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Characteristic investigation of MMC-HVDC system under internal AC bus fault conditions

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Abstract: In order to ensure the high-efficient and stable operation of the MMC-HVDC transmission system, it is necessary to analyse the failure mode and failure mechanism of MMC-HVDC in detail. First, this article briefly introduced the MMC-HVDC system working principle. Then, we deeply analyse characteristic investigation under internal AC bus fault including single-phase ground fault and two-phase short circuit fault. It is proved theoretically that when asymmetrical fault occurs in AC bus, negative sequence components will appear in the system and cause double frequency fluctuations in the active power. Finally, a simulation model of modular multilevel converter DC transmission is built in the PSCAD/EMTDC electromagnetic transient simulation platform, which validates the correctness of the theoretical derivation, and provides a basis for the research of system protection strategy.

1 Introduction

In recent years, the transmission of electric energy is moving in the direction of high voltage, large capacity, and long distance, which makes the HVDC transmission system return to people's vision again. Line commutated converter-based high-voltage direct current (LCC-HVDC) system has many shortcomings, such as prone to commutation failure, requiring a large number of additional filters and reactive power compensation device, can only work in the active AC network. Although some improvements have been made, but in the passive network power supply, new energy access to grid and offshore wind power have been unable to meet the power needs.

Modular multilevel converter (MMC) is a new topology, which can effectively compensate for the defects of thyristor commutation converter and solve the problem of high switching frequency and large loss in the traditional two or three level voltage source converter. The sub-module structure of MMC is relatively simple and easy to control, and can be easily expanded to the field of high voltage and large capacity. Therefore, the research on the field of MMC-HVDC transmission is particularly important [1–5].

The domestic research on MMC-HVDC system mainly focuses on system modelling and simulation and steady-state control strategy. The mechanism, configuration, and test technique of MMC-HVDC system relay protection are different from the traditional AC system. Therefore, MMC-HVDC system failure forms and failure mechanisms need to be analysed in detail. At present, the fault analysis of MMC-HVDC mostly focuses on the DC side. Compared with the DC-side faults, the AC faults in converter stations also have a very important influence on the stability and reliability of the system [6–8].

Compared with the fault of the power grid–side AC system, the internal AC bus is directly connected with the converter and is closest to the converter. When the AC bus fault occurs in the converter station, the impact on the converter is much greater than that in the AC system. The detailed simulation analysis of the single-phase grounding fault of the valve-side AC bus of the VSC-HVDC system is carried out in document [2], but there is no theoretical deduction. In document [3], the mathematical modelling of MMC-HVDC system under voltage imbalance of three-phase power grid is carried out, but only single-phase ground fault is analysed. The fault of internal AC bus includes single-phase ground fault and two-phase short circuit fault. Existing research focuses on single-phase ground fault. The influence caused by the two-phase short circuit fault in the actual situation is also great, and further researches are needed [9–12].

Here, the transient response of MMC-HVDC system is analysed theoretically under the condition of single-phase ground fault and two-phase short circuit fault in converter station. The simulation model is built through the PSCAD/EMTDC simulation platform. The AC current, AC current, DC voltage, and the active power of the system are analysed, which verify the correctness of the theoretical derivation.

2 Working principle and fault analysis of MMC-HVDC

2.1 Topology and working principle of MMC

The topology of the three-phase MMC main circuit is shown in Fig. 1 and consists of six bridge arms, each bridge arm consists of a number of sub-modules (SM) and a reactor, which are connected in series. Six bridge arms are symmetrical structure, there are $2N$ sub-modules on each phase, each of the upper and lower arms has N sub-modules to form an $N+1$ level inverter.

Sub-module is the most important part of MMC. There are mainly three types of topology: half bridge sub-module, full-bridge sub-module and double-clamp sub-module. In practical engineering and scientific research, half bridge sub-module is generally used as the research object. According to the different conduction state of the switch in the sub-module, it can be divided into three working states: inputting, removing, and locking.

Through the analysis of the working principle of the sub-module, the number of sub-modules on the MMC three-phase bridge arm determines the output voltage of the upper and lower bridge arms. Since each sub-module can separately control the input or the removal, the upper and lower arm output voltages are equivalent to the controllable voltage source, the specific equivalent circuit shown in Fig. 2.

