Study on the Short-Circuit Current of Asymmetrical AC Fault Near MMC

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***Abstract*—The mechanism of the contribution of modular multilevel converter (MMC) on short-circuit current under asymmetrical fault at the point of common coupling (PCC) was studied according to operation characteristics and control strategy applied in fault. A ± 320kV two-terminal MMC system was established in PSCAD/EMTDC to verify the conclusion. Simulation results show that after fault, MMC performs as a current source at AC side because of the characteristics of the inner loop current controller. After the controllers respond, the fault current does not contain DC component. The steady-state short-circuit current is symmetrical, which can be computed by the reference value of the inner loop controller. The limits of PI of the outer and inner loop controller affect steady-state short-circuit current. The flow directions of active power of MMC before and after fault are consistent, while the flow direction of reactive power is related to the control mode and operation state. The research provides valuable guide to parameters tunning of MMC controller and relay protection.**

Keywords—modular multilevel converter (MMC); asymmetrical fault; short-circuit current; controller parameters

I. INTRODUCTION

Compared with line commutated converter high voltage direct current (LCC-HVDC), voltage source converter (VSC) does not have commutation failure and reactive power compensation problems. It can independently adjust active and reactive power and has little harmonics, which is easy to build a multi-terminal system and supply power for weak or passive AC systems, especially suitable for renewable energy power generation connecting to grid[1-3]. While modular multi-level converter has greatly improved the transmission capacity and voltage level, making VSC-HVDC system widely used. With the development of large-scale clean energy consumption[4], several MMC-HVDC projects have rapidly constructed in Nanhui, Xiamen, Zhoushan, Nan'ao, Luxi, Zhangbei, Wudongde, etc. With the increase of voltage and transmission power of VSC-HVDC system, the fault current generated by the MMC is also very huge when the system faults. Therefore, analyzing the mechanism of MMC's short-circuit current is of great significance to power grid construction, power equipment selection and relay protection tunning.

At present, researchers have studied more on the AC side faults of LCC. Reference [5] analyzed how the DC system provides short-circuit current for the AC system based on the characteristics of LCC, and used a piecewise function to calculate the short-circuit current provided by LCC. Reference [6] established a fault analysis model according to DC current control mode, and proposed a method that can calculate the harmonics of DC multi-input systems under the asymmetric power grids. Reference [7] established the short-circuit current calculation model of LCC under various faults based on the working principle of the inverter control system. Due to the characteristics of MMC, AC side fault current analysis and calculation methods of LCC are not suitable for MMC. There are few papers to study the fault current on the AC side of MMC. Reference [8] analyzed the influencing factors of the three-phase short-circuit current at PCC point of MMC, but lack of research on asymmetric faults. Besides, several researchers proposed control strategy of MMC under fault or voltage imbalance [9-11]. However, the research on the characteristics and influencing factors of the short-circuit current is deficient when the MMC system occurs faults, especially in the case of asymmetric faults.

In this paper, according to the working principle, operation characteristics, and control strategy of asymmetric faults of MMC, the short-circuit current characteristics and influence mechanism of MMC-HVDC system are studied.

II. STRUCTURE AND CHARACTERISTICS OF MMC

According to Fig. 1, MMC has six bridge arms, and each bridge arm contains *N* series sub-modules (SM). The switching of the two IGBTs will determine the output voltage of the SM. Normally, dispatching system sends control commands to MMC, and the inner and outer loop controllers and the circulating current suppression controller (CCSC) generate three-phase modulation waves. The modulation waves generate trigger pulses under nearest level modulation (NLM) or carrier phase shifted sinusoidal pulse widen modulation (CPS-SPWM) and capacitance voltage balance strategy, and control the switching of SMs of each bridge arm to adjust the magnitude and phase of the output AC voltage of MMC.

