

Analysis of DC transmission line disconnection fault characteristics based on MMC-HVDC system under symmetrical monopole connection mode

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Abstract—DC transmission line disconnection fault is one of the common faults in DC side of MMC-HVDC system. Under the symmetrical monopole connection, the transmission line disconnection fault leads to the interruption of the power transmission of the flexible HVDC transmission system. During the period of transmission line disconnection fault, the submodule capacitor charges or discharges due to the function of the outer loop controller. The DC voltage of the faulty pole changes much comparing with the DC voltage of the healthy pole. The voltage of the two terminal AC side grounding reference point is no longer consistent, and the fault current with small amplitude but gradually increasing on the healthy pole DC line. There is a gradually increasing DC voltage offset component in the AC voltage of converter valve side. Finally, the validity and correctness of the transmission line disconnection fault analysis was verified by a two-terminal MMC-HVDC system which was established in PSCAD/EMTDC.

Keywords—MMC-HVDC system; symmetrical monopole; DC transmission line disconnection fault; fault analysis;

I. INTRODUCTION

Modular multilevel converter (MMC) has the advantages of flexible operation and control, independent regulation of active power and reactive power, high waveform quality, especially suitable for renewable energy access [1]. In recent years, it has become a hot topic in industry and academia. When the higher voltage level of the grid to which MMC-HVDC system is connected, the fault in DC side of the MMC-HVDC system may cause a negligible influence on the power grid because of the greater the power of the transmission. DC transmission line disconnection fault is one of the three common faults in DC side of MMC-HVDC system. No matter whether the overhead line or the cable is used in the DC transmission line, it is possible to suffer from the breakdowns due to the thunderbolt and the mechanical stress damage in the system operation. Therefore, the corresponding research on the DC transmission line disconnection fault occurred in the MMC-HVDC system was carried out in this paper. The research has important practical significance and theoretical value for the safe and stable operation of the power grid.

At present, the research on MMC is mostly focused on modeling and simulation [2-3], control and protection strategy [4-5], and stability analysis of wind farm integration [6-7]. In [8], the fault characteristics of pole-to-ground in MMC-HVDC system were introduced in detail, and different grounding modes adopted in MMC-HVDC system were analyzed. The overcurrent characteristics was analyzed in [9] and a fault current calculation method of pole-to-pole fault for dc grids was proposed. The simulation and analysis on the transmission line fault of MMC-HVDC system were carried out in [10], but it only analyzed the grounding fault of the transmission line and did not mention the line disconnection fault. In [11], the impact analysis of DC fault mode on bipolar MMC-HVDC system was carried out, the fault mechanism of pole-to-ground was mainly studied, but the line disconnection fault was not analyzed.

The characteristics of DC transmission line disconnection fault based on MMC-HVDC system under symmetrical monopole connection mode is discussed in this paper. It is organized as follows. Section II introduces, the principle of the steady state operation of the MMC. Section III gives the details of the mechanism of the DC voltage change and the fault current and the AC voltage offset component in the valve side of the converter when the single pole transmission line disconnected. Section IV shows the validity and correctness of the transmission line disconnection fault analysis by using a two-terminal MMC-HVDC system which was established in PSCAD/EMTDC. Section V draws the conclusion of this paper.

II. OPERATION PRINCIPLE OF MMC

As is shown in Fig.1, each phase of the MMC consists of upper and lower bridge arms and each of the arm is made up of a current limiting reactance L_0 and N cascaded submodule. Each submodule consists of two insulated gate bipolar transistors T_1 and T_2 , two anti-parallel diodes D_1 and D_2 and a parallel capacitor C . T_1 and T_2 are switched alternately according to the trigger signal, and $2N$ submodule of each phase generates a step wave of the $N+1$ level voltage on the AC side. In order to maintain constant DC voltage of the system, the number of submodules per phase should be N .