In Fig. 2, P and N are the positive and negative poles of the MMC DC side, respectively. O is the reference neutral point, u_{si} is the fundamental voltage of the three-phase AC bus, i_{si} is the fundamental current of the three-phase AC bus, where $i = a,b,c$. R and L are, respectively, the equivalent resistance and inductance of the AC-side connecting MMC converter, R_s and L_s are, respectively, the equivalent resistance and inductance of each arm,

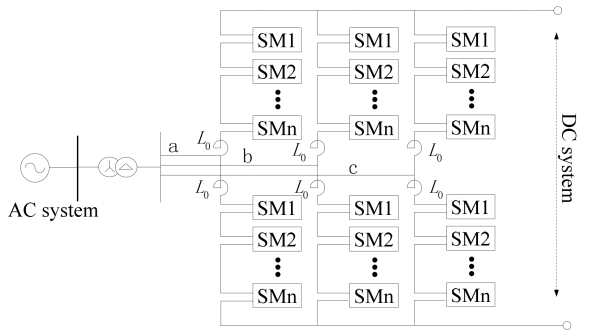

Fig. 1 *Three-phase MMC main circuit topology*

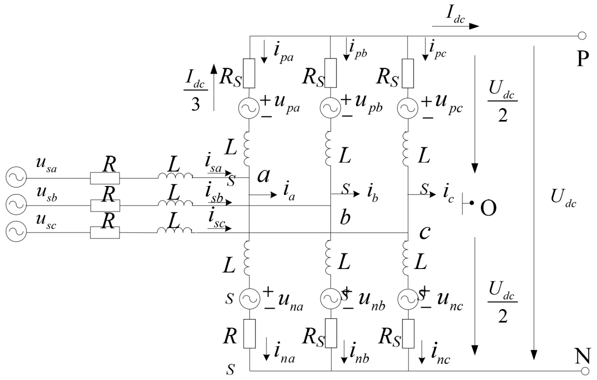

Fig. 2 *Equivalent circuit model of MMC*

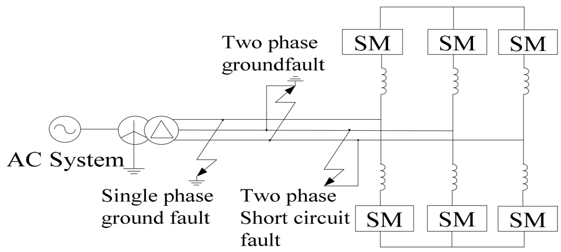

Fig. 3 *Schematic diagram of the asymmetrical fault of the AC bus in the station*

u_{pi} and u_{ni} are the output voltage of the upper and lower arm of each phase, U_{dc} and I_{dc} are the voltage and current on DC side [2].

Under steady-state conditions, MMC is a three-phase symmetrical structure, the analysis of the relationship among the AC-side voltage, the DC-side voltage, and the upper and lower arm voltages can take one phase as an example. Now take A phase as an example, ignoring the voltage drop across the bridge arm resistor *R* and the arm reactor *L*, the voltage of the phase A upper and lower bridge arms can be obtained from the Kirchhoff's voltage law as follows:

$$\begin{cases} u_{\rm pa} = \frac{1}{2}U_{\rm dc} - u_{\rm ao} \\ u_{\rm na} = \frac{1}{2}U_{\rm dc} + u_{\rm ao} \end{cases} \tag{1}$$

Simplify available:

$$u_{ao} = \frac{1}{2}(u_{na} - u_{pa}) \tag{2}$$

$$U_{dc} = u_{na} + u_{pa} \tag{3}$$

As can be drawn from (2) and (3), in order to keep the DC-side voltage constant, the amount of three-phase sub-module input at any time is constant when the MMC is in normal operation. That is, the multilevel voltage waveform of the converter is realised by modulating the number of the upper and lower arm sub-modules.

Due to the symmetrical three-phase structure of the MMC, the current I_{dc} on the DC side of the MMC is distributed evenly among the three-phase units, which is $I_{dc}/3$, and the current distributed to the upper and lower bridge arms is $i_{si}/2$ for each phase. If the circulation current is not considered between the phases, the superposition theorem can be used to obtain the current of the upper and lower bridge arms of the A phase:

$$\begin{cases} i_{\rm pa} = -\frac{1}{3}I_{\rm dc} - \frac{1}{2}i_{\rm sa} \\ i_{\rm na} = -\frac{1}{3}I_{\rm dc} + \frac{1}{2}i_{\rm sa} \end{cases} \tag{4}$$

