteristics and coordinated control strategies of the multi-terminal cascaded hybrid HVDC.

Based on the basic control strategies, this paper analyses the control characteristics of cascaded hybrid HVDC, and also investigates the coordinated control strategy to avoid power reverse transmission and improve the DC side operation and AC side voltage stability. The organization of this paper is as follows. Section II introduces the topology and basic control strategies of the cascaded hybrid HVDC. Section III analyses the control characteristics when MMCs are in master-slave strategy. Section IV designs the coordinated control strategy. Section V validates the theoretical analysis by simulations. Finally, Section VI concludes the paper.

2. The multi-terminal cascaded hybrid HVDC system

2.1. The structure of hybrid HVDC

As Figure1 shows, the hybrid HVDC with cascaded multi-infeed MMC inverters has one LCC inverter and three MMC inverters, which has been planned to construct in China. It can be seen that the rated power and voltage of the hybrid HVDC are 4000 MW and 800 kV, where three 400 kV/667 MW MMC inverters are in series with a 2000 MW LCC. The MMCs are all half-bridge inverters and infeeding into different AC areas, which are connected through varied distances. The distance between AC systems at inverter side is far and the electrical connection is weak.

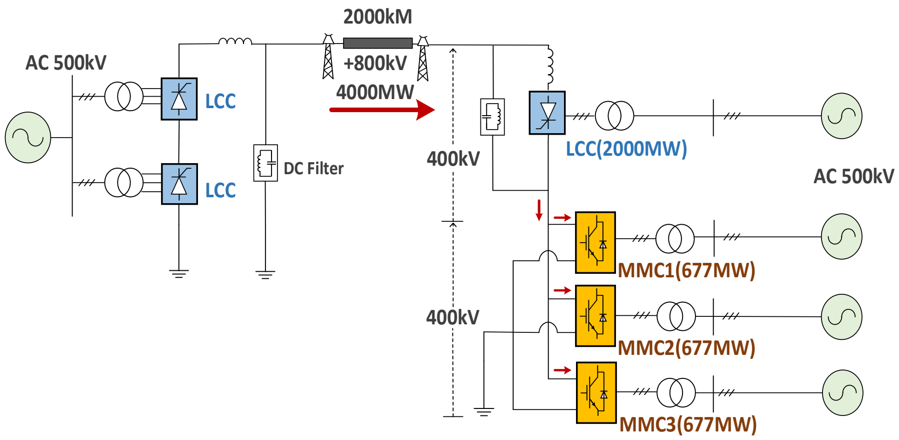


Figure 1. The cascaded hybrid HVDC system.

2.2. The basic control strategies

The control strategies of LCC are all classical control modes. LCC rectifiers adopt constant current control (CC), and the constant ignition angle control (CIA) is configured as standby control. LCC inverters adopt constant voltage control (CV), and configures constant extinction angle control (CEA) and constant current control as standby control. In addition, both sides are equipped with voltage dependent current order limit control (VDCOL).

As for the control strategies of the three MMC inverters, the cascaded MMC is designed in master-slave control, namely MMC1 controls the DC voltage while MMC2 and MMC3 control their active power. And the reactive power controls are all set in constant reactive power control.

Thus, the complete UI characteristic of the hybrid HVDC can be obtained, which is shown in Figure 2. The complete rectifier and inverter UI curves are the blue lines and yellow lines respectively as shown in the left side coordinates of Figure 2.

