Modeling on Transient Characteristic and Suppression Control of DC Fault in MMC-HVDC System

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Abstract. This paper focuses on analyzing the transient characteristic of DC transmission line fault in the modular multilevel converter based high voltage direct current (MMC-HVDC) system. Equivalent circuit models of DC transmission line pole-to-ground fault, pole-to-pole fault and line breaking fault are established respectively in this paper. The mechanism of DC faults is analyzed and mathematical expressions of fault voltage and fault current are derived. The transient processes of these faults are analyzed based on the equivalent circuit models. The suppression control for DC fault based on virtual impedance is studied to reduce the over current level. Simulation results with a 2-terminal MMC-HVDC model on the RT-LAB platform verify the modeling and analysis on transient characteristic and the effect of suppression control of DC transmission line fault.

1. Introduction
The MMC-HVDC system, as a new type of transmission technology [1], adopts the sub-module with the semiconductor devices in cascaded connections. The most serious operation problem of MMC-HVDC system is the DC line transmission fault [2]-[3]. DC faults mainly include pole-to-ground fault, pole-to-pole fault, line breaking fault, and then the qualitative analysis and simulation of transient characteristics are studied in [4]-[6]. Several protection schemes have been proposed to deal with the pole-to-pole fault [7]-[9]. This paper proposes a circuit model analysis method, which can neglect submodule switching of the real-time changes during transient process. Besides, it establishes the equivalent circuit models of three kinds DC faults and analyzes the mechanism of DC faults under the DC system. The over current suppression control based on virtual impedance, characteristics of AC and DC outlet impedance were mathematically mapped to the control scheme respectively, was studied to reduce the over current level. A 2-terminal MMC-HVDC model is established on RT-LAB and simulation results also correspond with the theoretical fault transient analysis and the effect of suppression control.

2. Modeling of MMC-HVDC System
The MMC-HVDC system consists of 2-terminal MMC converter and high voltage DC bus. The single station system topology of MMC-HVDC is shown in Figure 1. The ground method uses three star-connected reactors with a neutral ground resistance [10].
2.1. Analysis of transient characteristics of pole-to-ground fault

The voltage to ground of positive line \( U_{dc,p} \) and negative line \( U_{dc,n} \) can be expressed as

\[
U_{dc,p} = -(I_{0,1} + I_{0,2})R_f \quad U_{dc,n} = -(I_{0,1} + I_{0,2})R_f \quad -U_{dc}
\] (1)

Fault current \( I_f \) can be given as

\[
I_f = I_{0,1} + I_{0,2}
\] (2)

![Figure 1. Single station system topology of MMC-HVDC.](image)

The equivalent circuit of the positive ground fault before converter station stopped is shown in Figure 2. The equivalent resistance and equivalent inductance of transmission line are defined as \( R_L \) and \( L_L \).

![Figure 2. The circuit of the positive ground fault: (a) the simplified circuit. (b) the equivalent circuit.](image)

The positive ground fault can be characterized by the following equation.

\[
\frac{3C_s(L_a + L_{q1} + L_{g1})/3 + 0.5L_e}{n} \frac{d^2u_c}{dt^2} + (R_{a1}/3 + R_{g1} + R_f + 0.5R_e)(L_a + L_{q1} + L_{g1})/3 + 0.5L_e \frac{du_c}{dt} + u_c = 0
\] (3)

The initial condition of the positive ground fault can be defined as

\[
U_c(0_+) = U_c(0-) = U_{dc}/2 \quad I(0_+) = I(0-) = I_{dc,p}
\] (4)

Where the \( I_{dc,p} \) is the current of positive line.

The formula for calculating the fault current \( I_{0,1} \) can be derived as
\[ I_{0,1} = \frac{(n I_{dc, p} + 3C_0 p U_{dc})p e^{\delta t} - (n I_{dc, p} + 3C_0 p U_{dc})p_2 e^{\delta t}}{2n\sqrt{\delta^2 - \varepsilon}} \]  

\textbf{Where}

\[ \delta = \frac{R_l + 3R_{g1} + 3R_j + 1.5R_e}{2(L_a + L_{g1} + L_{s1} + 1.5L_g)}, \varepsilon = \frac{3n}{4C_0(L_a + L_{g1} + L_{s1} + 1.5L_g)}, p_1 = -\delta + \sqrt{\delta^2 - \varepsilon}, p_2 = -\delta - \sqrt{\delta^2 - \varepsilon} \]  

\[ 2.2. \text{ Analysis of transient characteristics of pole-to-pole fault} \]

The formula for calculating the voltage of capacitance \( U_c \) can be given as

\[ U_c = \frac{\omega_0 U_{dc}}{\omega} e^{-\delta t} \sin(\omega t + \beta) - \frac{nI_{dc, p} - p}{6\omega C_0} e^{-\delta t} \sin(\omega t) \]  

The formula for calculating the discharging current \( I \) can be derived as

\[ I = \frac{3U_{dc}}{2n(2L_a + 3L_g)} e^{-\delta t} \sin(\omega t) + \frac{\omega_0 I_{dc, p}}{\omega} e^{-\delta t} \sin(\omega t - \beta) \]  