2.2 Analysis of internal AC bus fault in MMC-HVDC system

2.2.1 Classification of internal AC fault station: Internal AC bus fault is mainly caused by the insulation damage between the secondary winding of the converter transformer and the bridge arm of converter. The internal AC bus fault is divided into three-phase symmetrical fault and asymmetric fault, Three-phase symmetrical faults include three-phase short-circuited faults and three-phase short-circuited ground faults. Three-phase asymmetrical faults include single-phase ground fault, two-phase ground fault, and two-phase short circuit fault, asymmetric fault diagram shown in Fig. 3. Compared with grid-side AC system, the probability of failure of AC bus in converter station is low, but when it fails, the converter valve will be damaged and seriously affects the normal operation of MMC-HVDC system. Therefore, it is necessary to analyse its fault characteristics [8].

After the three-phase asymmetrical fault occurs in the AC bus of MMC-HVDC system, the main way to analyse fault characteristics is to analyse the characteristics of zero sequence current loop and fault discharge circuit. Here, A phase ground fault and *A*, *B* two-phase short circuit fault are examples to analyse the internal AC bus fault.

2.2.2 Analysis of fault characteristics: According to the instantaneous power theory, the active power transmitted by the three-phase AC system to the MMC is:

$$p_s = u_{\rm sa}i_{\rm sa} + u_{\rm sb}i_{\rm sb} + u_{\rm sc}i_{\rm sc} \tag{5}$$

where i_{sa}, i_{sb} and i_{sc} are three-phase internal AC bus currents, u_{sa}, u_{sb} and u_{sc} represent three-phase internal AC bus voltages.

In the steady-state case, the Parker transformation on the above equation can obtain:

$$p_s = \frac{3}{2}\left(u_{\rm sd}i_{\rm sd} + u_{\rm sq}i_{\rm sq}\right) \tag{6}$$

When the system has an asymmetrical fault, the Clark transformation is introduced. The transformation matrix is:

$$T_{\alpha\beta} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{7}$$

The (5) is converted to the stationary coordinate system, and the expression of the active power in the two-phase stationary coordinate system is:

$$p_s = \frac{3}{2}\left(u_{s\alpha}i_{s\alpha} + u_{s\beta}i_{s\beta}\right) \tag{8}$$

Asymmetrical faults occur on the internal AC bus. The voltage and current include the negative sequence components in addition to the positive sequence components. The expressions are as shown in (9) and (10).

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} = \begin{bmatrix} u_{s\alpha}^{+} \\ u_{s\beta}^{+} \end{bmatrix} + \begin{bmatrix} u_{s\alpha}^{-} \\ u_{s\beta}^{-} \end{bmatrix} \tag{9}$$