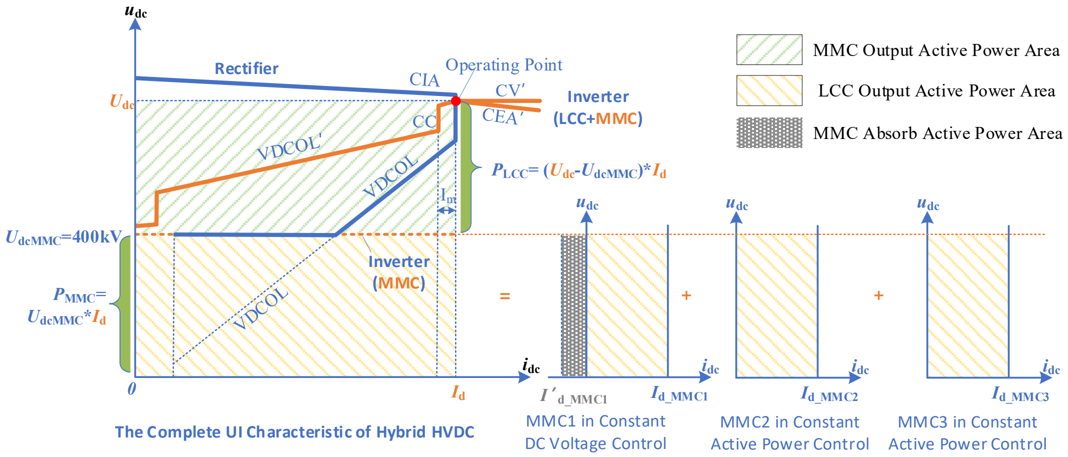


Figure 2. The complete UI curves of cascaded hybrid HVDC.

3. Control characteristics of master-slave strategy

Based on the obtained UI curves, the control characteristics when MMCs are in master-slave strategy is discussed in this section. As for the distribution characteristic between MMC inverters, the master-slave control strategy makes the MMC inverters in constant active power control have fixed outputs, while the MMC inverter in constant DC voltage control acts the role of a balance node. And MMC1 is

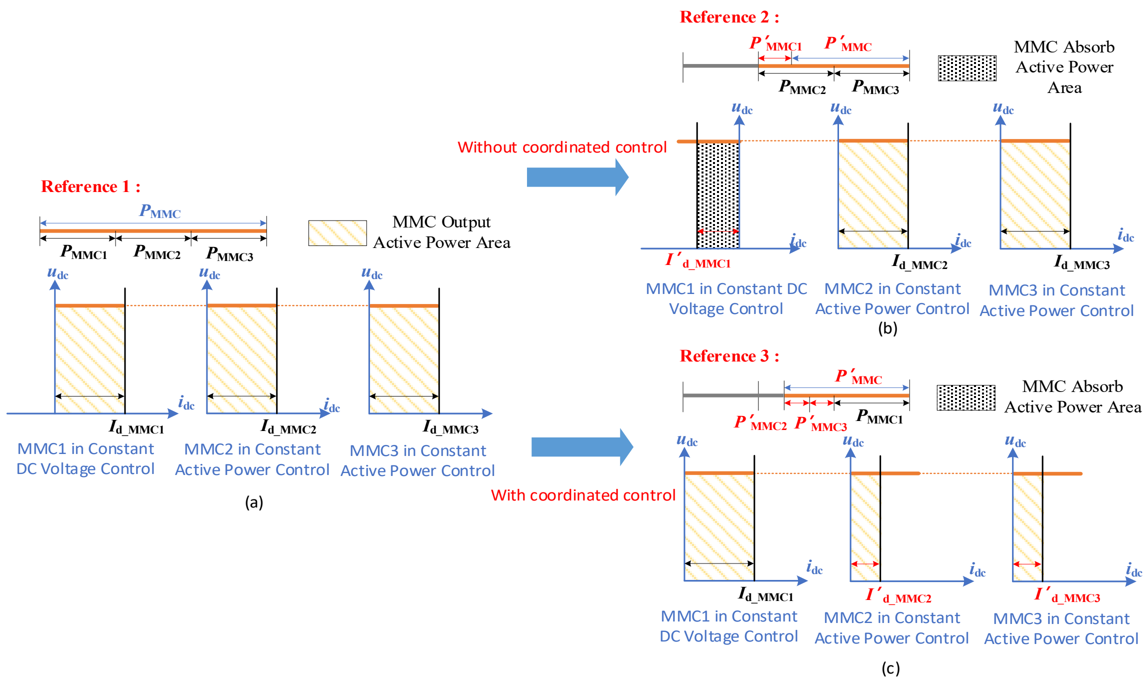


Figure 3. Control characteristics when MMCs are in master-slave strategy.

