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Transient overvoltage on overhead metal return lines of ±500 kV MMC-HVDC grid

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Abstract: The ±500 kV half-bridge modular multilevel converter-high-voltage DC (MMC-HVDC) grid project with overhead transmission line is under construction in China at present. For MMC-HVDC grid, only one electrical grounding point is allowed and thus, the metal return lines on the same towers with positive and negative polar lines are necessary. However, current studies mainly focused on the control methods of MMC-HVDC substation and few studies have been done on the transient overvoltage of overhead transmission line for the MMC-HVDC project. This study analysed the main transient overvoltage types of metal return lines of ±500 kV half-bridge MMC-HVDC grid which transmit electric power by overhead lines and clear the grounding fault by DC breakers. Based on a ±500 kV MMC-HVDC grid project, the simulation models were built using PSCAD and the possible transient overvoltage types were studied. The results showed that the most serious overvoltage was caused by the DC breaker clearing the grounding fault. Then the insulation coordination design for metal return lines was carried out. The recommended arcing horn clearances at different altitude were given. The research results provided support for the insulation design of the transmission line.

1 Introduction

Generally, the voltage-sourced converter (VSC)-based high-voltage DC (HVDC) projects transmit electric power by cables. So, the optional return modes are cable or ground [1–6]. However, for the ±500 kV half-bridge modular multilevel converter (MMC)-HVDC grid project with overhead transmission line which is under construction in China at present, the transmission lines are intended to use overhead lines and only one electrical grounding point is allowed. Then the overhead metal return lines are necessary.

Current studies mainly focused on the control methods of MMC-HVDC substation and few studies have been done on the transient overvoltage of overhead transmission line for the MMC-HVDC project [7–10] and less attention was paid to the return lines. However, for overhead transmission project, the environmental factors have a great influence on the reliability of the line. Also, because the insulation level of the return lines is low, the return line may be the weak point. It is necessary to be analysed the transient overvoltage of metal return lines of ±500 kV half-bridge MMC-HVDC grid which transmit electric power by overhead lines and clear the grounding fault by DC breakers.

This paper focuses on the overvoltage level of overhead metal return lines in MMC-HVDC grid. Firstly, it pointed out the main overvoltage types of overhead metal return lines in MMC-HVDC grid. Based on a ±500 kV MMC-HVDC grid, the simulation models were built using PSCAD and the possible transient overvoltage types were studied. Then the insulation coordination design for metal return lines was carried out. The recommended arcing horn clearances at different altitude were given.

This paper is organised as follows. Section 2 is devoted to analyse the main overvoltage types of overhead metal return lines in MMC-HVDC grid, while Section 3 presents the transient overvoltage results based on a four-terminal MMC-HVDC grid according to Section 2. Then the insulation coordination design for metal return lines was carried out and the arcing horn clearances are given in Section 4. Finally, conclusions are drawn in Section 5.

2 Transient overvoltage of overhead metal return line in MMC-HVDC grid

2.1 Induced overvoltage on metal return line caused by single-pole grounding fault

When the MMC-HVDC system is under bipolar operation, the grounding fault of a pole will induce overvoltage at the metal return lines by coupled capacitance and inductance between the lines. The magnitude of the overvoltage U_{sp} can be estimated by the following equation

$$U_{sp} = \frac{U_D(Z_0 - Z_1)}{Z_0 + Z_1 + 2R_e} + U_D \tag{1}$$

where Z_0 and Z_1 are zero sequence and positive sequence wave impedance of transmission line, respectively; R_e is the grounding resistance.

2.2 Fault clearing overvoltage

The only way for half-bridge MMC-HVDC grid clearing the grounding fault is DC circuit breaker (CB). When the CB breaks the fault, it is equivalent to superimposing a current source with a reverse fault current on the CB. The current wave propagation and reflection on the adjacent sound line from transient overvoltage. Then the overvoltage would occur on the metal return line and the adjacent return lines too. The fault current is related to the main circuit parameters of converter station, the operation characteristics of DC CB, and the fault grounding resistance.

2.3 Closing and reclosing overvoltage

When the DC CB breaks switch on or reclose, because of the difference between the initial voltage of the line to the ground and the forced voltage at the end of the transition process, the overvoltage would be caused on the pole lines and also the metal return lines.

3 Overvoltage results

3.1 Main circuit parameters

The research object is a four-terminal ±500 kV MMC-HVDC grid with half insulated gate bipolar transistor (IGBT) bridge. There are 245 electric levels for the bridge.

