Analysis and Protection of DC Short Circuit Fault in True Bipolar MMC-HVDC System

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Abstract: With the introduction of modular multilevel converter (MMC), the development of high voltage direct current transmission (HVDC) technology has been promoted. As flexible DC transmission technology is gradually extended to overhead line transmission, DC fault clearing and fault protection issues have become particularly important. In this paper, the current characteristics of different stages of DC short-circuit faults are studied for the overhead line true bipolar MMC-HVDC system. The simulation model of the true bipolar system is built by PSCAD/EMTDC software. The simulation results verify the correctness of the analytical calculation. Finally, in order to suppress the sudden increase of bridge arm current during fault, a bridge arm protection method for DC short-circuit fault is proposed. The simulation results show that the protection method can effectively protect the sub-module device in case of fault, and can shorten the fault recovery time, this protection method effectively protects the devices of the AC system and sub-modules.

1. Introduction

The probability of a short circuit fault in an overhead line in a direct current transmission project is large, the problem of fault clearing and fault protection is particularly acute. In the existing fault clearing mode, although the DC breaker can cut off the fault current [1-2] in a short time, due to the limitation of the DC breaker technology, its breaking current capability is limited. Another way is to use sub-modules with fault self-cleaning capability, such as full-bridge sub-modules, clamped dual sub-modules, etc. [3-4]. Due to economic problems, its application in practical engineering is limited. In [5], for the true bipolar system, the current calculation formula under DC single-pole ground fault is derived.

Although the above research results promote the development of flexible DC technology, the research on fault characteristics and fault protection of true bipolar MMC-HVDC system is not perfect. This paper introduces the basic operating characteristics of true bipolar MMC. By analyzing the characteristics of true bipolar MMC-HVDC DC single pole ground fault, the equivalent mathematical model of the converter before and after blocking is established. The analytical formula of the derivation is calculated by PSCAD simulation verification. Finally, a bridge arm bypass protection method for DC short-circuit fault is proposed. It is verified by simulation that the protection method can effectively limit the short-circuit current and shorten the short-circuit fault recovery time.

2. Bipolar MMC-HVDC system operating principle

The true bipolar MMC-HVDC system has two converter stations and DC circuits. As shown in Figure...
1, the single-ended converter station consists of two inverters with the same structure, and the common connection point is grounded in the station. Similar to the traditional DC transmission, the two poles are independent of each other under normal conditions; when a pole fails, the non-fault pole can form a power supply loop through the earth to maintain normal operation.

![Figure 1. True bipolar configuration MMC-HVDC system.](image1)

The structure of a single MMC is shown in Figure 2. The three phases have a total of six bridge arms, and each phase of the upper and lower bridge arms is composed of a bridge arm reactor L and N submodules in series. This paper is based on the half-bridge MMC. By controlling the breaking state of the internal components of the sub-module, the switching of the sub-module can be controlled, so that the sub-module outputs two levels of 0 or $U_c$. In order to keep the voltage on the DC side constant, the sum of the number of sub-modules put into the upper and lower arms of each phase at any time is $N$.

3. Analysis of single pole grounding fault in bipolar MMC-HVDC system

3.1 Fault characteristics before the inverter is locked

For the bipolar MMC-HVDC system, the fault characteristics of the DC-side bipolar short-circuit are basically the same as those of the single-pole grounding. Therefore, this paper takes the single-pole grounding short-circuit fault on the DC-side positive bus as an example to analyze the change in different fault phases. The path and variation law of the current of the bridge arm current is the positive direction from top to bottom. The fault process can be divided into three phases: before latching, after latching, and after tripping of the AC breaker.

Before the inverter is locked, the sub-module shunt capacitor is over-current caused by rapid discharge of T1. The capacitor discharge equivalent circuit is shown in Figure 3. At the same time, the AC system injects short-circuit current into the short-circuit point through the diode D2 in the sub-module. The bridge arm current at this stage is formed by superposing the AC short-circuit current and the capacitor discharge current of the sub-module.

![Figure 3. Submodule capacitor discharge equivalent circuit.](image2)
At the moment of the fault, the second-order discharge loop is composed of the sub-module capacitance, the bridge arm reactance and the resistance. The following equation can be listed as the differential equation is

$$L \frac{d^2 i_c}{dt^2} + R_{loss} \frac{di_c}{dt} + \frac{i_c}{C} = 0$$  \hspace{1cm} (1)$$

The single-phase bridge arm discharge process is analyzed under the single-pole ground fault of the A phase. In the discharge circuit, the reactor in the A phase of the inverter and the reactor in the lower arm are connected in series, so the equivalent inductance is \(L = 2L_0\). The sub-modules of the A-phase upper and lower arms are put into operation in series, and the equivalent capacitance is \(C = C_0/n\).

Where \(n\) is the number of A-phase bridge arm sub-modules, \(U_{dc}\) is the sum of the DC voltages of the input modules. \(R_{loss}\) stands for DC link resistance, including line resistance, short-circuit point transition resistance (grounding resistance), and grounding resistance.