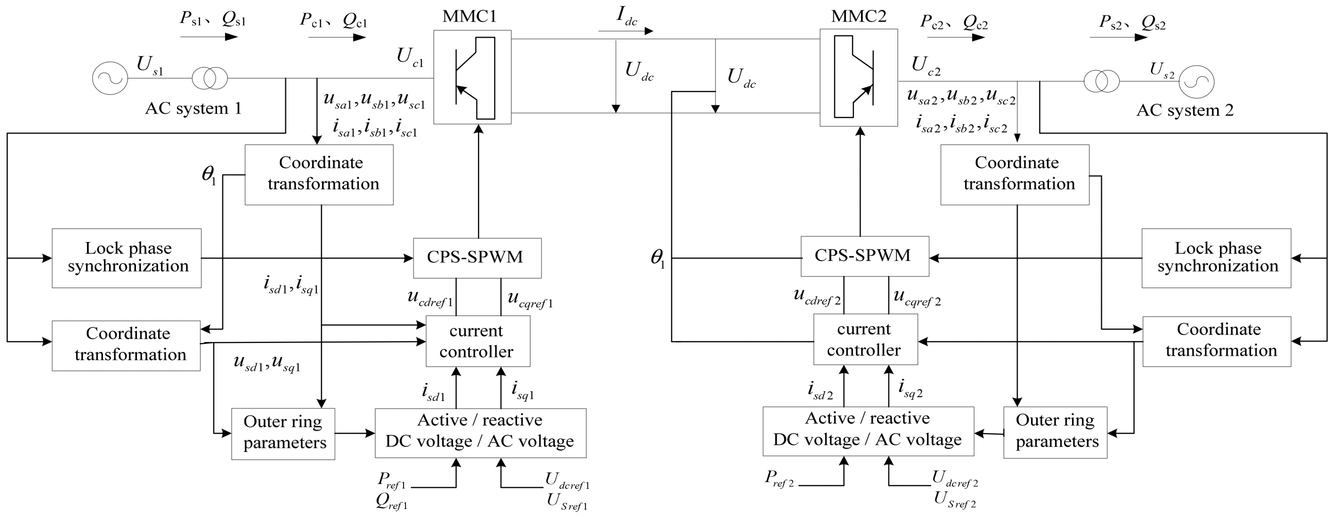

Fig. 4 *MMC-HVDC system control structure diagram*

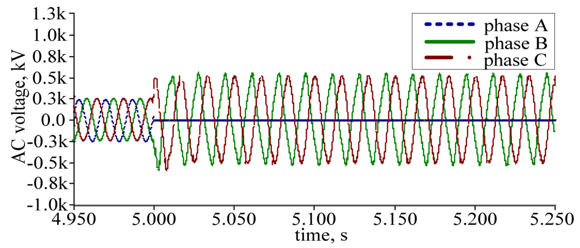

Fig. 5 *AC bus voltage in single phase ground fault*

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} i_{s\alpha}^{+} \\ i_{s\beta}^{+} \end{bmatrix} + \begin{bmatrix} i_{s\alpha}^{-} \\ i_{s\beta}^{-} \end{bmatrix} \quad (10)$$

where $u_{s\alpha}^{+}$, $u_{s\beta}^{+}$, $i_{s\alpha}^{+}$ and $i_{s\beta}^{+}$ are the components of positive sequence AC bus voltage, current in α axis and β axis, $u_{s\alpha}^{-}$, $u_{s\beta}^{-}$, $i_{s\alpha}^{-}$ and $i_{s\beta}^{-}$ represent the components of negative sequence AC bus voltage, current in α axis and β axis.

Substituting (9) and (10) into (2) gives the active power P_s represented by the positive and negative components of the two-phase stationary coordinate system:

$$\begin{aligned} p_s = {} & \frac{3}{2}\left(u_{s\alpha}^{+} i_{s\alpha}^{+} + u_{s\beta}^{+} i_{s\beta}^{+}\right) + \frac{3}{2}\left(u_{s\alpha}^{-} i_{s\alpha}^{-} + u_{s\beta}^{-} i_{s\beta}^{-}\right) \\ & + \frac{3}{2}\left(u_{s\alpha}^{+} i_{s\alpha}^{-} + u_{s\beta}^{+} i_{s\beta}^{-}\right) + \frac{3}{2}\left(u_{s\alpha}^{-} i_{s\alpha}^{+} + u_{s\beta}^{-} i_{s\beta}^{+}\right) \end{aligned} \quad (11)$$

The two-phase stationary coordinate system is transformed to synchronous rotating coordinate system, the transformation matrix is:

$$T^{+}(\omega t) = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \quad (12)$$

$$T^{-}(\omega t) = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \quad (13)$$

Through coordinate transformation, the active power expression in synchronous rotation coordinate system is:

$$\begin{aligned} p_s = {} & \frac{3}{2}\left(u_{\mathrm{sd}}^{+} i_{\mathrm{sd}}^{+} + u_{\mathrm{sq}}^{+} i_{\mathrm{sq}}^{+}\right) + \frac{3}{2}\left(u_{\mathrm{sd}}^{-} i_{\mathrm{sd}}^{-} + u_{\mathrm{sq}}^{-} i_{\mathrm{sq}}^{-}\right) \\ & + \frac{3}{2}\left(u_{\mathrm{sd}}^{+} i_{\mathrm{sd}}^{-} + u_{\mathrm{sq}}^{+} i_{\mathrm{sq}}^{-} + u_{\mathrm{sd}}^{-} i_{\mathrm{sd}}^{+} + u_{\mathrm{sq}}^{-} i_{\mathrm{sq}}^{+}\right)\cos(2\omega t) \\ & + \frac{3}{2}\left(u_{\mathrm{sd}}^{+} i_{\mathrm{sq}}^{-} - u_{\mathrm{sq}}^{+} i_{\mathrm{sd}}^{-} + u_{\mathrm{sq}}^{-} i_{\mathrm{sd}}^{+} + u_{\mathrm{sd}}^{-} i_{\mathrm{sq}}^{+}\right)\sin(2\omega t) \end{aligned} \quad (14)$$

Comparing (14) with (6), we can see that the active power P_s injected into converter station contains not only DC component but also second harmonic component when asymmetrical fault occurs in the bus. The DC component is composed of the product of the positive sequence voltage and the positive sequence current and the sum of the products of the negative sequence voltage and the negative sequence current. The fluctuation component consists of the product of the positive sequence voltage and the negative sequence current, the negative sequence voltage and the positive sequence current. The magnitude of the fluctuation component depends on the magnitude of the negative sequence component. The larger the negative sequence component, the larger the fluctuation. Compared with the single-phase ground fault, the AC voltage unbalance caused by the two-phase short circuit fault is higher, and the negative sequence component is larger, resulting in greater fluctuation of the active power.