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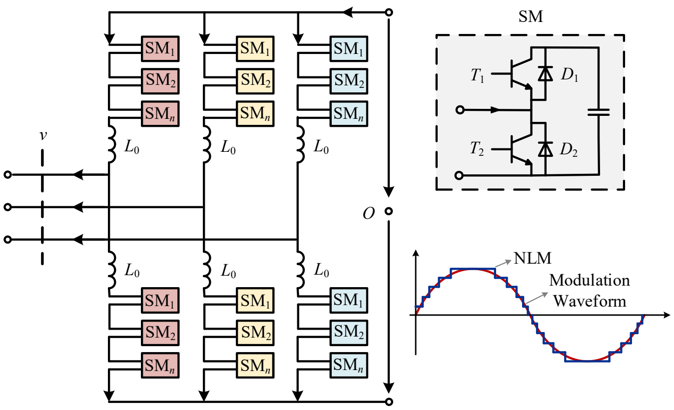


Fig. 1. Typical topology of MMC

The MMC control system is established in the dq synchronous reference frame. When the AC system is asymmetric, the inner loop control is decomposed into positive and negative sequence current decoupling control. The control block is shown in Fig. A1. It mainly includes phase sequence separation module, PLL, positive and negative sequence inner loop current controller, outer loop power controller, CCSC and current limit. The phase sequence separation module is designed following the phase-shifting method[12]. In the PLL, the positive sequence q-axis component of the grid voltage is controlled by PI, and the output angular frequency is integrated to generate the phase of the positive sequence grid voltage. The outer loop power controller, positive and negative sequence inner loop current controller and CCSC is designed following [13]. The outer loop power controllers generate the reference values of the inner loop current controllers, and the MMC adjusts the amplitude and phase of AC voltage to control the output current under the inner loop controller. The CCSC suppresses the circulating current by supplementing the double frequency component on the bridge arm voltage. In particular, the overload capacity of MMC is limited. If fault occurs, the overcurrent may destroy the converter valves. Therefore, a current limit[14] is added in the MMC control system to protect the converter valve.

III. Analysis Of Asymmetrical AC Faults Near MMC

The short-circuit current of asymmetric AC fault near MMC is different from that occurs in the generator. Ignoring the effect of harmonics, when an asymmetrical AC fault occurs near the generator, the magnitude and phase of the fundamental frequency component of the short-circuit current will be affected by changes in the grid structure and the current will contain a decreasing DC component. Unlike generator, MMC can respond quickly within milliseconds, and the output voltage varies little before the action of controller, thus the DC component of the short-circuit current can be ignored. Therefore, after controller action, the short-circuit current generated by MMC does not contain a DC component[8]. The magnitude and phase of the output voltage of the MMC change after the controller responds, so that the inner loop current controller can tracks the reference value.

The AC fault near MMC is shown in Fig. 2. R_S and L_S are equivalent resistance and inductance of AC grid, respectively. U_S and U_C are the voltage of PCC and the AC side of the MMC, respectively. R_g and L_g are filter resistance and inductance of MMC, respectively. R_{dc} and L_{dc} are the resistance and inductance of the DC link, respectively.

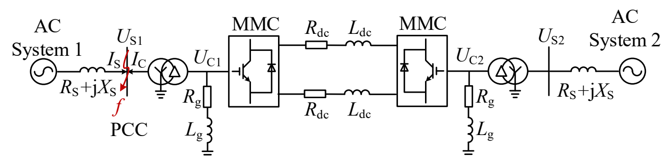


Fig. 2. Schematic diagram of AC fault in two terminals MMC-HVDC system

Based on the control system in Fig. A1, the positive and negative sequence components of the three-phase voltage and current are separated and u_q is locked by PLL. The inner loop controller decouples the positive and negative sequence currents, thus reducing the impact caused by the harmonics and the negative sequence.

If the overcurrent causing by the fault occurs, the protection device will be triggered to lock the MMC. The research in this paper is based on the MMC controller that can limit the overcurrent without triggering the protection, so the influence of the tunning value of the protection device on the short-circuit current is neglected. An AC fault near MMC can be equivalent to the fault occurring at PCC, so this paper focuses on the fault of PCC. According to the control shown in Fig. A1, this paper study how the inner loop controllers, outer loop controllers and other links of MMC work when an asymmetric fault occurs.

A. The Response of the Outer Loop Power Controller

When an asymmetric fault occurs near MMC, the grid voltage will drop. If the MMC is controlled by the fixed active and reactive power control strategy, the transmission power MMC will deviate from the reference value.

