Modeling and Analysis of Short-Circuit Fault Current for MMC-HVDC Grid with DC Circuit Breaker

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Abstract. DC line fault is one of the important factors restricting the development of flexible DC system. DC circuit breaker is an effective means to realize the short circuit fault isolation on DC side of flexible DC system. Therefore, it is necessary to add DCCB into the short-circuit current calculation and modeling of MMC-HVDC power grid for comprehensive analysis. Firstly, the external characteristics of the hybrid HVDC circuit breaker and the modular multilevel converter (MMC) are modelled. Then, the modeling of short-circuit fault current in different stages was analysed. The analysis method of short circuit fault current of four-terminal MMC system with DC circuit breaker is obtained. Finally, the simulation results and the calculation results are compared and results show the effectiveness of the short-circuit calculation method proposed by this paper.

1. Introduction

The flexible DC grid technology based on the modular multilevel converter (MMC) has a broad application prospect in large-scale new energy grid-connection and long-distance transmission. However, due to the relatively low damping of the DC system, the fault development of the DC system is faster and the control and protection is more difficult compared with the AC system. At present, the effective method is mainly to install a DC circuit breaker to quickly cut off the fault current and take the fault part out of operation to avoid large-scale outages of the converter and ensure the safe and stable operation of the system[1-3].

The analysis and calculation of short-circuit fault current is of great significance to the selection and configuration of system parameters, especially DC circuit breaker parameters. Recently, the research on the short-circuit fault currents calculation and analysis in flexible DC systems is mainly focused on the two-end flexible systems. There are few study about short-circuit fault current of multi terminal flexible DC system that takes the external characteristics of DC circuit breakers into account in the multi-terminal DC systems. In the reference[4], although the analytical formula of fault current of MMC-HVDC grid system is reasonably simplified and the approximate computational method of fault current is obtained, the effect of DC circuit breaker is not considered in the simplified analysis process. Reference [5] deduces the analytical formula of the multi-terminal MMC pole to pole fault current...
calculation method, and the simplified MMC model under fault condition is provided. However, the simplification and calculation of DCCB mathematical model are not given.

For the purpose of solving the above problems to propose a short-circuit modeling and calculation method for multi-terminal flexible DC system considering hybrid DC circuit breaker. Firstly, the mathematical model of a four-terminal MMC-HVDC system with DC circuit breaker is established, and then the equivalent models of the DCCB under different time sequences are analyzed. Finally, the effectiveness of the fault current calculation algorithm is verified by comparing the transient simulation and theoretical calculation results.

2. Equivalent circuit of the four-terminal biple MMC DC System with DC circuit breaker

2.1. Simplified model of cascade full bridge hybrid DCCB

State Grid Corporation of China has proposed a cascaded full bridge hybrid DCCB [6]. This solution makes it easier to achieve voltage sharing among modules, and to drive IGBT synchronous by replacing the IGBT module series with a sub-module of full bridge cascade structure. Therefore, in this paper, the DC circuit breaker topology is taken as an example for fault circuit calculation and analysis of the multi-terminal MMC-HVDC system. It is also applicable to other hybrid DC circuit breakers alike. Fig. 1a and 1b are the structure and corresponding breaking waveforms of cascaded full bridge hybrid DCCB. The detailed breaking principle of the DC circuit breaker can be found in the reference [7].

![Figure 1. (a) Configuration of cascade full bridge hybrid DCCB; (b) Waveforms of breaking process.](image)

According to the chapter one in [7], in Figure 1b, at t₀–t₁ time, the DCCB can be equivalent to the impedance. At t₁–t₂ time, the DCCB can be equivalent to the capacitor. At t₂–t₃ time, the DCCB can be equivalent to the DC voltage source.

2.2. Equivalent circuit of the four-terminal MMC DC Grid with DCCB

The structure of the four-terminal bipole MMC DC grid with DCCB is shown in Figure 2a. The four-terminal DC grid consists of two rectifier stations and two inverter stations. The DC side is the bipole configuration. Each end of the line is equipped with a DC circuit breaker. The equivalent circuit of the MMC converter station is referred to [5]. Therefore, the four-terminal biple MMC DC grid with DCCB can be equivalent to the circuit shown in Figure 2b.