possible to become a rectifier as the total power of three MMCs is actually decided by the orders from LCC rectifiers and MMC inverters in constant active power control. As Figure 3 (a) and (b) shows, actually, when the order from LCC rectifiers suddenly decreases due to AC/DC faults, the total output active power of MMCs is decreased to P'_{MMC}. And if the reference of MMC inverters in constant active power control still stays at a large value, the MMC in constant DC voltage control may absorb active power from AC system to satisfy the extra active power need of the other two MMCs, which decreases the stability of the connected AC systems. The sum of the three yellow square areas are the output active powers of three MMC inverters, where the black square area indicates the MMC1 are absorbing active power from AC system when it becomes a rectifier.

4. Coordinated control strategy of the hybrid HVDC

To avoid the problem mentioned above, a coordinated control strategy is proposed in this section. The transmission active power of DC line (P_{dc}) can be written as

$$P_{\mathrm{dc}} = P_{\mathrm{LCC}} + P_{\mathrm{MMC}} = P_{\mathrm{MMC1}} + P_{\mathrm{MMC2}} + P_{\mathrm{MMC3}} \tag{1}$$

Thus, when the fault happens, set active power reference of MMC2 and MMC3 to

$$P_{\mathrm{ref}}' = P_{\mathrm{MMC2}} = P_{\mathrm{MMC3}} = 0.5\times\left(P_{\mathrm{dc}} - P_{\mathrm{LCC}} - P_{\mathrm{sMMC1}}\right) \tag{2}$$

where P_{sMMC1} is the rated output active power of MMC1 and is fixed. P_{dc} and P_{LCC} are the measured values in real-time. It can be seen from equation (2) that the active power reference P'_{ref} is only decided by P_{dc} and P_{LCC}, and the power variation of parallel-connected MMCs is distributed to the MMCs in constant active power, which restricts the fluctuation of P_{MMC1}. Therefore, MMC inverters will not change to rectifiers and the power reverse transmission is prevented as shown in Figure 3 (c).

The block diagram of proposed coordinated control strategy is presented in Figure 4. P_{m} and P_{ref} are the controlled output active power of MMC and its reference; K_{p} and K_{i} are the outer loop PI parameters; i_{dref} is the active current output by the control and i_{dlim} is the limiter. P'_{ref} is obtained in real time from equation (2), and due to the capacity limitation of MMC, the limiter (0MW-1000MW) is set and the rate limiter limits the adjusting rate. When the hybrid system is in rated operation, *Ctrl*=0, and the active power references of MMC2 and MMC3 are the fixed value P_{ref}. When AC/DC fault occurs, *Ctrl*=1 after 2ms fault detection, and the active power references are changed to P'_{ref}. After the fault is cleared, the value of *Ctrl* is still equal to 1 until system returns to rated operation. (Since fault detection is not the content of this paper, the simulation is implemented by time delay.)

