Analysis of Fault Waveforms of Key Electrical Parameters in Hybrid Multi-terminal DC System

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Abstract. LCC-VSC hybrid multi-terminal HVDC system combines the advantages of traditional HVDC and flexible HVDC technology, and becomes one of the new directions of HVDC development. In this paper, taking the Baihetan Jiangsu HVDC transmission project as an example, under the appropriate simplified model, the critical electrical stresses of the DC side faults of a typical LCC-VSC hybrid multi-terminal DC system are analyzed. The simulation results verify the correctness of the simplified analysis in this paper.

1. Introduction

LCC-VSC hybrid multi-terminal DC system combines the advantages of traditional DC transmission and flexible DC transmission technology. Generally, LCC is used in rectifier side and VSC is used in inverter side[1]. According to different connection modes, hybrid multi-terminal DC technology can be divided into series type, parallel type and hybrid type, which has become one of the new directions of DC transmission development.

The hybrid cascaded multi-terminal DC transmission technology studied in this paper is a kind of hybrid multi-terminal DC transmission technology, which adopts LCC in rectifier side and LCC in inverter side in series with low-end VSC[2]. According to the capacity of VSC, the receiving end can be cascaded into multiple VSC drop points to the load center, and each drop point can support each other. This topology not only gives full play to the advantages of LCC which is suitable for long-distance transmission[3], solves the problems of commutation failure and dynamic reactive power support at inverter side, but also optimizes the structure of receiving end power grid through multiple landing points, so as to improve the reliability of DC receiving[4]. Compared with the inverter side full VSC scheme, this topology has the advantages of low loss, low investment, strong fault ride through capability, local fault isolation and controllable technical risk. Therefore, hybrid cascaded multi-terminal DC transmission technology can be used as a priority solution for multi infeed HVDC transmission[5]. With the increasing demand for large-scale renewable energy and the increasing problem of conventional multi infeed HVDC, hybrid cascaded multi-terminal HVDC technology is bound to play an important role in the field of HVDC in the future. The Baihetan–Jiangsu ±800kV DC transmission project will adopt this scheme for the first time.

The network topology and converter control of hybrid cascaded multi-terminal DC system are more complex, how to configure the DC and AC side protection, and whether the existing relay protection configuration methods and principles are applicable are the problems to be solved urgently.
2. Basic structure of the system

Take the Baihetan-Jiangsu HVDC transmission project as an example, a hybrid cascade multi terminal DC system model is built in PSCAD, as shown in Figure 1.

As the DC line protection involves traveling wave protection, the DC side line adopts a frequency-dependent parameter model, as shown in Figure 2. The AC line protection is a power frequency protection, so the π-type equivalent model can be used, and its parameters are shown in Figure 3.
3. Theoretical analysis

3.1. DC side voltage
After a unipolar grounding fault occurs on the positive line, the voltage at the LCC outlet of the sending and receiving ends quickly drops to zero. The three VSCs at the low end of the inverter side are connected in parallel, and one of them is controlled by a constant voltage. Therefore, the DC side voltage of the three VSCs can be basically kept stable, and is not affected by the failure of the DC line. For the high-end LCC, after the DC side fails, the voltage drops, and the DC side voltage drops accordingly. Since the inverter side LCC and three VSCs are connected in series, the sum of the two voltages is the inverter side voltage. As the inverter side voltage decays to 0, the high-end LCC voltage becomes the opposite of VSC, that is -400kV.

\[ U_{DC-MMCl} = U_{DC-MMC2} = U_{DC-MMC3} \]
\[ U_{DC-INV} = U_{DC-LCC} + U_{DC-MMCl} \] (1)

3.2. DC side current
After a unipolar ground fault occurs on the positive line, when the fault traveling wave propagates at the sending and receiving end LCC, the voltage at the outlet quickly drops to zero. Because there is no energy storage element in the LCC, and the thyristor has a strong ability to withstand overcurrent, the sending end converter valve will still conduct and commutate according to the established sequence. For the LCC on the rectifier side, a DC line failure is equivalent to a sudden change in the load on the DC side. At this time, the rectifier side will increase the AC side output, which will increase the fault current at the outlet of LCC1. After a period of time, it will be controlled by the low voltage current limiter. The local current will gradually stabilize to the set value of the low-voltage current-limiting control. The current at the exit of LCC2 on the inverter side will quickly drop to zero in a short time due to unidirectional conductivity. The impedance value of the parallel damping circuit of the thyristor is relatively large, which can basically block the current feeding from the receiving end to the fault point. However, during the flow-through period of the receiving end LCC2, no power is delivered to the MMC. In the three sets of MMCS, MMC1 is for constant voltage control, MMC2 and MMC3 are for constant power control, so MMC1 as a balance node will provide power support to MMC2 and MMC3. Therefore, the output of MMC1 will also increase in a short time, and the power direction will be reversed; therefore, the current direction of MMC1 will change and the amplitude will increase.