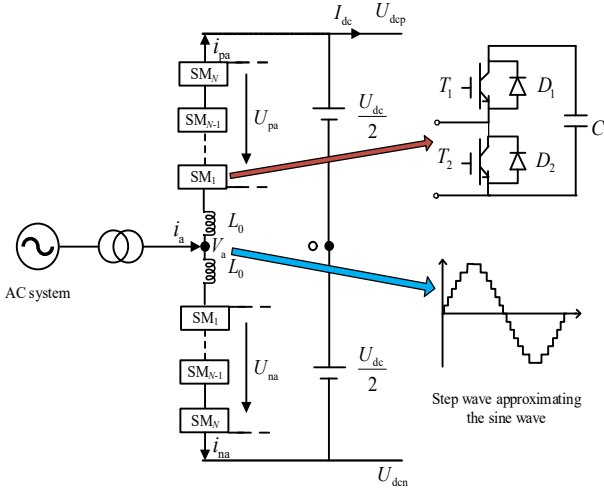


Fig.1 Single phase circuit of MMC

Where, U_{dc} and I_{dc} are DC voltage and DC current respectively; V_a and I_a are respectively the output current and voltage of phase a ; U_{pa} , U_{na} , i_{pa} , i_{na} are respectively the voltage and current of the upper and lower bridge arm of phase a , U_{dcp} and U_{dcn} are respectively the positive and negative pole bus voltage.

Neglecting the influence of bridge arm resistance, as is shown in Fig.1, the voltage of the upper and lower bridge arm of phase a of MMC can be drawn from (1):

$$\begin{cases} U_{pa} = \frac{U_{dc}}{2} - V_a + L_0 \frac{di_{pa}}{dt} \\ U_{na} = \frac{U_{dc}}{2} + V_a - L_0 \frac{di_{na}}{dt} \end{cases} \quad (1)$$

Assuming that the second order harmonic of the bridge arm current is suppressed by the circulating suppressor, the expression of the upper and lower bridge arm currents of phase a of the MMC is expressed as (2).

$$\begin{cases} i_{pa} = \frac{1}{2} i_a + \frac{1}{3} I_{dc} \\ i_{na} = \frac{1}{2} i_a - \frac{1}{3} I_{dc} \\ i_a = i_{pa} + i_{na} \end{cases} \quad (2)$$

The internal voltage of the converter is defined as (3)

$$e_{va} = V_a - L_0 \frac{di_a}{dt} = \frac{U_{na} - U_{pa}}{2} \quad (3)$$

Substituting (1) with (2) and (3), (4) can be obtained.

$$\begin{cases} V_{pa} = \frac{U_{dc}}{2} - e_{va} \\ V_{na} = \frac{U_{dc}}{2} + e_{va} \end{cases} \quad (4)$$

In normal operation, the DC voltage of the flexible HVDC system is constant, and the positive and negative pole bear half of the rated DC voltage.

$$\begin{cases} U_{dcp} = +\frac{U_{dc}}{2} = \frac{NU_{sm}}{2} \\ U_{dcn} = -\frac{U_{dc}}{2} = -\frac{NU_{sm}}{2} \end{cases} \quad (5)$$

The expression of the AC voltage of valve side can be obtained by Kirchhoff's law.

$$\begin{cases} V_a = e_{va} + \frac{L_0}{2} \frac{di_a}{dt} + \frac{U_{dc}}{2} + U_{dcp} \\ V_b = e_{vb} + \frac{L_0}{2} \frac{di_b}{dt} + \frac{U_{dc}}{2} + U_{dcn} \\ V_c = e_{vc} + \frac{L_0}{2} \frac{di_c}{dt} + \frac{U_{dc}}{2} + U_{dcn} \end{cases} \quad (6)$$

III. THEORETICAL ANALYSIS OF TRANSMISSION LINE DISCONNECTION FAULT

The transmission line disconnection fault analysis in this paper is based on the symmetric monopole two-terminal MMC-HVDC system shown in Fig. 2. The converter station adopts star type reactance L_g and resistance R_g grounding in AC side.

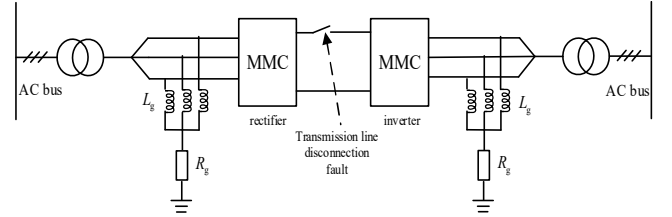


Fig.2 Schematic diagram of transmission line disconnection fault for symmetric monopole two-terminal MMC-HVDC system

The constant power control in rectifier and the constant voltage control in inverter is taken as an example. As is shown in Fig.2, the transmission of power will be aborted when the transmission line disconnection fault occurs in the MMC-HVDC system. Under the action of the constant power controller, the submodule capacitor of the upper and lower bridge arm of the rectifier station will continue to charge and the capacitor voltage will increase. Due to the function of constant DC voltage controller, the submodule capacitor will be discharged because of the unbalanced input and output power in the inverter station. The DC voltage between positive and negative poles basically maintain near the normal value. Due to the unbalanced capacitor voltage of the submodule capacitor of rectifier and inverter, the voltage of the AC side neutral points of rectifier and inverter is not same and a fault current will be generated between the two side neutral points of the converter station, going through the AC side grounding resistance and reactance, the healthy pole bridge arm and the DC transmission line. The fault current loop is shown in Fig.3.

