Research on Switching Overvoltage of MMC-MTDC System with Hybrid DC Circuit Breaker

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Abstract. The modular multilevel converter based multi-terminal HVDC (MMC-MTDC) system with hybrid DC breakers should consider the influence of the action of the DC breaker on the switching overvoltage, which puts higher requirements on the overvoltage protection of the system. Flexible DC demonstration project in Zhangbei will realize the first engineering application of hybrid DC circuit breaker. Based on this project, an overvoltage protection scheme for MMC-MTDC system is proposed. Firstly, this paper investigates the effect of the operation mode of the DC grid on the switching overvoltage level. Secondly, typical faults and the protection action sequence of various faults are analyzed in detail. The characteristics and laws of various switching overvoltage are deeply studied. Finally, the switching overvoltage of converter station is calculated on the basis of the control and protection system, and the recommended values of the insulation level of converter station equipment for the ±500kV MMC-MTDC system with hybrid DC circuit breaker are given.

1. Introduction
In recent years, the state continuously increases investment in clean and renewable energy such as wind power and solar energy. MMC-MTDC system can provide a power transmission platform for the interconnection and transmission of various new energy resources, so that the power grid structure can be appropriately adjusted to meet the requirements of the future energy pattern [1-2]. The Zhangbei project forms a ±500kV flexible DC grid through the ring overhead line. The failure probability of overhead line is higher than the DC cable line, so the hybrid DC circuit breaker is equipped at both ends of the overhead line to isolate the fault [3-5]. This new combination of flexible DC transmission lines and hybrid DC circuit breaker must be verified for overvoltage, and take the opportunity to promote key technology improvements and equipment innovations.

The fault mechanism of the converter station is studied in depth, and the key position of the converter station and the characteristics of switching overvoltage on the equipment are analyzed [6-8]. We use PSCAD to calculate the switching overvoltage level of faults at each electrical node of the converter station. Then we determine the protection level of the arrester according to the insulation margin, and finally get the recommended value for insulation level of each equipment [9-10].

2. Research model of MMC-MTDC transmission system
The Zhangbei demonstration project uses Kangbao, Fengning, Zhangbei and Beijing as access points, and the four ends are connected by overhead lines to form a parallel ring network structure. The
grounding mode is metallic return operation, and Beijing station serve as the grounding point of the DC system. Among them, Zhangbei and Kangbao are the new energy access stations, Fengning station is connected to the pumped storage groups, and Beijing station is used as the receiving end to absorb power. The flexible DC converter station uses MMC composed of half-bridge sub-modules. The main equipment parameters of converter station are shown in table 1.

In the field of high voltage and large capacity, DC transmission project generally adopts a symmetrical bipolar structure to improve its reliability. We built a simulation model of a four-terminal true bipolar flexible DC overhead transmission system with hybrid high-voltage DC circuit breakers in PSCAD. The four-terminal flexible grid topology is shown in figure 1. Taking Beijing station as an example, figure 2 shows a typical structure diagram of flexible DC converter station.

| Equipment                        | Beijing | Fengning | Kangbao | Zhangbei |
|----------------------------------|---------|----------|---------|----------|
| Sub-module capacitance (mF)      | 15      | 8        | 8       | 15       |
| Number of sub-modules            | 244     | 244      | 244     | 244      |
| IGBT parameter                   | 4.5kV/3kA | 4.5kV/2kA | 4.5kV/2kA | 4.5kV/3kA |
| Converter station capacity (MW)  | 3000    | 1500     | 1500    | 3000     |
| Bridge arm reactor (mH)          | 75      | 100      | 100     | 75       |
| Polar reactor (mH)               | 150     | 150      | 150     | 150      |
| Neutral wire reactor (mH)        | 300     | 300      | 300     | 300      |

Figure 1. Four-terminal flexible grid topology.  
Figure 2. Typical structure diagram of converter station.

3. Influencing factors of switching overvoltage in MMC-MTDC

3.1. The influence of main wiring mode on switching overvoltage

There are two main wiring modes for MMC-MTDC system, bipolar wiring and monopolar metallic return wiring. Under these two main wiring modes, the overvoltage levels of the electrical nodes in converter station may be significantly different. In order to verify the influence of the main wiring mode on switching overvoltage, we simulate various faults by taking Zhangbei station as an example. The fault points are set at the positive pole of the converter station, and each converter station operates at rated power. The results are shown in table 2.

| Electrical nodes of Zhangbei station | Top of valve grounding | reactor side of breaker grounding | Line side of current limiting reactor grounding |
|-------------------------------------|------------------------|---------------------------------|-----------------------------------------------|
| Bipolar                             | Monopolar              | Bipolar                         | Monopolar                                    |
Under the operation of the symmetrical bipolar structure, the switching overvoltage level of the DC side is relatively high. In the case of ground fault at top of valve, the maximum difference of voltage at top of valve between the two modes reaches 1.53 pu, so the calculation of overvoltage level in the DC side is performed in this way. For the monopolar metal return operation mode, the switching overvoltage level on the metallic return and bottom of valve is relatively high, and the voltage difference is 0.06 pu, so switching overvoltage level on the metallic return is calculated in this way.