\[ I_{DC-LCC} = I_{DC-MMCl} + I_{DC-MMC2} + I_{DC-MMC3} \]
\[ I_{DC-REC} = I_{DC-INV} = I_{DC-LCC} \] (2)

3.3. Active power
After a single-pole grounding fault occurs on the positive line, the above analysis shows that the voltage at the LCC outlets of the sending and receiving ends quickly drops to zero, and the converter valve at the sending end will still conduct commutation according to the established sequence. For the rectifier side LCC1, the current at the outlet will gradually stabilize to the set value of the low-voltage current-limiting control. The current at the exit of LCC2 on the inverter side will quickly drop to zero in a short time due to unidirectional conductivity. Therefore, the power of the LCCs on both sides will gradually drop to zero after a fault. The total active power on the inverter side is the sum of the power of 1 LCC and 3 VSCs. As a balance node, MMC1 will provide power support to MMC2 and MMC3, so the power of MMC2 and MMC3 will not be affected too much.

\[ P_{DC-INV} = P_{DC-LCC} + P_{DC-MMCl} + P_{DC-MMC2} + P_{DC-MMC3} \]
\[ P_{DC-REC} = P_{DC-INV} + I_{DC-LCC}^2 R_{DC} \] (3)
3.4. AC side current and voltage

According to the above analysis, for the MMC with constant voltage control, the voltage remains stable, the power is reversed, and the output increases. Therefore, the DC side current is first reduced to 0, and then reversely increased to about twice the original value, so the AC side current is reduced first When it reaches 0, it is increased in the reverse direction to approximately twice the original value; the DC current of the two VSCs controlled by constant power maintains the original level after a short fluctuation, so the AC current maintains the original level after a short fluctuation.

4. Simulation

4.1. DC side voltage

The PSCAD simulation results are shown in Figure 4, where Vdc_rec and Vdc_inv are the DC voltages on the rectifier side and the inverter side, Vdc_inv_lcc is the DC voltage of the high-end LCC on the inverter side, and Vdc_mmc1, Vdc_mmc2, and Vdc_mmc3 are the low-end three on the inverter side. A DC voltage of VSC, of which MMC1 is a constant voltage control. The simulation results are consistent with the theoretical analysis results.

![Figure 4. DC side voltage waveform of each converter.](image)

4.2. DC side current

The PSCAD simulation results are shown in Figure 5, where Idc_rec and Idc_inv are the DC currents on the rectifier side and the inverter side respectively, Idc_inv_lcc is the DC current of the high-end LCC on the inverter side, and Idc_mmc1, Idc_mmc2, and Idc_mmc3 are the low-end three on the inverter side. DC current of a VSC. The simulation results are consistent with the theoretical analysis results.

![Figure 5 Simulation waveform of DC side current.](image)

4.3. Active power

The PSCAD simulation results are shown in Figure 6, where Pdc_rec and Pdc_inv are the active power of the rectifier side and the inverter side, Pdc_inv_lcc is the active power of the inverter side high-end LCC, Pdc_mmc1, Pdc_mmc2, and Pdc_mmc3 are the inverter side low-end three, respectively. The active power of a VSC. The simulation results are consistent with the theoretical analysis results.
4.4. AC side current and voltage
The PSCAD simulation result is shown in Figure 7, where Iac_mmc1, Iac_mmc2, and Iac_mmc3 are the currents on the AC side of MMC1, MMC2, and MMC3, respectively. Through the above analysis, it is known that all the VSC AC voltages remain unchanged, and the change envelope of the AC current remains consistent with the DC side.

The PSCAD simulation results are shown in Figure 8, where Vac_mmc1, Vac_mmc2, and Vac_mmc3 are the voltages on the AC side of MMC1, MMC2, and MMC3, respectively. The simulation results are consistent with the theoretical analysis results.

For the high-end LCC, after the DC side fails, the DC voltage is reversed to -1 times the original, and the DC current is cut off, so it is equivalent to disconnecting from the AC measurement. At this time, the AC measurement voltage is completely determined by the opposite infinity system. The circuit decays to zero.

The PSCAD simulation results are shown in Figure 9. The above figure is the simulation waveform of a single-phase ground fault, and the following figure is the simulation waveform of a three-phase ground fault. Iac_inv_lcc is the AC current of the high-end LCC on the inverter side, and Vac_inv_lcc is the inverter side. The AC voltage of the high-end LCC. The simulation results are consistent with the theoretical analysis results.
5. Conclusion
DC fault analysis is one of the key technologies for rapid and reliable identification and development of multi-terminal flexible DC systems. Taking advantage of the boundary characteristics of the multi-terminal flexible DC grid, this paper reasonably simplifies the multi-terminal flexible DC system. The advantages of this method mainly include: fast action speed, which can move quickly about 1ms after the fault; fault identification based on local information, no communication is required; strong resistance to transition resistance.
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