In order to eliminate the effect of the double frequency component of the power on the outer loop controller during asymmetric fault, the active and reactive power of MMC are calculated by (1).

$$\begin{cases} P = \dfrac{3}{2}(u_d^+ i_d^+ + u_q^+ i_q^+ + u_d^- i_d^- + u_q^- i_q^-) \\ Q = \dfrac{3}{2}(-u_d^+ i_q^+ + u_q^+ i_d^+ + u_q^- i_d^- - u_d^- i_q^-) \end{cases} \tag{1}$$

The positive sequence dq axis current reference value i_{dref0}^+ and i_{qref0}^+ generated by the outer loop control are calculated by (2).

$$\begin{cases} i_{dref0}^+ = k_{pp1}(P^{ref} - P) + k_{ii1}\int(P^{ref} - P)dt \\ i_{qref0}^+ = k_{pp2}(Q^{ref} - Q) + k_{ii2}\int(Q^{ref} - Q)dt \end{cases} \tag{2}$$

where k_{pp1}, k_{pp2}, and k_{ii1}, k_{ii2} are the proportional and integral coefficient of the outer loop power controller, respectively; P^{ref}, Q^{ref} and P, Q are the reference and actual values of active and reactive power, respectively.

Normally, the reference values of active and reactive power of the fixed power MMC are the same as that of AC grid, so the reference values of dq axis current are derived by (3):

$$\begin{cases} i_{\mathrm{dref0}}^{+} = P / u_{\mathrm{d}} \\ i_{\mathrm{qref0}}^{+} = -Q / u_{\mathrm{d}} \end{cases} \tag{3}$$

After an asymmetric AC fault occurs near MMC, the reference value of active and reactive power deviates from the actual value of the AC system. The reference value of dq axis current calculated by (2) and (3) will increase until the limit of the PI. Assuming that active power P and reactive power Q are both positive during normal operation, i_{dref0}^{+} is positive and i_{qref0}^{+} is negative according to (3). And i_{dref0}^{+} will positively increase and i_{qref0}^{+} is negatively increase after fault according to (2). When MMC performs the fixed power control, dq axis current reference values are both positive or negative before and after the fault, thus the direction of active and reactive power flow of hybrid AC/DC system remain unchanged. If Q^{ref} is 0, i_{qref0}^{+} will be 0 before and after the fault.

When MMC adopts fixed DC voltage control, the positive sequence current reference values i_{dref0}^{+} and i_{qref0}^{+} can be obtained by (4).

$$\begin{cases} i_{\mathrm{dref0}}^{+} = k_{\mathrm{pp3}}(U_{\mathrm{dc}}^{\mathrm{ref}} - U_{\mathrm{dc}}) + k_{\mathrm{ii3}}\int (U_{\mathrm{dc}}^{\mathrm{ref}} - U_{\mathrm{dc}})\mathrm{d}t \\ i_{\mathrm{qref0}}^{+} = k_{\mathrm{pp4}}(U_{\mathrm{ac}}^{\mathrm{ref}} - U_{\mathrm{ac}}) + k_{\mathrm{ii4}}\int (U_{\mathrm{ac}}^{\mathrm{ref}} - U_{\mathrm{ac}})\mathrm{d}t \end{cases} \tag{4}$$

where k_{pp3}, k_{pp4} and k_{ii3}, k_{ii4} are the proportional and integral coefficients of outer loop controller, respectively; $U_{\mathrm{dc}}^{\mathrm{ref}}$, $U_{\mathrm{ac}}^{\mathrm{ref}}$ and U_{dc}, U_{ac} are the reference value and actual value of DC and AC voltage, respectively.

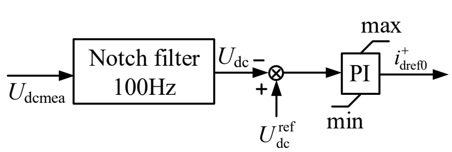


Fig. 3. DC voltage controller

When an asymmetric fault occurs, U_{dc} will contain a double frequency component due to the influence of the negative sequence voltage[17]. Therefore, in order to eliminate the influence of the double frequency fluctuation component in the DC voltage, as shown in Fig. 3, a double frequency notch filter is added.