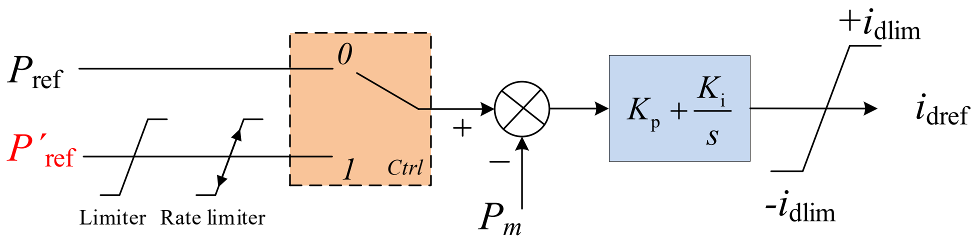


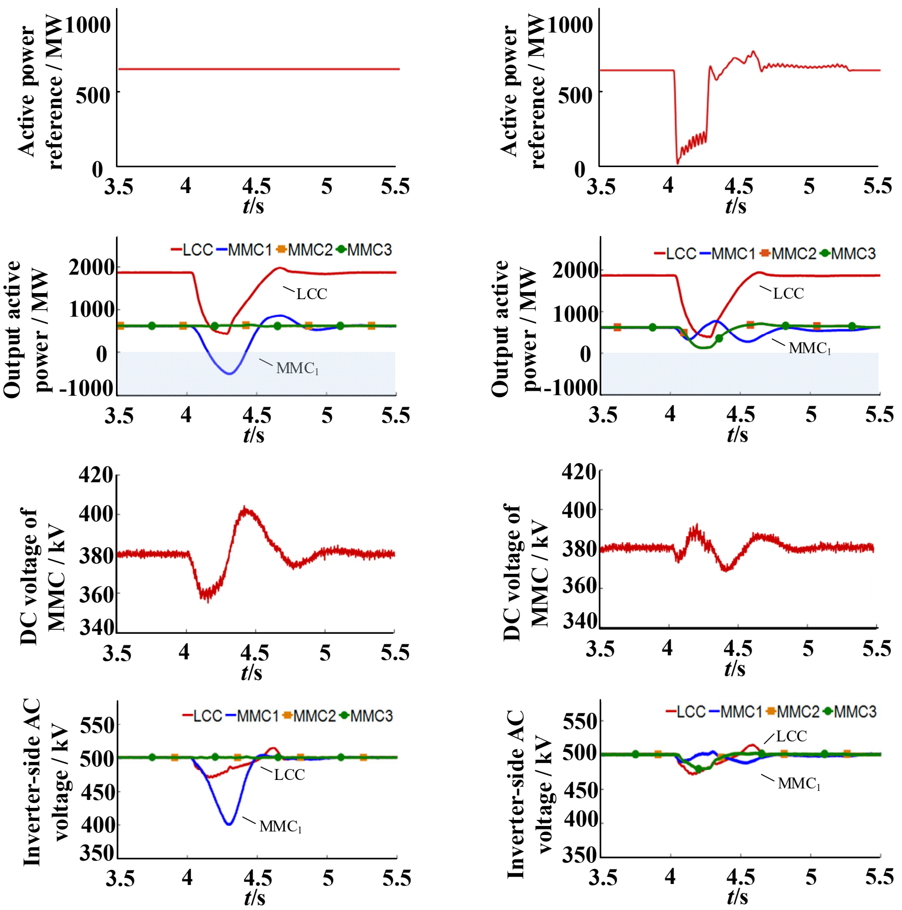
Figure 4. The coordinated control strategy of MMCs in constant active power control.

5. Simulation verifications

To verify proposed strategies, the simulations are implemented in PSCAD software, where the topology and rated parameters of hybrid HVDC for simulations are the same with the settings in Figure 1. The DC voltage reference of MMC1 is 400kV. Considering the loss, the output active power references (P_{ref}) of MMC2 and MMC3 are 620MW.

5.1. Rectifier-side short circuit fault

At 4s, a 0.1s single phase to ground fault happens at the rectifier-side AC system. The simulation results with and without coordinated control strategy are presented in Figure 5. When the fault happens, LCC rectifiers would change to CIA and LCC inverter also changed to CC and VDCOL control. Such that the current order from LCC rectifiers suddenly decreases, and the transmission power of the system is reduced. Without coordinated control, the references of MMC2 and MMC3 still stay at a large value, so MMC1 absorbs active power from AC system to satisfy the extra active power need of the other two MMCs, which decreases the stability of the connected AC systems. With coordinated control, the active power reference is changed to P'_{ref}, and MMC1 would not change to rectifier and the power reverse transmission is prevented. Meanwhile, the fluctuations of DC voltage and inverter-side AC voltage are significantly reduced, which improve the DC side operation and AC side voltage stability. After the fault is cleared, the hybrid system can return to rated operation steadily.