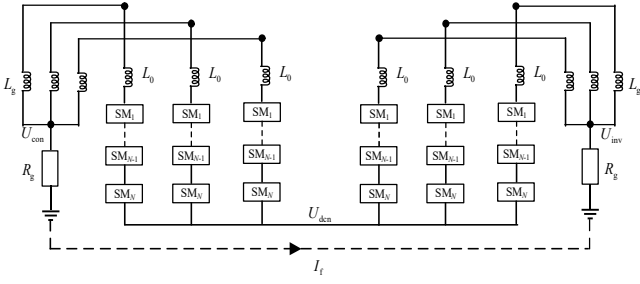


Fig.3 Fault current circulation circuit

Where, U_{con} is the neutral point to ground voltage of the rectifier side, U_{inv} is the neutral point to ground voltage of the inverter side.

When the constant power converter is in the rectifying mode, during the period of line disconnection fault, the submodule capacitor is continuously charged under the function of constant power controller, the voltage is gradually increased and the submodule capacitor voltage can be calculated by (7).

$$U_{sm}(t) = \sqrt{\frac{P \cdot t - \sum_{j=0}^{t/\Delta t - 1} \frac{(NU_{sm}(j) - NU_{sm0})^2}{8R_g} \Delta t}{3NC}} + U_{sm0}^2 \quad (7)$$

Where, $U_{sm}(t)$ is the submodule capacitor voltage value at time t ; P is the transmission active power; U_{sm0} is the submodule capacitor voltage before the fault; Δt is the sampling time interval; $U_{sm}(j)$ is the submodule capacitor voltage value at the j time interval within time t .

When the constant power converter is in the inverter mode, the submodule capacitor is continuously discharged under the function of constant power controller and the DC voltage is reduced until the modulation ratio between the DC voltage and the AC phase voltage amplitude of the converter valve side reaches its limit value, and the submodule capacitor voltage can be obtained by (8).

$$U_{sm} = 2\sqrt{2}U_{ac} \cdot M_{max} / (\sqrt{3}N) \quad (8)$$

Where, U_{ac} is the effective value of line voltage at AC side; M_{max} is the limiting value of modulation ratio.

According to operation principle of two-terminal MMC-HVDC system, (9) can be obtained.

$$\begin{cases} U_{con} = \frac{NU_{smcon}}{2} + U_{den} \\ U_{inv} = \frac{NU_{sminv}}{2} + U_{den} \end{cases} \quad (9)$$

Where, U_{smcon} is the submodule capacitor voltage of the rectifier side, and U_{sminv} is the submodule capacitor voltage of the inverter side.

Therefore, voltage difference ΔU between the neutral points of two terminal converter station can be obtained as (10).

$$\Delta U = U_{con} - U_{inv} = \frac{N}{2}(U_{smcon} - U_{sminv}) \quad (10)$$

Due to the existence of voltage difference between the neutral points of two terminal converter station, fault current I_f can be calculated as (11).

$$I_f = \Delta U / (2R_g) \quad (11)$$

Consequently, the three phase AC voltage of the valve side of the rectifier station can be expressed as (12).

$$\begin{cases} V_a = e_{va} + \frac{L_0}{2} \frac{di_a}{dt} + \frac{NU_{smcon}}{2} + U_{den} \\ V_b = e_{vb} + \frac{L_0}{2} \frac{di_b}{dt} + \frac{NU_{smcon}}{2} + U_{den} \\ V_c = e_{vc} + \frac{L_0}{2} \frac{di_c}{dt} + \frac{NU_{smcon}}{2} + U_{den} \end{cases} \quad (12)$$

Due to the continuous charging of the submodule capacitor of the rectifier, the submodule capacitor voltage and the neutral point potential of rectifier continue to increase. According to (12), there is a continuous increase of offset component in the AC voltage of the valve side. Finally, the analysis of inverter side is similar to the rectifier side.