When an asymmetric fault occurs, due to the severity of fault is different, active power flowing into and out of the MMC is different. Severe faults such as two-phase grounding fault will cause DC voltage to rise or fall, and the positive sequence d axis current reference value i_{dref0}^{+} will reach the PI limit. However, light faults, such as single-phase grounding and two-phase short-circuit faults, will cause DC voltage to fluctuate, and the positive sequence d axis current reference value i_{dref0}^{+} will fluctuate around a certain value between the upper and lower limits of PI. Meanwhile, AC grid voltage drops and deviates from the reference value, thus the reference value of the positive sequence q axis current i_{qref0}^{+} will also reach the current limit. Similarly, assuming that the active and reactive power of MMC adopting the fixed DC voltage control flow to the AC grid before the fault, the active power P and reactive power Q are both negative. According to (3), i_{dref0}^{+} is negative and i_{qref0}^{+} is positive before fault. It can be obtained from (4) is that i_{dref0}^{+} increases negatively and i_{qref0}^{+} increases positively after the fault. And the reference values of dq axis current remain unchanged before and after the fault. After the fault, the active and reactive power are still flow to the AC grid from MMC. Normally, MMC performing the fixed AC voltage control absorbs reactive power, while generates reactive power to compensate for the falling voltage after a fault. i_{qref0}^{+} obtained from equations (3) and (4) before and after the fault are opposite, and will increase to the current limit negatively after the fault. Before and after the fault, direction of the reactive power of MMC adopting fixed AC voltage control is opposite.

When an asymmetric fault occurs near MMC, the flow direction of active power is not affected, but the control strategy and operation mode of MMC will influence the flow direction of reactive power. Reactive power of MMC performing fixed reactive power control does not change direction during normal operation or after a fault. If MMC adopting fixed AC voltage control generates reactive power before the fault, transmission direction of reactive power does not change after the fault. If MMC absorbs reactive power before the fault, transmission direction is opposite after the fault. Normally, the active power of MMC-HVDC system is large, and active power transmission direction is same before and after the fault. Therefore, for the same fault, the short-circuit current of rectifier is smaller than that of inverter.

B. The Response of the Current Limit

When a fault occurs, the reference value of positive sequence dq axis reactive current generated by the outer loop power controller are large, and may reach the current limit. i_{dref}^{+} and i_{qref}^{+} can be reduced to the current limit by (5).

$$\begin{cases} i_{\mathrm{dref}}^{+} = i_{\mathrm{dref0}}^{+}, i_{\mathrm{qref}}^{+} = i_{\mathrm{qref0}}^{+} & \sqrt{(i_{\mathrm{dref0}}^{+})^2 + (i_{\mathrm{qref0}}^{+})^2} \le I_{\mathrm{lim}} \\ i_{\mathrm{dref}}^{+} = \dfrac{I_{\mathrm{lim}} \cdot i_{\mathrm{dref0}}^{+}}{\sqrt{(i_{\mathrm{dref0}}^{+})^2 + (i_{\mathrm{qref0}}^{+})^2}}, & \\ i_{\mathrm{qref}}^{+} = \dfrac{I_{\mathrm{lim}} \cdot i_{\mathrm{qref0}}^{+}}{\sqrt{(i_{\mathrm{dref0}}^{+})^2 + (i_{\mathrm{qref0}}^{+})^2}} & \sqrt{(i_{\mathrm{dref0}}^{+})^2 + (i_{\mathrm{qref0}}^{+})^2} > I_{\mathrm{lim}} \end{cases} \tag{5}$$

where I_{lim} is the current limit value, and is tunned according to the overload level of MMC and the overcurrent with which the converter valve is subjected.

C. Response of the Inner Loop Current Controller

$$\begin{cases} L\dfrac{di_d^+}{dt} = -Ri_d^+ + \omega L i_q^+ - v_d^+ + u_d^+ \\ L\dfrac{di_q^+}{dt} = -Ri_q^+ - \omega L i_d^+ - v_q^+ + u_q^+ \end{cases} \quad (6)$$

$$\begin{cases} L\dfrac{di_d^-}{dt} = -Ri_d^- - \omega L i_q^- - v_d^- + u_d^- \\ L\dfrac{di_q^-}{dt} = -Ri_q^- + \omega L i_d^- - v_q^- + u_q^- \end{cases} \quad (7)$$

The mathematical model[18] of MMC under dq coordinates is shown in (6)-(7). v_d^+, v_q^+, v_d^- and v_q^- are the input parameters of the inner loop current controller, and can be calculated by (8) and (9).

