Analysis of Fault Characteristics of AC Line Interconnected with MMC

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Abstract. Affected by the control strategy of suppressing the negative sequence current and limiting the amplitude of the positive sequence current after the MMC fault, the fault characteristics of the converter side of the AC line interconnected with the MMC show that the negative sequence current is very small and the positive sequence current amplitude is different from the rated value. Compared with the fault characteristics of the traditional power supply, there are obvious differences between the minor characteristics and the fault characteristics of the traditional power supply. And it has been simulated and verified on the RTDS simulation platform.

Keywords: MMC, AC line, fault characteristics, pilot protection, RTDS.

1. Introduction
MMC-based flexible DC transmission technology can solve the risk of commutation failure in conventional DC. At the same time, it has received wide attention due to its more flexible control methods, less reactive power demand and no need for filtering [1-3]. The pilot protection of the AC line interconnected with MMC is also affected by the inverter control strategy and is not applicable [4]. This paper analyzes the fault current characteristics of the converter side and the synchronous grid side of the AC line interconnected with MMC according to the control strategy of MMC. And the simulation on RTDS simulation platform verified the correctness of the analysis.

2. Analysis of Line Fault Current Characteristics
The three-terminal MMC connection is shown in Figure 1. MMC1 is interconnected with the synchronous grid 1, MMC2 is interconnected with the synchronous grid 2, and MMC3 is interconnected with the wind farm.

2.1. Fault characteristics of converter side
The dynamic equation of MMC1 AC side is:

\[ U_{abc} = L \frac{d}{dt} I_{abc} + RI_{abc} + U_{abc} \]  

(1)

The dynamic equation of MMC1 AC side in the two-phase rotating coordinate system is:
In order to eliminate the coupling effect between dq, feedforward decoupling and PI adjustment are used for control:

\[
\begin{bmatrix}
    u_{cd} \\
    u_{cq}
\end{bmatrix} = \begin{bmatrix}
    u_{sd} \\
    u_{sq}
\end{bmatrix} - \omega L \begin{bmatrix}
    i_q \\
    -i_d
\end{bmatrix} - \begin{bmatrix}
    K_p
    \int (i_q - i_d) \\
    \int (i_q - i_d)
\end{bmatrix} + \begin{bmatrix}
    K_i
    \int (i_q - i_d)
\end{bmatrix}
\]

Combining formulas (2) and (3) can get:

\[
L \frac{d}{dt} \begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} - R \begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} = K_p \begin{bmatrix}
    i_d^* - i_d \\
    i_q^* - i_q
\end{bmatrix} + K_i \begin{bmatrix}
    \int (i_d^* - i_d) \\
    \int (i_q^* - i_q)
\end{bmatrix}
\]

When the switching frequency is high enough and the current inner loop has a faster response speed, the transient process can be ignored; that is, it is approximately considered:

\[
\begin{cases}
    i_d \approx i_d^* \\
    i_q \approx i_q^*
\end{cases}
\]

According to the outer loop control:

\[
\begin{align*}
    i_d^* &= K_p (U_{dref} - U_{dc}) + K_i \int (U_{dref} - U_{dc})dt \\
    i_q^* &= K_p (Q_{ref} - Q) + K_i \int (Q_{ref} - Q)dt
\end{align*}
\]
Perform Parker’s inverse transformation to get:

\[
\begin{align*}
    i_{01}(t) &= I_m \cos(\omega t + \theta_i + \varphi) \\
    i_{02}(t) &= I_m \cos(\omega t + \theta_i + \varphi - \frac{2}{3} \pi) \\
    i_{03}(t) &= I_m \cos(\omega t + \theta_i + \varphi + \frac{2}{3} \pi)
\end{align*}
\]

among them, \(\varphi = \arctan\left(\frac{i_d^*}{i_q^*}\right); \ I_m = \sqrt{(i_d^*)^2 + (i_q^*)^2}; \ \theta_i\) is the initial phase of phase A current;

When a non-ground fault occurs, the current measured at the protection installation of the AC line interconnected with the MMC is three-phase symmetric; when a ground fault occurs, the current measured at the AC line protection installation is zero sequence current and positive sequence current the superimposed current.