IV. SIMULATION VERIFICATION

A two-terminal MMC-HVDC system was built under PSCAD/EMTDC for simulation verification. The schematic diagram of the two-terminal MMC-HVDC system is shown in Fig.2. The system parameter is shown in table I.

The rectifier adopts constant active power and reactive power control, and the inverter adopts constant DC voltage and AC voltage control. In the simulation, DC transmission line disconnection fault occurred at 2s in positive pole, and fault was cleared at 2.5s.

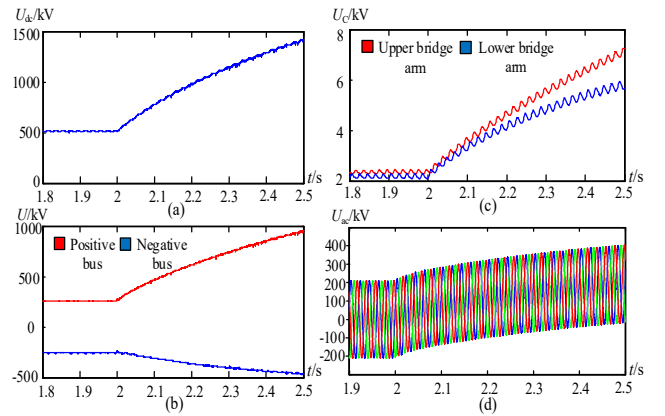


Fig.4 Voltage waveforms of rectifier under transmission line disconnection fault. (a) DC voltage between positive and negative pole. (b) DC voltage of positive and negative pole bus. (c) Submodule capacitor voltage of upper and lower bridge arm. (d) AC voltage on valve side of rectifier.

Under the function of constant power controller, in Fig.4(a), the voltage of the positive and negative pole bus

increases gradually. In Fig.4(b), DC voltage continuous increases. In Fig.4(c), the submodule capacitor voltage of upper and lower bridge arm continuous increases. The submodule capacitor of the lower bridge arm also has a certain discharge process due to existence of fault current. So the voltage change amplitude of positive pole is larger than that of negative pole. In Fig.4(d), the AC voltage of valve side has a large continuously increasing DC offset component.

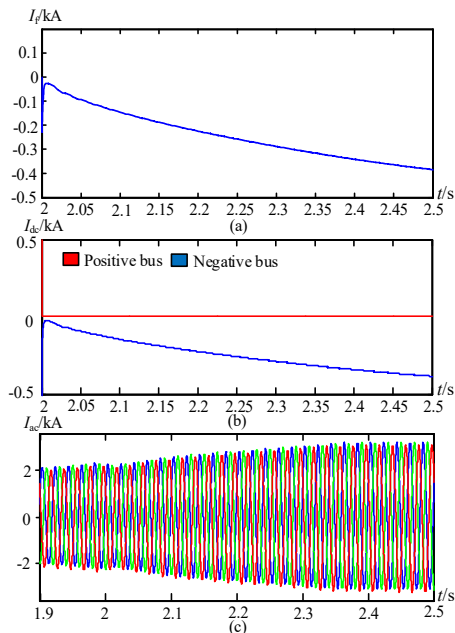


Fig.5 Current waveforms of the studied system under transmission line disconnection fault. (a) fault current. (b) current of positive and negative pole line. (c) AC current on valve side of rectifier.

As is shown in Fig.5(a), the fault current increases with the increase of two terminal neutral point voltage difference, however, due to the larger grounding resistance, the value is small. In Fig.5(b), the current of positive pole line is 0 due to the fault occurs at positive pole, the current flowing over the negative pole line is the fault current. In Fig.5(c), the AC current of valve side is no longer symmetrical due to the existence of the fault current.

TABLE I. PARAMETERS OF SIMULATION SYSTEM

Parameters		Values
AC	AC system voltage	500kV
	Transformer ratio	525/260
	L_g	2H
	R_g	500 Ω
	U_{dc}	525kV
DC	Transmission line inductance	0.025H
	Transmission line resistance	0.15 Ω

V. CONCLUSION

For the transmission line disconnection fault, under the function of constant power controller, the submodule capacitor continues to charge and the fault pole has larger voltage change amplitude than healthy pole. Moreover, the AC voltage of the valve side has a large DC offset component, so the design of the flexible HVDC system

should consider the overvoltage threat caused by transmission line disconnection fault. Due to the larger grounding resistance, the effect of the fault current on converter and transmission line can be ignored.

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