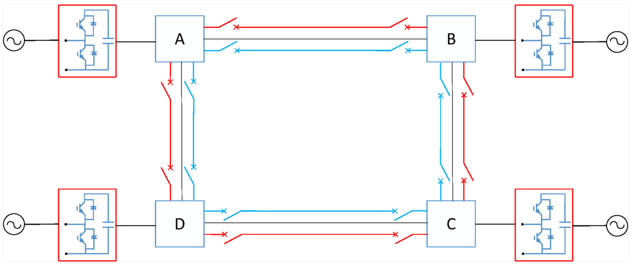

Fig. 1 *Schematic diagram of four-terminal MMC-HVDC grid*

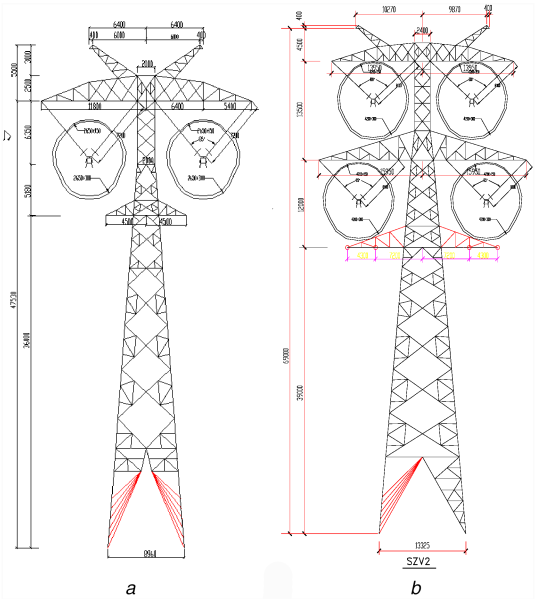

Fig. 2 *Typical tower diagrams*
(a) Typical single-circuit tower diagram, ***(b)*** Typical double-circuit tower diagram

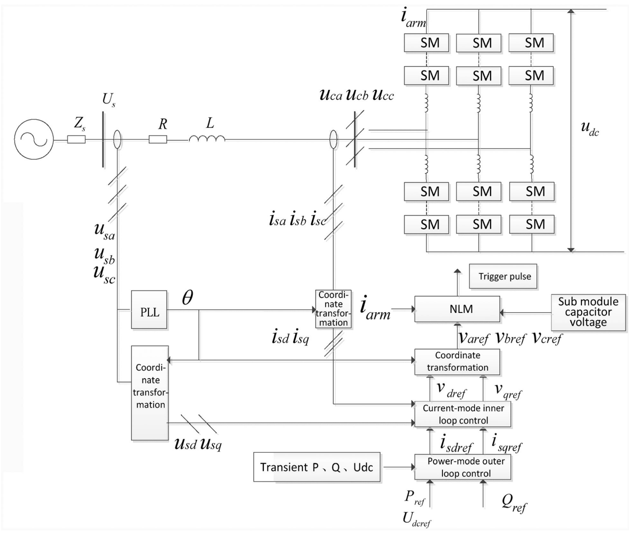

Fig. 3 *MMC control system*

The rated voltage of AC source for substations *A* and *B* are 220 and 500 kV for converter stations *C* and *D*. The rated capacity of converter stations *A* and *D* are 3000 and 1500 MW for converter stations *B* and *C*.

The structure of the four-terminal ±500 kV MMC-HVDC grid is illustrated in Fig. 1. The length from *A* to *B* is 50 km, *B* to *C* is 205 km, *C* to *D* is 251 km, and *A* to *D* is 187 km.

The type of the pole conductor is 4 × JL/G2A-720/50, the type of the ground wire is OPGW-150, and the type of the metal return line is JNRLH60/G1A-400/35. The typical tower diagram is shown in Fig. 2.

The reference voltage of the pole line arrester is 629 kV, residual voltage of 904 kV under switch operation with 2 kA coordinate current.

The converter station-level control is achieved by using a double closed-loop controller. The control principle used in the simulation is shown in Fig. 3 [11–16].

3.2 Simulation results

3.2.1 Overvoltage during bipolar operation: During the bipolar operation, the maximum overvoltage on the metal return occurs when the *A–D* line is out of operation. When the monopole grounding fault occurs on the *B–C* line, the maximum overvoltage of the *B–C* return line is 489.05 kV (Table 1).

3.2.2 Overvoltage during monopolar operation: When the monopole runs, the maximum overvoltage of the metal return occurs when the *C–D* pole line and the return line exit. When the monopole grounding fault of the *B–C* line is cleared, the overvoltage of the *B–C* return line is the maximum and the value of 478.15 kV (Table 2).

3.2.3 Metal return line overvoltage caused by fault in converter station: The failure within the converter station will also produce overvoltage in neutral bus, such as grounding fault between the valve bottom and the bridge arm.

By strict consideration, the 385 kV transient overvoltage was simulated and supplied to the neutral bus in converter station *C*, shown in Fig. 4, which was equal to the switching protective level of EM MOA, and then the overvoltage on the metal return line could be calculated. The overvoltages distribution along the four metal return lines are shown in Fig. 5. The maximum transfer overvoltage appears on the metal return line of the *C–D* line is 407 kV, which is less than the maximum overvoltage of 489 kV generated by the pole line ground fault clearing.

When the simulated 385 kV overvoltage was supplied to the neutral bus in converter station *D*, the maximum transfer overvoltage appears on the metal return line of the *A–D* line is 405 kV.