![Zero sequence network diagram](image)

**Figure 2.** Zero sequence network diagram

The zero-sequence network is shown in Figure 2. When a single-phase to ground short circuit occurs, the zero-sequence current expression at the fault point is:

\[
I_{fA}^0 = \frac{U_{\|}}{Z'_x + Z'_z + Z'_N + 3R_f} = \frac{U_{\|}}{Z_{xG}} \angle - (\theta_{M} + \theta_{xAG})
\]

(8)

The zero-sequence current on the converter side is:

\[
I_{MA}^0 = \frac{(1 - \alpha)Z_L^0 + Z_N^0}{Z_T^0 + Z_L^0 + Z_N^0} I_{fA}^0
\]

(9)

When a ground fault occurs, the current on the converter side only contains positive sequence components and zero sequence components. Because MMC adopts the control strategy of limiting the amplitude of the positive sequence current, the amplitude of the positive sequence current is limited very small. Therefore, after a ground fault occurs, if the transition resistance is not large, the zero-sequence current amplitude of the M-side current is much greater than the positive sequence current amplitude, and the three-phase current amplitudes are approximately equal.
2.2. Synchronous grid side fault characteristics

In the case of a single-phase grounding fault, the phase difference between the positive and negative sequence components of the fault phase fault current is 0°, and the phase difference between the positive and negative sequence components of the non-fault phase fault current is 120°. At this time, the magnitudes of the positive and negative sequence component currents of the fault current are the same.

When a two-phase short circuit occurs, the phase difference between the positive and negative sequence components of the fault current of the fault phase is 60°, and the phase difference between the positive and negative sequence components of the non-fault phase fault current is 180°. At this time, the magnitudes of the positive and negative sequence components of the fault current are equal.

When two-phase short-circuit to ground occurs, the phase difference between the positive and negative sequence components of the fault current of the fault phase is 60°, and the phase difference between the positive and negative sequence components of the non-fault phase fault current is 180°. At this time, the magnitudes of the positive and negative sequence components of the fault current are not equal.

After a three-phase short-circuit fault occurs in the synchronous power grid, the potential and phase of the power supply will not change suddenly, which leads to changes in the amplitude and phase of the current, and because the current on the inductor cannot change suddenly, a DC component will be generated.

3. RTDS simulation verification

In order to verify the performance of the new principle of longitudinal protection mentioned above, the three-terminal MMC model shown in Figure 1 was built in RTDS. In steady state, MMC1 adopts constant DC voltage control, and the reactive power command is 0MW; MMC2 adopts constant power control, the active command is 200MW, and the reactive power command is 0MW; MMC3 adopts constant AC voltage and constant frequency control. The number of MMC half-bridge sub-modules is 200, DC voltage level is ±200kV, AC line length is 50km, AC voltage level is 230kV, AC voltage frequency is 50Hz, AC line positive sequence impedance is 0.076+j0.37661Ω/km, AC line zero-sequence impedance of the line is 0.284+j0.824Ω/km. The ground fault and non-ground fault are simulated and analyzed by taking A-phase single-phase ground fault and AB two-phase short-circuit fault as examples.

![Figure 3. Single-phase earth fault converter side fault characteristics](image-url)
As shown in Figure 3, when a phase A single-phase grounding short circuit occurs in the line, the q-axis current always remains at 0. The active power sent by the MMC will decrease, which will cause the DC voltage to rise, so the d-axis current rises quickly at this time, and after rising to the limiting value, it stabilizes at the limiting value unchanged. The AC three-phase current appears due to the DC current. The characteristics of the similar phases of the three-phase currents.

![Graph](image1.png)

**Figure 4.** Phase-to-phase faulty converter side fault characteristics

As shown in Figure 4, when the AB two-phase short circuit occurs on the line, the q-axis current remains constant at 0. The active power sent by the MMC will decrease, and then the DC voltage will rise, so at this time the d-axis current is affected by the outer loop constant DC voltage control and will continue to rise until it rises to the limit value unchanged. At this time, the MMC side AC current It is a three-phase symmetrical current with a constant amplitude.

4. Conclusion

In the case of an asymmetrical fault in the AC line interconnected with the MMC, the current sent by the converter to the AC line only contains the positive sequence current, that is, the current is three-phase symmetric. And after entering the current-limiting working mode with the MMC, the amplitude of the positive sequence AC current emitted by the inverter will be constant. When an internal ground fault occurs in the AC line, the zero-sequence current at the protection installation on the converter side is much greater than the positive-sequence current, and the phases of the three-phase currents are similar. In the case of a symmetrical fault in the area, the AC current emitted by the converter is three-phase symmetrical, there is no DC component, and as the converter enters the current limiting mode, the current amplitude will remain constant.

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