3 Simulation and analysis of fault characteristics

3.1 Simulation model

In order to verify the fault characteristics of modular multi-level converter-based HVDC transmission system of AC bus, a two-terminal MMC-HVDC transmission system is set up in the PSCAD/EMTDC electromagnetic transient simulation software. The specific parameters are as follows: The voltage level of the AC system is 220 kV and the turns ratio of converter transformer is 220/230 kV with Ynd connection, the system impedance is 1 Ω, DC power is 1200 MW, DC-side output voltage is ±230 kV, the number of sub-modules of the bridge arm is 30, sub-module capacitance is 3500 uF, bridge arm reactor is 50 mH. The rectifier side adopts constant power and reactive power control strategy, and the inverter station side adopts constant DC voltage and constant reactive power control strategy. The control structure of the system is shown in Fig. 4.

3.2 Simulation and analysis of single-phase ground fault

Setting an internal AC bus A phase ground fault on the rectifier side, after the system is stable operation, the fault occurred in 5 s. From the simulation results of Figs. 5 and 6, when the single-phase ground fault occurs in the AC bus, the voltage of the A phase will change to 0, and the voltage of the non-fault phase will be changed to $\sqrt{3}$ times .There was a significant overcurrent in the fault phase current, up to a maximum of 20%, compared with the original one, and no obvious overcurrent occurred in the non-fault phase.

As can be seen from the simulation results in Fig. 7, when a single-phase ground fault occurs in the system, a negative sequence component appears in the system, resulting in fluctuation of active power, which reaches 1.1 times as much as the original. From Fig. 8, when the single-phase ground fault occurs, there is a large sinusoidal fluctuation in the positive and negative DC voltage of