\textbf{Where}

\[ \delta = \frac{3R_l + 3R_j}{2(2L_a + 3L_g)}, \omega = \sqrt{\frac{n}{2C_0(2L_a + 3L_g)}} - \delta^2, \omega_0 = \sqrt{\delta^2 + \omega^2}, \beta = \arctan\frac{\omega}{\delta} \]  

\[ 2.3. \text{ Analysis of transient characteristics of line breaking fault} \]

The formula for calculating the voltage of capacitance \( U_c \) can be derived as

\[ U_c = \frac{(2nI_{dc, N} + 3C_0 p U_{dc})p e^{\delta t} - (2nI_{dc, N} + 4C_0 U_{dc})p_2 e^{\delta t}}{4nC_0\sqrt{\delta^2 - \varepsilon}} \]  

The formula for calculating the fault current \( I \) can be given as

\[ I = \frac{(2nI_{dc, N} + 3C_0 p U_{dc})p_1 e^{\delta t} - (3nI_{dc, N} + 3C_0 p U_{dc})p_2 e^{\delta t}}{4n\sqrt{\delta^2 - \varepsilon}} \]  

\textbf{Where}

\[ \delta = \frac{6R_l + 2R_j + 3R_e}{2(2L_a + 2L_j + 2L_g + 3L_e)}, \varepsilon = \frac{2n}{C_0(2L_a + 2L_j + 2L_g + 3L_e)}, p_1 = -\delta + \sqrt{\delta^2 - \varepsilon}, p_2 = -\delta - \sqrt{\delta^2 - \varepsilon} \]  

DC line voltage \( U_{dc} \) can be expressed as

\[ U_{dc} = U_{dc, p} - U_{dc, n} \]  

\textbf{3. Simulation Verification}

This paper studies a 2-terminal MMC-HVDC system. The main parameters are listed in Table 1.
Table 1. Main circuit parameters of the MMC-HVDC system

| Parameters                          | Value       | Parameters                          | Value       |
|-------------------------------------|-------------|-------------------------------------|-------------|
| Rated power $P$                     | 20MW        | Neutral point ground inductance $L_g$ | 0.5H        |
| Rated DC-link voltage $U_{dc}$      | ±20kV       | Ground fault resistance $R_f$        | 10mΩ        |
| Rated AC grid voltage $U_s$         | 10kV        | Short-circuit contact resistance $R_{st}$ | 10mΩ        |
| Fundamental frequency $f_s$         | 50Hz        | Transformer magnetization resistance (p.u.) | 500         |
| Arm inductance $L_a$                | 10mH        | Transformer magnetization inductance (p.u.) | 5000        |
| AC-side inductance $L_s$            | 1mH         | Overhead line length                | 20km        |
| AC-side resistance $R_s$            | 10mΩ        | Line resistance                     | 11.4000mΩ/km |
| Capacitance $C_0$                   | 3000μF      | Line inductance                     | 0.9356nH/km |
| Number of sub-module per arm $n$    | 20          | Line capacitance                    | 12.3000nF/km |
| Neutral point ground resistance $R_g$ | 20Ω            |                                      |             |

After the system stable operating of 2.5 s, the neutral point of the positive line is set with a metal ground fault, pole-to-pole fault and line breaking fault, and the simulation waveform is shown in Figure 3-5.

4. Suppression Control of DC Fault

4.1. Analysis of suppression control of dc fault

The over current suppression control for DC fault based on virtual impedance is shown in Figure 6. The characteristics of AC and DC outlet impedance were mathematically mapped to the control scheme respectively.
In the frequency domain, the added impedance can be deduced as

\[
Z_{\alpha\omega}(j\omega) = R_{\alpha\omega}(j\omega) + L_{\alpha\omega}(j\omega) = \frac{R_{s}(L_{s}\omega)^2}{R_{s}^2 + (L_{s}\omega)^2} + \frac{R_{d}^2 L_{d}\omega}{R_{d}^2 + (L_{d}\omega)^2}
\]  

(14)

As a result, the average peak current of bridge arm \(i_{\text{arm}_m}\), defined as a kind of more intuitive overcurrent evaluation indexes both in average and transient to measure the effect of the overcurrent suppression control, can be expressed as

\[
i_{\text{arm}_m} = i_{\text{ac}_m} + i_{\text{dc}_m} = \frac{1}{2} \sqrt{i_{id}^2 + i_{iq}^2} + \frac{1}{3} |I_{dc}|
\]

(15)

Over current suppression control based on virtual impedance can significantly reduce the overcurrent level.

### 4.2 Simulation verification of suppression control of dc fault

The maximum rated of \(i_{\text{arm}_m}\) is about 1 kA observed in the steady state operation, so the peak current can be set as 2 kA, which means that the IGBTs must be blocked before the arm current reaches 2 kA.
5. Conclusion

This paper proposes a circuit model analysis method for the MMC-HVDC system, and establishes the equivalent circuit models by analyzing three kinds of DC faults mechanisms. The mathematical expression of the fault voltage and fault current are deduced. The over current suppression control based on virtual impedance was studied. A 2-terminal MMC-HVDC model is established on RT-LAB platform and the simulation results also verify the fault transient analysis.

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