### 3.2. The influence of power command value on switching overvoltage

Fengning station adopts constant voltage control mode. When the DC voltage of Fengning station changes beyond the dead zone of converter station, other converter stations switch from the fixed DC power control mode to the DC voltage slope control mode. The control principle is shown in figure 3. It can be seen that the slope control coefficient $k$ is related to the power command value $P_{dc}$.

![Figure 3. The control principle of MMC-MTDC system.](image)

Taking the DC bus pole-to-ground fault in Beijing station as an example, different power command values are set to simulate and explore the influence of power command value on switching overvoltage. The overvoltage level statistics in the converter station are shown in table 3.

Through a large number of calculations, it can be found that when the power command value of Beijing station is gradually increased from 300MW to 3000MW, the overvoltage of the grid side of converter transformer, the top of valve and the DC line is gradually increased, and the voltage level of the valve side of converter transformer and bridge arm reactor, the bottom of valve, and metallic return line is gradually reduced. Among them, the maximum variation range of the AC side overvoltage amplitude is 0.05 pu, and of the DC side is 0.08 pu. Therefore, the two steady-state modes of operation, heavy load flow mode and light load flow mode, should be considered comprehensively when calculating the switching overvoltage of the converter station. The power of each converter station in light load flow mode is 10% of the rated value.

### Table 3. The main equipment parameters of converter station.

| Power command value (MW) | Converter transformer | Top of valve (kV) | Reactor side of breaker (kV) | Bottom of valve (kV) | Metallic return (kV) |
|--------------------------|-----------------------|------------------|-----------------------------|---------------------|---------------------|
|                          | Grid side (kV) | Valve side (kV) |                             |                     |                     |
| 300                      | 427.2            | 448.2            | 741.8                       | 884.0               | 430.5               | 179.0               |
| 1000                     | 427.8            | 444.7            | 742.6                       | 892.2               | 426.6               | 178.7               |
| 2000                     | 428.4            | 437.8            | 743.9                       | 908.5               | 422.1               | 178.6               |
| 3000                     | 428.9            | 424.8            | 745.0                       | 921.9               | 416.4               | 178.5               |
4. Switching overvoltage and equipment insulation level of Zhangbei demonstration project

4.1. Typical fault of MMC-MTDC system

4.1.1. The DC side fault. The DC side fault mainly considers the line-to-ground fault of both transmission line side and valve side of current limiting reactor.

When these two kinds of faults occur, the line overcurrent protection causes the DC circuit breakers on both sides of the line to operate to cut off the line where the fault point is located, and the auto-reclosing of the circuit breaker is performed after the deionization time which is 300ms. Due to the ring network connection mode of the four-terminal converter station, the power can be diverted to the same-pole line after one DC line is cut off, and the power transmission of the four converter stations will not be affected. The ground fault and reclosing process on the DC side will also generate a transfer overvoltage on the adjacent DC line. The DC side switching overvoltage level should be determined by the overvoltage of itself and the adjacent converter station.

![Figure 4. The DC voltage, current of Kangbao station.](image)

Taking Kangbao Station as an example, we analyze the DC overvoltage during the ground fault on the line side of the current limiting reactor. The simulation set the fault occurred at 0.200s, and the fault is permanent ground fault of the positive line in Kangbao station (Kangbao-Fengning side). The DC circuit breaker at both ends of Kangbao-Fengning line opened and remove the faulty line at 2.006s, and the DC circuit breaker was reclosed at 0.506s. Then, at 0.512s, the two breakers operate again to cut off the faulty line. The DC voltage, current of Kangbao station the in this process is shown in figure 4(a) and figure 4(b). Before the fault is removed, the DC current flows along the Kangbao-Fengning line to the fault point. The sub-module continues to be normally put in and cut off, the capacitor voltage drops, and the DC voltage drops. After the fault is removed, the converter station resumes normal operation, the DC current and DC voltage are gradually restored. Then the power delivered by the Kangbao station will be transmitted by the Kangbao-Zhangbei line, and the power of the converter station will gradually return to normal.

|              | Beijing station | Fengning station | Kangbao station | Zhangbei station |
|--------------|-----------------|-----------------|-----------------|-----------------|
| Fengning side (kV) | 807.3           | 816.4           | 821.2           | 817.5           |
| Zhangbei side (kV) | 819.3           | 817.7           |                 | 823.7           |
| Kangbao side (kV) | 826.6           |                 |                 |                 |

As shown in table 4, the DC bus overvoltage level after the ground fault at the head of the DC line is compared and analysed. When converter stations are operating at rated power, the Zhangbei-Kangbao line and the Fengning-Zhangbei line exist as tie lines, where the transmitted power is small. For the same converter station, the switching overvoltage after the tie line is cut off due to the fault is smaller than the other line.
4.1.2. The AC side fault. The AC side fault mainly considers the metallic ground fault of grid side and valve side of the converter transformer. The metallic ground fault includes single-phase ground fault, two-phase short circuit, two-phase ground fault, and three-phase ground fault.