In Figure 2 (b), the four-terminal ring network MMC equivalent circuit can be divided into positive layer (RL circuit of the top quadrilateral A₁A₂A₃A₄), negative layer (RL circuit of the bottom quadrilateral B₁B₂B₃B₄) and converter station circuit (vertical RLC circuit). Wherein, A₁A₂A₃A₄ corresponds to the positive pole of MMC1-MMC4 in Figure 2 (a), and B₁B₂B₃B₄ corresponds to the negative pole of MMC1-MMC4. Suppose that the pole-to-pole short circuit fault occurs at A₁ between A₁ and A₂ converter, the A₁A₂ branch is divided into two parts. At this time, the circuit breaker has not yet operated, and the equivalent circuit of the system pole-to-pole fault is shown in Figure 2b.
3. Modeling and analysis of the four-terminal MMC DC grid with DCCB under bipolar short circuit fault

3.1. Modeling of the four-terminal MMC DC grid with DCCB under bipolar short circuit fault

When a pole-to-pole short-circuit fault occurs at the DC line, assuming that the DC grid detects fault and sends breaking command to the DCCBs on both ends of the fault line simultaneously. Obviously, the action sequence of the two DC circuit breakers on positive and negative lines close to the same converter is consistent. However, due to the different direction of short-circuit current and the difference of line impedance, the breaking sequence of DCCBs at both ends of the fault line is not completely consistent. Taking the DC circuit breakers between A1A2 line and B1B2 line as an example, shown in Figure 2b, the equivalent circuit of DCCBs can be theoretically divided into the following 8 types (CB1 is the circuit breaker near MMC1, and CB2 is the circuit breaker near the MMC2), as shown in Table 1.

Table 1. Equivalent circuit diagram of DCCB under different working conditions.

| Serial Number | For Short | Equivalent Circuit Diagram of DCCB | Serial Number | For Short | Equivalent Circuit Diagram of DCCB |
|---------------|----------|-----------------------------------|---------------|----------|-----------------------------------|
| 1             | 2O       | ![Diagram](#)                      | 2             | 1C1O     | ![Diagram](#)                      |
| 3             | 2C       | ![Diagram](#)                      | 4             | 1S1C     | ![Diagram](#)                      |
| 5             | 2S       | ![Diagram](#)                      | 6             | 1S1O     | ![Diagram](#)                      |
3.2. Analysis of the four-terminal MMC DC grid with DCCB under bipolar short circuit fault

In order to better calculate the short-circuit fault current, it is necessary to analyze the circuit breaker stage transition conditions to determine all stages of the fault breaking process.

In the normal operation of the four-terminal MMC DC grid, the equivalent circuit of each DC line is in the stage of 2O. As mentioned in Section 3.1, the DC breaker begin to break at the same time after receiving the breaking command when the fault occurs. At this time, the equivalent circuit of DCCB is 2C.

Assuming that the current direction of line A1A2 in the normal operation of the four-terminal flexible DC system is from A1 to A2, the initial value of the circuit breakers at both ends meets $i_{1s0} = -i_{2s0}$. Therefore, when the pole-to-pole short circuit fault occurs at A5, $i_{1s}$ will increase at a rate of $\frac{di_{1s}}{dt}$, while $i_{2s}$ will decreases firstly and then increases at a rate of $\frac{di_{2s}}{dt}$ in the opposite direction. If the fault point is closer to CB1, the impedance of the line where CB1 is located is smaller than the impedance of the line where CB2 is located, and the current change rate of the two lines meets $\frac{di_{1s}}{dt} > \frac{di_{2s}}{dt}$. Therefore, in this case, CB1 must transform from stage O to stage C before CB2. At this time, the equivalent circuit of DCCB is 1S1C. When the capacitance of the CB2 sub-module reaches the clamping voltage of MOV, the current of two DCCBs both work in the energy absorption branch, and the equivalent circuit of DCCB is 2S. Compared with CB2, CB1 takes the lead in the stage of equivalent DC source, and then completes the breaking of the fault current earlier. At this time, the equivalent circuit of DCCB is 1B1S. With the fault breaking of DCCBs at both ends, the fault isolation of the A1A2 line is finally realized. At this time, the equivalent circuit of the four-terminal system after the fault has gone through five stages: 2O-2C-1S1C-2S-1B1S, as shown in Figure 3a.