$$\begin{cases} v_{dref}^+ = u_d^+ + \omega L i_q^+ - k_{p1}(i_{dref}^+ - i_d^+) - k_{i1}\int (i_{dref}^+ - i_d^+)dt \\ v_{qref}^+ = u_q^+ - \omega L i_d^+ - k_{p2}(i_{qref}^+ - i_q^+) - k_{i2}\int (i_{qref}^+ - i_q^+)dt \end{cases} \quad (8)$$

$$\begin{cases} v_{dref}^- = u_d^- - \omega L i_q^- - k_{p3}(i_{dref}^- - i_d^-) - k_{i3}\int (i_{dref}^- - i_d^-)dt \\ v_{qref}^- = u_q^- + \omega L i_d^- - k_{p4}(i_{qref}^- - i_q^-) - k_{i4}\int (i_{qref}^- - i_q^-)dt \end{cases} \quad (9)$$

Substituting (8)-(9) into (6)-(7) to perform inverse Laplace transformation to obtain the decoupling control block of positive and negative sequence current in Fig. 4. The transfer function between $i_d^\pm$, $i_q^\pm$ and $i_{dref}^\pm$, $i_{qref}^\pm$ is shown in(10).

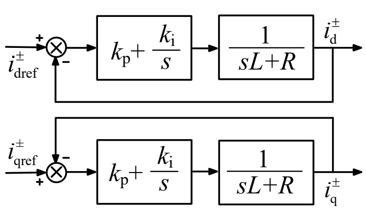


Fig. 4. Positive and negative sequence current decoupling control

$$\frac{I^\pm(s)}{I_{ref}^\pm(s)} = \frac{sk_p + k_i}{Ls^2 + (R + k_p)s + k_i} \quad (10)$$

When an asymmetric fault occurs near MMC, AC voltage drops, and the magnitudes of u_d^+, u_q^+, u_d^-, u_q^- are affected by severity of the fault. i_{dref}^- and i_{qref}^- of the negative sequence current controller are usually set to 0 to reduce the negative sequence current. If the reference value of positive and negative sequence inner loop controller and dq axis components of grid voltage are known, the dq axis output voltage of MMC can be calculated according to (6)-(7).

After an asymmetric fault occurs, the inner loop current controller changes the MMC output voltage to make i_d^+ and i_q^+ follow the reference value, and reduce i_d^- and i_q^- to 0. Therefore, MMC is equivalent to a current source on the AC side, and the output current is calculated through Park inverse transformation of i_{dref}^+ and i_{qref}^+. When i_{dref}^+ and i_{qref}^+ have few high-frequency components, MMC outputs a three-phase symmetrical current.

IV. Simulation Analysis

A 201-level two terminal MMC-HVDC system model in PSCAD/EMTDC in Fig. 2 is built to verify the theoretical analysis of the asymmetrical fault on the AC side of the MMC. The parameters are shown in Table AI. The interconnecting transformer adopts $Y_N\Delta$ wiring. The rated capacity of system is 1500MVA and the rated DC voltage is 640kV. The reference value of the transmission power of MMC adopting the fixed power control is P^{ref}=1000MW, Q^{ref}=300Mvar. That for MMC with the fixed voltage control is U_{dc}^{ref}=640kV, U_{ac}^{ref}=400kV.

A. Analysis of Simulation Results

When t=3.5s, the PCC of rectifier MMC and inverter MMC occur single-phase grounding short-circuit, and the faults last for 1s, respectively.

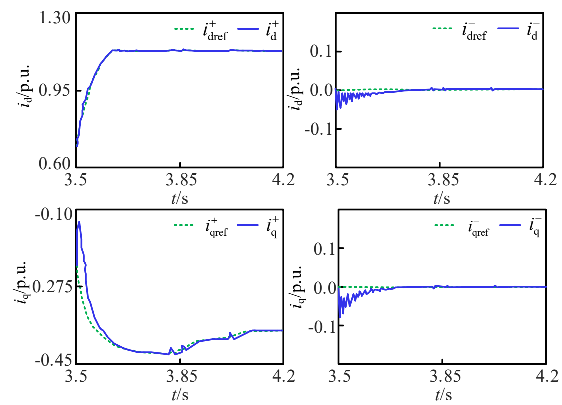


Fig. 5. Inner loop current controller tracking curve of rectifier MMC

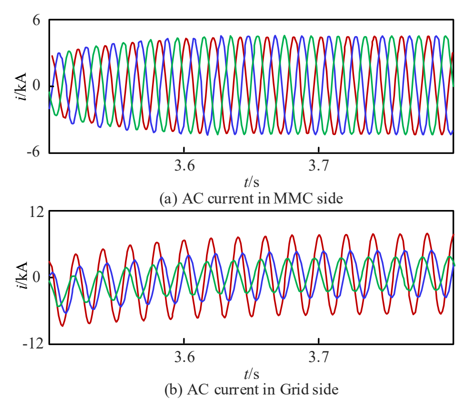


Fig. 6. Output current of rectifier MMC

Figure 5 and Fig. 6 show the current of the inner loop current controller of the MMC and the output current on the AC side. It can be known from Fig. 5 that when a single-phase grounding short-circuit occurs at the PCC of the rectifier MMC, i_{dref}^+