![Figure 5](image1)

Figure 5. The comparison of four kinds of metallic ground fault.

After such a fault occurs, a large transient overvoltage will be generated on the AC side and the DC side, so the control system should immediately block the converter valve and operate the AC/DC breaker. Figure 5 shows the overvoltage comparison of four metallic ground faults at Kangbao Station and Beijing Station. The comparison of grid side faults is shown in figure 5(a) and 5(b), and valve side faults is shown in figure 5(c) and 5(d). Among them, Kangbao station represents an indirectly grounded converter station, and Beijing station represents a directly grounded converter station. For grid side fault, the overvoltage level of the ungrounded station is higher when two-phase ground fault is higher, and the overvoltage level of the grounded station when asymmetric fault and two-phase short circuit occur. For valve side fault, single-phase ground fault of ungrounded station are more serious, and the overvoltage level of grounded station is higher when single-phase and three-phase ground fault occur.

4.2. Switching overvoltage, SIPL and SIWL of apparatus in converter station

Considering the control protection system and various operation modes, the switching overvoltage simulation is performed on various faults of the four-terminal MMC-HVDC transmission system.

![Figure 6](image2)

Figure 6. The overvoltage level of stations when Fengning station faulted.

![Figure 7](image3)

Figure 7. The switching overvoltage comparison of four stations.
Table 5. Switching overvoltage, SIPL and SIWL of the ±500kV MMC-MTDC system.

| Electrical node        | Switching overvoltage | Insulation margin coefficient | SIPL (kV) | SIWL (kV) |
|------------------------|-----------------------|-------------------------------|-----------|-----------|
|                        | Actual value (kV)     | P.U. value                    |           |           |
| 220kV AC bus           | 446                   | 2.4                           | 1.20      | 452       | 543       |
| 500kV AC bus           | 802                   | 1.6                           | 1.20      | 852       | 1022      |
| Valve side of transformer | 909               | 1.8                           | 1.15      | 936       | 1080      |
| Valve side of arm reactor | 946              | 1.9                           | 1.15      | 948       | 1090      |
| Top of valve           | 946                   | 1.9                           | 1.20      | 948       | 1138      |
| DC transmission line   | 867                   | 1.7                           | 1.20      | 936       | 1125      |
| Bottom of valve        | 588                   | 1.2                           | 1.15      | 588       | 678       |
| Metallic return        | 418                   | 0.8                           | 1.15      | 418       | 482       |

Figure 6 shows the overvoltage level of four stations when Fengning station faulted. The switching overvoltage level of the faulty converter station is higher than that of the non-faulty converter station. Figure 7 shows the maximum overvoltage of various electrical nodes is distributed in Zhangbei station and Beijing station. Therefore, it is possible to determine the insulation level of the equipment only by considering the switching overvoltage level of high power converter station.

According to the calculation result of the switching overvoltage, and referring to the relevant international standards and national standards for the requirements of the insulation margin coefficient of conventional DC transmission project, the switching impulse protection level (SIPL) and the switching impulse withstand level (SIWL) of converter station equipment of the ±500kV Zhangbei four-terminal MMC-HVDC are shown in Table 5.

5. Conclusions
Based on the ±500kV Zhangbei four-terminal MMC-HVDC demonstration project, the key factors affecting the switching overvoltage of MMC-MTDC system are studied. The different main wiring mode will affect the switching overvoltage. Therefore, the symmetrical bipolar structure operation mode and monopolar metal return operation mode should be considered comprehensively. Secondly, the power command value will also affect it, and the overvoltage of each key position of the converter station will change monotonously with the increase of the power command value.

The typical faults and protection action sequence of converter station are given, and the characteristics and laws of various switching overvoltage are obtained. Finally, the switching overvoltage level of the MMC-MTDC system are summarized so that the insulation coordination research of converter station are given. Based on this, the insulation level of each equipment of the four-terminal converter station is determined. These research results directly provide an important basis for the selection, manufacture and testing of the engineering equipment, and can also provide reference for the research of insulation coordination of converter stations for MMT-MTDC projects equipped with hybrid DC circuit breakers.

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