Assume that the distance between A1A2 is long enough, and the location of the fault point is far enough from CB1, so that $\frac{di_{2s}}{dt}$ is far greater than $\frac{di_{1s}}{dt}$, then there must be a length range on the line that meets the following condition, which is that, the charging voltage of the DCCB capacitor at both ends reaches the clamping voltage of MOV at the same time after the fault occurs. Therefore, when the fault point occurs between the above-mentioned position and the location of CB2, the equivalent circuit of the four-terminal system goes through 2O-2C-1S1C-2S-1B1S and 2O-1C1B-1S1B. When the fault point occurs at the above-mentioned position, the equivalent circuit of the four-terminal system goes through 2O-2C-2S-2B. On
In addition, we can find that when a short-circuit fault occurs on the line, there will be a current zero crossing between the $i_{15}$ and $i_{25}$. Assume that the time from fault occurrence to the current zero crossing is $T_0$. When the fault detection time is less than $T_0$, the DC circuit breaker can open the UFD directly at the zero crossing to break the fault current like the AC circuit breaker. In this condition, the breaking process of the circuit breakers at both ends is: 2O-1C1B-1S1B, as shown in Figure 3d. Therefore, it is necessary to increase the speed of fault detection as much as possible to provide greater operating space for DCCB to directly isolate faults at zero crossing.

4. Validations

4.1. Parameters of the four-terminal DC grid simulation system

The four-terminal pole-to-pole MMC grid system with DCCB shown in Figure 2a is modelled on Matlab/Simulink. The system parameters are shown in Table 2, including the MMC converter and the DC circuit breaker. The parameters of each converters are the same, as well as the DC circuit breakers.

Table 2. Parameters of the four-terminal DC grid system.

| Parameter                      | Value   |
|--------------------------------|---------|
| AC voltage $U_{ac}$            | 525 kV  |
| DC voltage $U_{dc}$            | ±500 kV |
| Fundamental frequency $f$      | 50 Hz   |
| Three winding transformer and wiring mode | 525/66/250; $Y\triangle$ |
| Arm inductor $L_x$             | 75 mH   |
| The capacitor of submodular $C$| 8000 μF |
| Arm resistance $R_x$           | 0.147 Ω |
| Number of submodular $N$       | 220     |
| Limiting current inductor $L_m$| 300 mH  |
| sub module capacitors $C_{cb}$ | 50μF    |
| Clamping voltage $V_{mov}$     | 800 kV  |

4.2. Verification of DCCB stage transition conditions

In order to verify the correctness of the mathematical model of the equivalent circuit of the four-terminal DC system, the analytical solution curve of $i_{15}$ and $i_{25}$ under different fault is compared with the simulation curve. According to the parameters in Table 2 and the system fault differential equation in Section 3 of reference [7], the analytical solution curve of $i_{15}$ and $i_{25}$ under fault is obtained. In this example, the fault point is set near the outlet of CB2. $L_{15}$ and $R_{15}$ are all line impedances, and $R_{25}$ and $L_{25}$ are zero. Therefore, the different equivalent circuit stages of the four-terminal DC system can be obtained only by changing the A1A2 line length. Figure 4 shows the calculation results of the fault current of different equivalent circuits obtained at different A1A2 line lengths. In each of the pictures in Figure 4, $i_{15\text{calc}}$ and $i_{25\text{calc}}$ are the calculation results, and $i_{15\text{sim}}$ and $i_{25\text{sim}}$ are the simulation results.
It can be seen that the dc fault currents obtained from the Simulink and calculation are almost consistent before the fault current begins to decline. There is a certain gap between the calculation results and the simulation results in the process of current drop, because the MOV in the Simulink is a nonlinear model while the calculation process is simplified to the DC voltage source model. The difference of MOV equivalence does not affect the blocking time and the maximum value of fault current. Similarly, the subsequent breaker parameter configuration and the selection of system protection setting value will not be affected.

Figure 5 shows the calculation results of the fault current when pole-to-pole fault occurs at the outlet of the CB1 under zero-crossing breaking strategy and normal strategy. Assuming that CB2 received breaking command before the crossing zero time and opens the mechanical switch at the zero-crossing time. It can be seen that the value of $i_{25b}$ no longer rises at zero-crossing point. $i_{25a}$ is the current under normal breaking strategy. Obviously, the fault breaking time of the former strategy is faster than that of the latter, and the system components avoid to bear peak voltage and current.

5. Conclusions
In this paper, an analysis method for calculating the fault current of a multi-terminal DC grid with DCCBs. According to the external characteristics of different transfer branches of hybrid high-voltage DC circuit breakers, equivalent models of each transfer branch are derived. For the MMC four-terminal DC transmission system, the equivalent mathematical model of the system under fault is given. Combined with the equivalent models of different branches of DC circuit breakers, the equivalent model
combinations of four-terminal MMC DC system under different working timings of DC circuit breakers are analyzed.

By comparing the system transient simulation and short circuit calculation results, the effectiveness of the proposed method is verified. The results show that the mathematical model determined by this method can effectively describe the overall trend of fault current, and can provide a basis for the calculation of DC line short-circuit faults and the selection of DC system parameters.

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