increases positively and reaches the limit after 3.62s, and i_{qref}^{+} increases negatively and maintains a certain value within the limit after 4.1s. The result proves that the transmission direction of active and reactive power of the MMC adopting fixed power control remains unchanged before and after the fault. i_d^+ , i_d^- , i_q^+ , i_q^- track their reference values respectively. Because the negative sequence component is suppressed to 0, the current of the interconnecting transformer on the valve side in Fig. 6 is a three-phase symmetrical sine wave from short-circuit to steady state. Because the interconnecting transformer adopts $Y_N\Delta$ wiring, the zero sequence current on the grid side can flow, and the grid-side current is the superposition of the positive sequence and zero sequence current component.

Figure 7, Fig.8, and Fig. 9 show the dq axis currents and enlarged diagrams and the currents on both sides of the interconnecting transformer when a single-phase grounding short-circuit occurs at the PCC of the inverter MMC. Reference [19-20] introduces the curves of power and voltage when an asymmetric fault occurs near MMC.

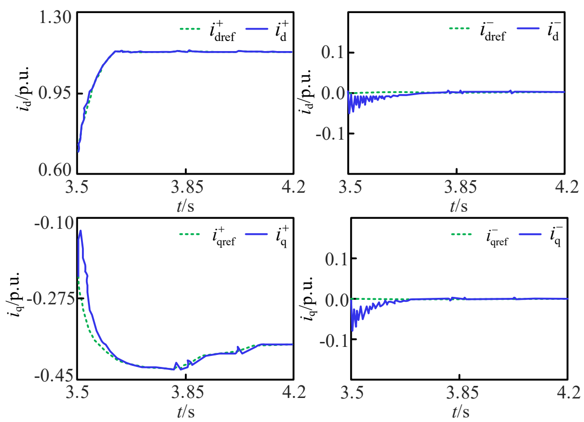


Fig. 7. Inner loop current controller tracking curve of inverter MMC

From Fig. 7, i_d^+ , i_d^- , i_q^+ , i_q^- can track their reference value, and the negative sequence current is suppressed to 0. i_{dref}^{+} reaches the PI limit after 3.6s, while i_{qref}^{+} remains at a certain value within the limit.

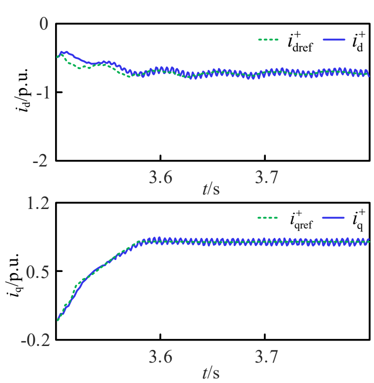
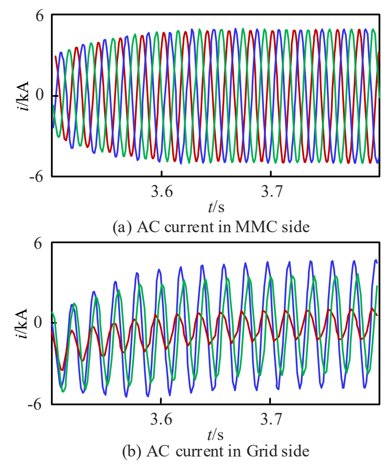


Fig. 8. Inner loop current controller tracking enlarge curve of inverter MMC

It can be seen from Fig. 8 that there is a higher even frequency fluctuation component in i_{dref}^{+} , because the double frequency notch filter in Fig. 4 only emilites the interference of the double frequency component, but U_{dc} also has other higher even frequency component. From (4), when i_{dref}^{+} does not reach the limit, it will produce a fluctuating component corresponding to U_{dc}, so MMC output current will be affected.