From (1) available capacity discharge current is

$$i_c = Ce^{-\delta t} \left[ \left( \frac{U_{dc}}{2} - \frac{U_{dc} \delta C - 2nL_0}{2C \omega} \omega \right) \cos(\omega t) + \left( \frac{U_{dc}}{2} + \frac{U_{dc} \delta C - 2nL_0}{2C \omega} \omega \right) \sin(\omega t) \right]$$  \hspace{1cm} (2)$$

The expression of the unknown is. According to formula (2), the variation range of the bridge arm voltage is

$$\omega = \frac{n}{\sqrt{2L_0C_0} - \delta^2}$$  \hspace{1cm} (3)$$

$$\delta = \frac{R_{loss}}{4L_0}$$  \hspace{1cm} (4)$$

### 3.2 Fault characteristics after the inverter is blocked

After the inverter is latched, the sub-module capacitor stops discharging, but the residual energy of the bridge arm inductor continues to provide short-circuit current to the DC-side short-circuit point through the diode of the sub-module, which constitutes the DC component of the bridge arm current, and the loop impedance It gradually decays under the action. At the same time, the AC system still injects short-circuit current into the short-circuit point through D2, which constitutes the AC component of the bridge arm current. During this process, the DC component is gradually attenuated to zero by the loop impedance, and the AC component is not attenuated. The equivalent circuit of the converter after blocking is shown in Figure 4.

![Converter equivalent circuit after blocking.](image-url)

**Figure 4.** Converter equivalent circuit after blocking.

Assume that the voltage of the A phase of the AC power source is \(u_a = U_m \sin(\omega t)\), Then the current of the upper and lower arms after the inverter is locked is

$$i_{up} = -\frac{I_{dc}}{2} \cos(\omega t + \phi) + I_{lock} e^{-\delta t}$$  \hspace{1cm} (5)$$
\[ i_{down} = \frac{I_m}{2} \cos(\omega t - \varphi) + I_{lock} e^{-\delta t} \]  

(6)

Where \( \omega \) is the power frequency angular frequency; \( I_m \) is the short-circuit current periodic component amplitude; \( I_{lock} \) is the initial value of the blocking transient bridge arm current. \( R_{ac}, L_{ac} \) are AC side equivalent resistance and reactance.

3.3 Fault characteristics of AC circuit breaker after tripping

After the AC breaker trips, the AC system stops injecting short-circuit current into the inverter, and the energy of the single-arm inductor can still be released to the DC side through the diode of the sub-module. The current on the DC side is gradually attenuated, and the time constant of the attenuation is determined by the DC loop resistance \( R_d \) and the equivalent inductance \( L \), that is, \( \tau = L/R_{loss} \).

4. DC single pole ground fault protection for bipolar MMC-HVDC system

According to the analysis in the second section, the AC system continues to inject short-circuit current to the fault point after the inverter is locked, and the presence of the bridge arm current has an adverse effect on the diode of the sub-module. Especially in the case of a small grounding resistance, the inductor current is attenuated slowly, causing the device to withstand overcurrent for a long time and prolonging the fault clearing time.

Therefore, this paper proposes a protection method for a bipolar MMC-HVDC system with single-pole ground fault. The specific method is to connect a bridge composed of a shunt resistor and a bypass thyristor on each phase of the MMC and the lower arm. Arm bypass. Taking the monopole MMC as an example, as shown in Figure 5.

As can be seen from Fig. 5, the bridge arm bypass is composed of two anti-parallel bypass thyristors S1 and S2 and a shunt resistor connected in series. In normal operation, the bypass thyristor is in the off state and the bridge arm bypass does not function. When the DC single-pole ground fault is detected, the IGBT is immediately blocked and the bypass thyristor S1 is triggered (assuming the converter is in the rectified state; if the inverter is operating in the inverter state, the bypass thyristor S2 is triggered. In the state, only one of the two bypass thyristors is turned on, and the other does not operate in the off state).

Selecting a smaller shunt resistor \( R_p \) allows the inductor current to flow mostly through the bridge bypass, thereby reducing the fault current flowing through the submodule and providing fault protection for the submodule devices. The current in the bypass of the bridge is gradually attenuated due to the presence of the bypass resistor. When the current decays below the holding current of the thyristor, the bypass thyristor is turned off by itself.
5. Simulation and verification
In this paper, the unipolar ground fault transient characteristic analysis method and fault protection strategy are proposed. The simulation model of bipolar MMC-HVDC system is built under PSCAD/EMTDC.

It is assumed that a single-pole grounding short-circuit fault occurs on the overhead line at the DC-side outlet of the inverter at t=0.3s, and the inverter is blocked after 10ms (t=0.31s) after the fault occurs, after 100ms (t=0.4s) AC circuit breaker action.

Figure 6 shows the fault current waveform. The simulation calculation curve in the figure is basically consistent with the fault analysis process and the analytical calculation expression. It can be seen that the fault process can be divided into three phases: before latching, after latching, and after tripping of the AC breaker. Figure 7 shows the fault current comparison before and after the parallel bypass thyristor. The current flowing through the bridge arm and the DC side after the bypass thyristor is triggered is rapidly reduced, and the DC current is attenuated to zero in a short time after the AC breaker is disconnected, indicates that the protection method is effective.

![Figure 6. DC side current under fault.](image1)

![Figure 7. Current waveform comparison](image2)

6. Conclusion
In this paper, the characteristics of DC faults in this topology are clarified by studying the discharge mechanism of the sub-module capacitors, short-circuit path and bridge arm current during the DC bipolar ground fault of the true bipolar MMC-HVDC system.

By simulating the short-circuit fault analysis, it can be seen that the bridge arm current will suddenly increase when the short circuit occurs, which will affect the sub-module device. Therefore, this paper proposes a bridge arm protection method for DC short-circuit fault, which is to use the bridge arm. The shunting action of the bypass rapidly reduces the fault current flowing through the bridge arm and the DC side. The simulation results show that the protection method can not only limit the fault current, but also reduce the current flowing through the bridge arm and the DC side, and shorten the fault recovery time. It can better serve the internal components of the inverter and the AC system fault protection.

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