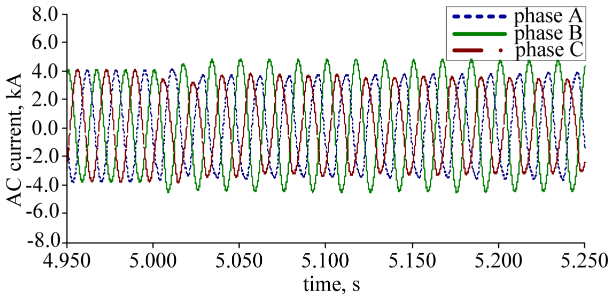

Fig. 6 *AC bus current in single-phase ground fault*

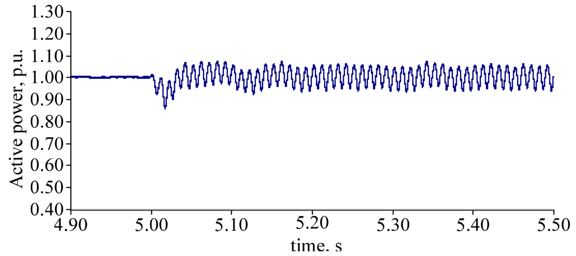

Fig. 7 *Active power of the system in single phase ground fault*

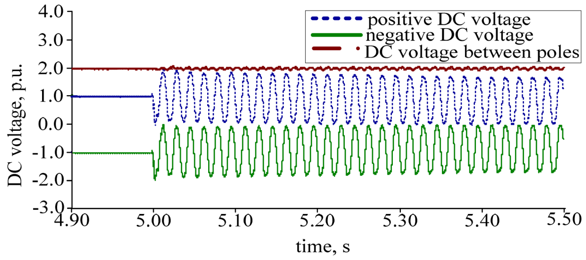

Fig. 8 *DC voltage in single phase ground fault*

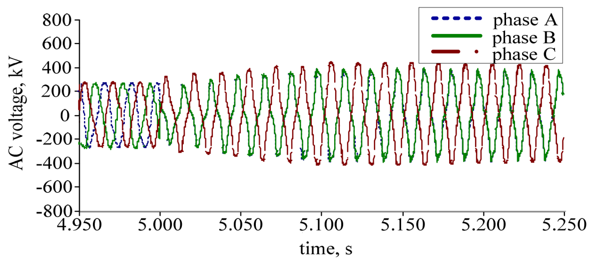

Fig. 9 *AC bus voltage in two-phase short circuit fault*

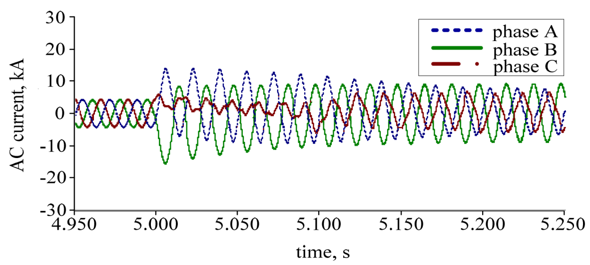

Fig. 10 *AC bus current in two-phase short circuit fault*

the DC side, but the voltage between the two poles remains basically unchanged.

3.3 Simulation and analysis of two-phase short circuit fault

Schematic diagram of two-phase short circuit fault is shown in Fig. 3, after the system is in stable operation, phase A and phase B of the AC bus on the rectifier side are short-circuited in 5 s. From the simulation results of Figs. 9 and 10, when the two-phase short circuit fault occurs on the AC bus, the voltages of phase A and phase B are equal and in the same direction, the voltage of non-

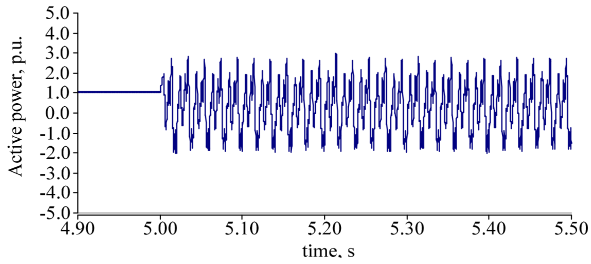

Fig. 11 *System active power in two-phase short circuit fault*

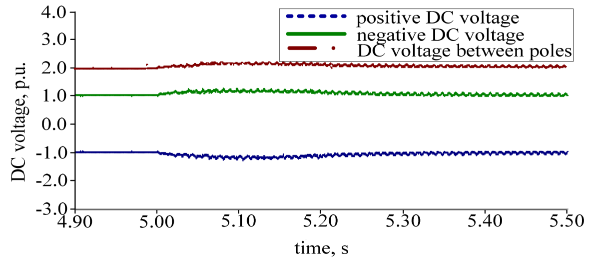

Fig. 12 *DC voltage in two-phase short-circuit fault*

fault phase becomes obviously larger. The currents of phase A and phase B are equal in magnitude and opposite in direction, and serious overcurrent has appeared, with the maximum current being four times of the original one.

From the simulation result in Fig. 11, when the two-phase short circuit occurs, the negative sequence component in the system is larger than single-phase ground fault, resulting in more serious fluctuation of active power, and the maximum value is three times of the original one. As shown in Fig. 12, when the two-phase short circuit fault occurs in the system, only slight fluctuations occur in the DC voltage on the direct current side. The positive and negative DC voltages are kept at +1 pu and −1 pu, the DC voltage between the two poles remains in 2 pu.

4 Conclusion

Here, the fault characteristics of single-phase ground fault and two-phase short circuit fault in MMC-HVDC system are analysed, then the following conclusions are obtained by combining the simulation results:

(i) When single-phase grounding fault and two-phase short-circuit fault occur in internal AC bus, the negative sequence component is generated in the system, which causes the active power to fluctuate. The negative sequence component of two-phase short-circuit fault is larger than single-phase ground fault, resulting in more dramatic fluctuations in active power.
(ii) After a single-phase fault occurs, the fault phase voltage becomes zero, non-fault phase voltage into line voltage. When a two-phase short-circuit fault occurs, the magnitude of the fault phase voltage is equal and in the same direction; the currents are equal in magnitude and opposite in direction. Under the two kinds of faults, the current will increase at the fault point, and the magnitude of the overcurrent of the two-phase short-circuit fault is greater than the single-phase ground fault.
(iii) When the single-phase ground fault occurs, the reference point of potential has changed, positive DC voltage and negative DC voltage have shown significant fluctuations, but the DC voltage between the two poles does not change. After two-phase short circuit fault occurs, the reference point of potential does not change, the positive and negative DC voltage only have slight fluctuations and the DC voltage between the two poles does not change significantly.

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