(a) AC current in MMC side

(b) AC current in Grid side

Fig. 9. Output current of of inverter MMC

As shown in Fig. 9, the valve-side current of the transformer is not a perfect sine wave, and the grid-side current is the sum of the positive and zero sequence components.

The valve-side current of the interconnecting transformer is shown in Fig. A2 when a two-phase short-circuit and a two-phase grounding short-circuit occur at the PCC of MMC. It can be seen from Fig. 6, Fig. 9 and Fig. A2 that the output current of MMC is symmetrical after a short-circuit after MMC controller responds.

There is no zero sequence current in a two-phase fault, only positive sequence current can flow through the interconnecting transformer. If a two-phase grounding short-circuit occurs in inverter MMC with fixed DC voltage control, U_{dc} cannot remain stable and i_{dref}^{+} reaches the current limit. The valve-side current is a perfect three-phase sine wave. It can be seen from Fig. 7 that when the short-circuit time increases, i_{dref}^{+} increases negatively to the current limit, while i_{qref}^{+} gradually increases positively from the negative value to the current limit. It proves that flow direction of active power of MMC remains unchanged before and after the fault, while the MMC absorbing reactive power before will provides reactive power to maintain AC voltage stability after the fault.

B. Asymmetric Fault Current Calculation

Because of the inner loop current controller and the current limit module, MMC suffering from an AC asymmetric fault can be equivalent to a positive sequence current source. i_d^+ and i_q^+ track their reference values i_{dref}^{+} and i_{qref}^{+} , so i_{dref}^{+} and i_{qref}^{+} can be transformed into current source through the Park inverse transformation by (11). When the frequency of fluctuation components of i^+_{dref} and i^+_{qref} is low, because zero sequence current cannot flow through the transformer, the current on the valve side is relatively perfect. The maximum output current of MMC is lower than the limit I_{lim}.

$$\begin{bmatrix} i_{\text{a}} \\ i_{\text{b}} \\ i_{\text{c}} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta-2\pi/3) & -\sin(\theta-2\pi/3) \\ \cos(\theta+2\pi/3) & -\sin(\theta+2\pi/3) \end{bmatrix} \begin{bmatrix} i_{\text{dref}} \\ i_{\text{qref}} \end{bmatrix} \quad (11)$$

where θ is the positive sequence voltage phase.

The symmetrical component method can be used to calculate the short-circuit current injected into the fault point by the AC system, so as to calculate the asymmetrical AC fault current near MMC. The fault current is the phasor sum of the AC system injection current and the grid-side current of the interconnecting transformer. When a two-phase fault occurs, the grid-side current only contains a positive sequence component, which can be obtained by (11). If the interconnecting transformer is the grid-side Y-type grounding connection, the grid-side current is the superposition of the positive and the zero sequence current when a ground fault occurs. In particular, the zero-sequence component of the grid-side current of the interconnecting transformer has nothing to do with MMC because MMC controller only generates positive sequence components. When there is an asymmetric fault at the PCC of MMC, the theoretical and simulated values of the short-circuit current are shown in Table I.

It can be seen from Table I that the method proposed in this paper to calculate the asymmetrical fault current near MMC has a high accuracy and is within the allowable range of error. Because the high frequency component of the DC voltage is low, even if MMC adopts the fixed DC voltage control, the positive sequence current reference value is not affected, and the calculation method can still get a accurate result.

TABLE I. CALCULATION RESULTS OF ASYMMETRICAL FAULTS NEAR RECTIFIER MMC

MMC tpye	Fault type	Simulation value of MMC output current /kA	Calculated value of MMC output current /kA	Simulation value of AC system current /kA	Calculated value of AC system current /kA	Simulation value of fault current /kA	Calculated value of fault current /kA	Relative error of fault current /%
Rectifier	$f^{(1)}$	4.21	4.20	21.48	21.49	23.50	24.19	2.85
	$f^{(2)}$	4.50	4.51	18.69	18.7	17.00	17.15	0.87
	$f^{(1,1)}$	4.71	4.70	21.49	21.50	22.09	22.70	2.69
Inverter	$f^{(1)}$	4.81	4.79	21.61	21.60	29.20	29.50	1.02
	$f^{(2)}$	4.79	4.79	18.69	18.72	21.10	21.29	0.89
	$f^{(1,1)}$	4.79	4.79	21.59	21.60	26.89	27.21	1.18

V. CONCLUSION AND FUTURE STUDY

This paper analyzes the characteristics and influence factors of the short-circuit, and proposes a method to calculate the short-circuit current when an asymmetric AC short-circuit occurs at the PCC. The analysis method is also applicable to three-phase symmetric faults.