(a) Without coordinated control **(b) With coordinated control**

Figure 5. Response to rectifier-side short circuit fault.

5.2. Inverter-side short circuit fault

At 4s, a 0.1s single phase to ground fault happens at the inverter-side AC system of LCC. The simulation results with and without coordinated control strategy are presented in Figure 6. When the fault happens, the commutation failure occurs in the LCC inverter. Hence the control of LCC inverter will change to CEA mode, and the transmission power of the system is reduced. Without coordinated control, MMC1 becomes a rectifier and absorbs active power from AC system, resulting in large voltage fluctuations of the connected AC system. With coordinated control, MMC1 would not change to rectifier and the voltage fluctuations are significantly reduced, which improve the DC side operation and AC side voltage stability.

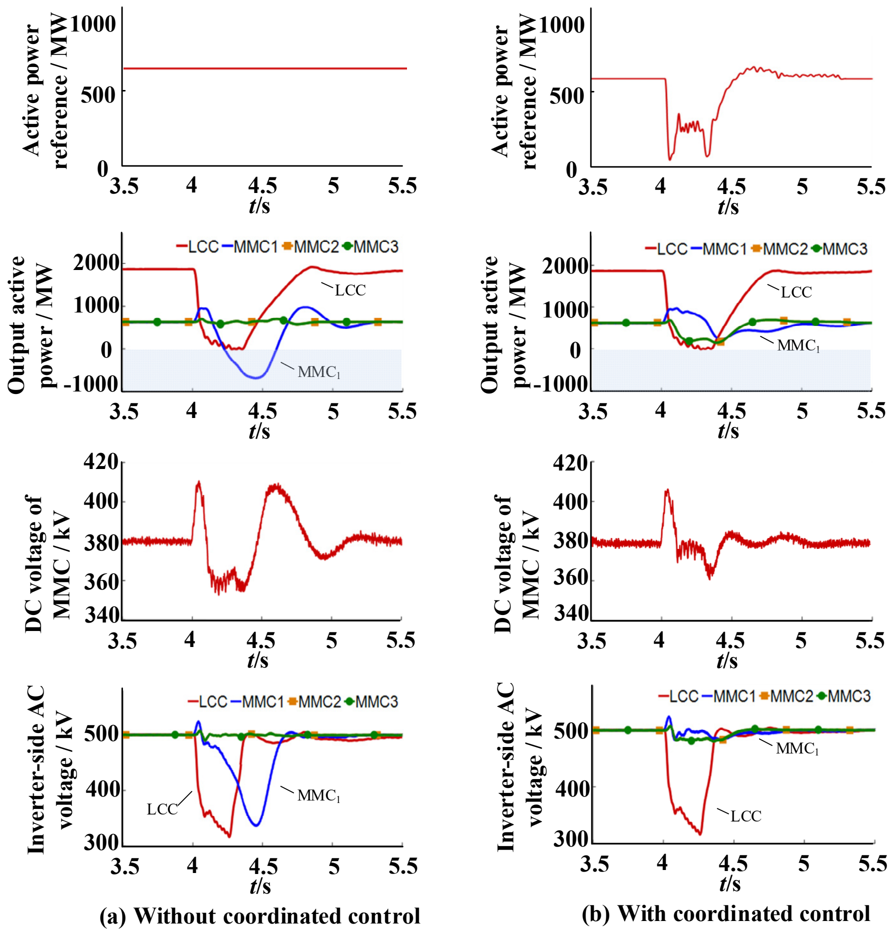


Figure 6. Response to inverter-side short circuit fault.