4 Insulation coordination

The metal return line is grounded by 15 Ω resistance at the converter station *D*. So, the operation voltage is low in operation and, therefore, contamination is generally not effective for the insulator pieces number selection.

On the other hand, during the monopolar operation, while one side of the metal return lines suffered the shielding failure or back flashover and insulator flashed, the DC current flowing through the insulator is DC operating current, which is up to hundreds or thousands ampere. As there is no zero point for the DC current, the insulator is dangerous and may be burnt off. So, between the two terminals of the insulators, the arc horn should be equipped, and the air gap is selected according to 0.85 times of the effective string length.

According to IEC 60071-3, the 50% switching impulse flashover voltage of air gap can be calculated by the below equation, which can be used for insulation coordination of metal return lines

$$U_{50\%s} = \frac{K_a}{(1 - 2\sigma_s)} U_{rp} \quad (2)$$

Where U_{rp} is the maximum overvoltage, K_a the discharge voltage correction coefficient of air density and humidity of the under the switch impulse voltage, and σ_s the standard deviation.

According to the overvoltage results above, the maximum value is 489 kV. By using (2), the positive 50% operation impulse discharge voltage requirement could be calculated, and altitude correction is carried out according to IEC 60071-2. Then the length of the arc horn gap and the insulator number could be obtained (Table 3).

Table 1 Overvoltage during bipolar operation

Location of metal return line	Maximum overvoltage	Fault pole line	Connection mode
A–D	416.19	*A–D*	3 stations with 2 lines
C–D	399.67	*C–D*	2 stations with 1 line
B–C	489.05	*B–C*	4 stations with 3 lines
A–B	426.24	3 stations with 4 lines	—

Table 2 Overvoltage during monopolar operation

Location of metal return line	Maximum overvoltage	Fault pole line	Connection mode
A–D	402.92	*A–D*	2 stations with 1 line
C–D	401.71	*C–D*	2 stations with 1 line
B–C	478.15	*B–C*	4 stations with 3 lines
A–B	426.43	*A–B*	4 stations with 3 lines

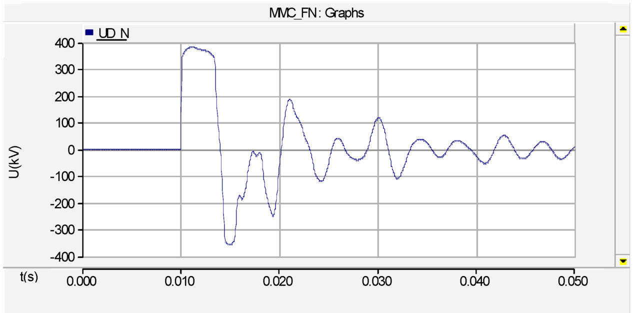

Fig. 4 *Simulated 385 kV transient overvoltage waveform*

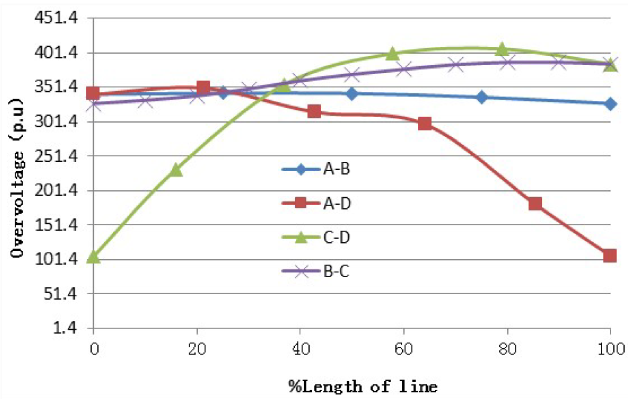

Fig. 5 *Overvoltage distribution along the four metal return lines*

5 Conclusion

i. For the ±500 kV half-bridge MMC-HVDC grid project with overhead transmission line which is under construction in China at present, the transmission lines are intended to use overhead lines and only one electrical grounding point is allowed. Then the overhead metal return lines are necessary. As there is strong coupling effect between the pole lines and the metal return lines on the same tower, when one pole line encountered the grounding fault caused by lightning shielding failure or pollution flashover, the overvoltage certainly would be caused on the metal return lines.

ii. The operation mode of the DC power grid is complex. The converter stations and the transmission lines all have the possibility of withdrawing from the operation. For the four-terminal transmission grid, the maximum overvoltage occurred when the grid loop was open. It means that the overvoltage was higher when there were transmission lines exit.

iii. The overvoltage of the metal return line caused by reclosing is less than that caused by the grounding fault clearing.

iv. The overvoltages generation mechanism is not yet clearly analysed. The influence of the tower size, the network structure, and the control strategy should be further studied to support the project design.

Table 3 Required values of air gaps and insulator number of metal return line under switch impulse overvoltage for a four-terminal MMC-HVDC grid

Altitude, m	Gap length of arc horn, mm	Effective string length of insulators, mm	Number of insulators (170 mm/piece)
0	982	1227	8
1000	1133	1416	9
2000	1328	1660	11

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