1) When an AC asymmetric fault occurs near MMC, the output current of MMC does not contain a DC component after the controller responds.

2)Whether the reference value by the outer loop power controller reaches the PI limit is related to the degree of the PCC voltage drop. The more serious the fault, the easier it is to reach the current limit. When the reference value reaches the limit, the influence of power and voltage fluctuations on the three-phase symmetry of MMC output current decreases.

3)During the fault, the inner loop current controller makes the positive sequence current track the reference value, and suppresses the negative sequence current to 0, so MMC performs as a positive sequence current source on the AC side.

4)The active power flow direction is the same before and after the fault, while the reactive power is related to the control scheme and operation mode of MMC.

5)The steady-state short-circuit current provided by the MMC is three-phase symmetrical, which can be obtained by the Park inverse transformation of the dq-axis current reference value. The magnitude of the short-circuit current is related to the control scheme, operation mode, PI limit of outer loop power controller, and current limit. The maximum value will not exceed the limit given by the current limit module.

The future work will study the short-circuit current changes considering transient state of controllers and the influence of the control strategies of AC system.

APPENDIX

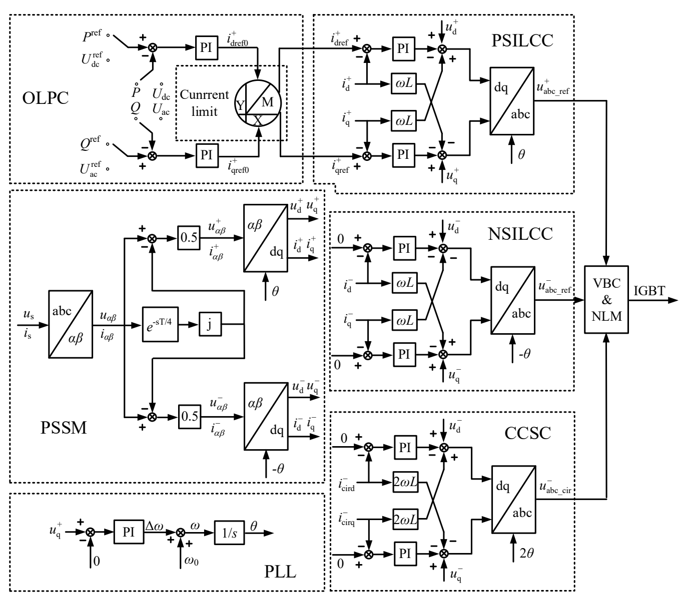


Fig. A1. Block diagram of MMC's control system

TABLE AI. PARAMETERS OF TWO TERMINAL MMC-HVDC SYSTEM

Parameter	Value	Unit
R_S	1.634	Ω
L_S	0.0479	H
L_T	0.0505	H
R_f	0.01	Ω
L_g	1000	H
R_g	1000	Ω
I_{lim}	1.3	p.u.

where L_T is leakage reactance of converter transformer, and R_f is short-circuit resistance

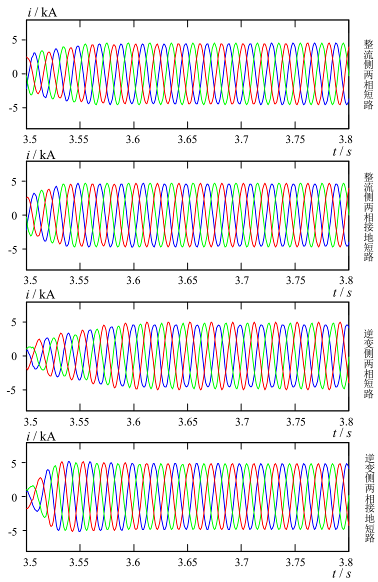


Fig. A2. Current waveform of valve side of converter transformer

When two-phase short-circuit and two-phase grounding short-circuit occur in the rectifier MMC and inverter MMC respectively, the currents of valve side of converter transformer are shown in Fig. A2. The simulation results are consistent with the theoretical analysis.

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