5.3. DC-side short circuit fault

At 4s, a 0.5s DC ground fault happens at the transmission line. The simulation results with and without coordinated control strategy are presented in Figure 7. Due to the reverse block of the thyristors of LCC inverters, MMCs will not discharge through the fault. Therefore, this hybrid HVDC has excellent DC fault ride through capability. Without coordinated control, the DC voltage of MMC fluctuates greatly, and MMC1 becomes a rectifier and absorbs active power from AC system. With coordinated control, the voltage fluctuations are significantly reduced, and MMC1 would not be in rectifier state for a long time.

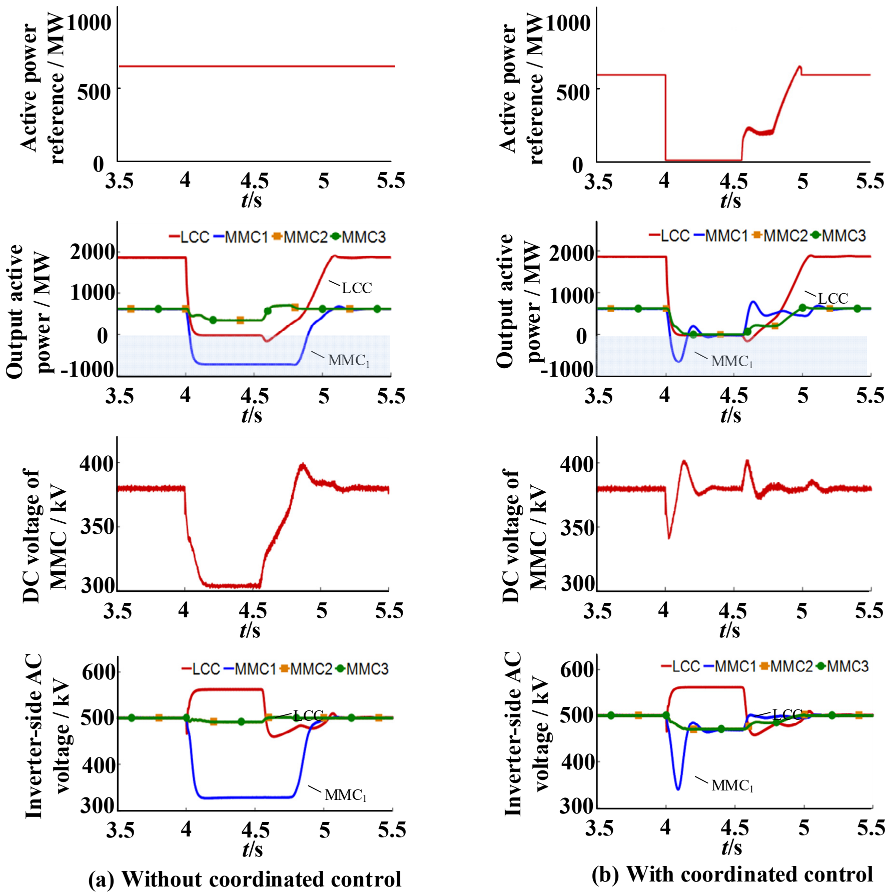


Figure 7. Response to DC-side short circuit fault.

6. Conclusions

This paper studies the coordinated control strategy of the multi-terminal cascaded hybrid HVDC. Based on the theoretical analysis and simulation results, following conclusions can be obtained.

- The proposed coordinated control strategy can prevent MMC inverters in constant DC voltage becoming rectifiers and avoid the power reverse transmission, which improves the DC side operation and AC side voltage stability.
- The proposed coordinated control strategy can achieve desired simulation results for AC/DC faults, such that the stability of the hybrid system is enhanced.
- The proposed coordinated control strategy can still alleviate large fluctuations in the fault recovery process, so that the system can steadily return to rated operation state.

Acknowledgments

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