Quantitative Analysis of AC/DC Side Harmonic Transfer Characteristics for Modular Multilevel Converter and Suppression Measures

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ABSTRACT MMC (Modular Multilevel Converter) is the preferred topology for renewable energy delivery, but renewable energy resources, such as wind farms, contain much harmonic components. Compared with two-level VSC (Voltage Source Converter), the internal dynamic characteristics of MMC have great impact on the harmonic transmission. This paper quantitatively analyzes the harmonic transferring mechanism from one side to the other side of MMC, and deduces the time-domain analytical expression of the harmonic response on the MMC’s other side. Firstly, the influence of background harmonic on MMC’s control system and electrical system are quantitatively analyzed. On this basis, the equivalent circuit of MMC’s electrical system considering its internal dynamics is established to accurately calculate the effect of background harmonic on the MMC’s other side. In addition, the harmonic transferring impedance in frequency-domain is also defined in this paper, based on that the influence of background harmonic on the MMC’s other side can be calculated quickly. According to the harmonic transferring characteristics analyzed above, a zero-sequence virtual damping strategy is proposed for the first time to suppress the background harmonic transferring. Finally, a 232-level 500kV MMC simulated model is built in MATLAB/Simulink to verify the accuracy of the harmonic transferring calculation method and the effectiveness of the virtual damping suppression strategy.

INDEX TERMS Modular multilevel converter, impedance model, harmonic transmission, flexible dc power grid, stability.

I. INTRODUCTION Modular multilevel converter (MMC) has the advantages of easy expansion, which can effectively implement the electrical energy transformation under high voltage level [1], [2]. With the development of new energy generation, more and more weak systems and renewable energy sources, such as photovoltaics and wind power generation, are connected and transferred through MMC [3]–[5]. However, weak AC systems and renewable energy farm are vulnerable to harmonic disturbances and non-linear equipment [6], [7]. In recent years, with the appearance of the SSO (Sub-synchronous Oscillation) phenomenon of doubly-fed wind turbine, harmonic stability has attracted wide attention. Therefore, when MMC is connected to the wind farms or others, the stability is easily affected [8]–[10]. What’s more, the harmonic in MMC’s line currents will flow into its arms and distort the arm current, thus the capacitor voltage of MMC’s sub-module will also be influenced, increasing the difficulties of balancing the capacitor voltage and of suppressing the arm circulating current [11]. In some extreme cases, AC side background harmonic of specific frequencies will cause resonance of the whole DC network and spread to other interconnected AC systems through the DC bus, leading to the system instability [12].

At present, there are many researches about the influence of AC side background harmonic on two-level VSC systems. The transferring mechanism of AC harmonic through the
traditional VSC was studied in [13]. It pointed out that the DC bus inductor and MMC’s arm capacitor will cause the DC network resonance. However, there are relatively few researches about the influence of background harmonic on MMC.

Compared with traditional VSC topologies, in MMC, its arm voltage will play a key role in the harmonic transferring process, but it has not been studied in detail. In fact, the background harmonic will generate the harmonic modulation wave in MMC’s control system. At the same time, the background harmonic will also generate a series of harmonic components in MMC’s sub-module, which means the coupling process of harmonic components in MMC is very complex [14]. Reference [12] qualitatively analyzed the impact of background harmonic on multi-terminal DC transmission system ignoring the influence of the sub-module’s capacitor voltage fluctuation and the arm circulating current on the harmonic transferring process, which leads to the result that the process of harmonic transmission cannot be quantitatively analyzed. Based on the average switching function model, the harmonic coupling relationship of MMC’s sub-module is introduced in [15] and the detailed analytical expression of the arm circulating current has been derived, but the derivation is based on the premise that the modulation wave only contains the DC component and the fundamental-frequency component without considering the harmonic components of the modulation wave. The steady-state harmonic of MMC are derived by iterative method in reference [16]. The derivation process is complicated and the coupling relationship between the background harmonic and the MMC’s steady-state electrical quantities is not considered, thus it cannot be used for quantitative analysis of harmonic transferring characteristics.

As for the harmonic transferring suppression strategy, reference [12] proposed an additional control strategy based on PR controller. Since PR controller has its inherent resonance frequency, it only suppresses the background harmonic of the frequency near its resonant frequency. When the background harmonic frequency changes, the effect of PR controller will be weakened. Reference [17] proposed an AC side current and DC side voltage decoupling control method requiring pre-calculation of modulation wave, which will affect its dynamic characteristics and will be more complex to implement.

Therefore, it is necessary to propose an analytical analysis method for the MMC’s harmonic transferring characteristics and the corresponding harmonic suppression strategy. This paper presents a quantitative analysis method of harmonic transmission on the basis of the impedance modeling and average switching function model. Firstly, the influence of background harmonic on MMC’s control system is quantitatively analyzed in time domain, then the coupling relationship between its control system and the electrical system is deduced. Finally, the equivalent circuit for the harmonic transferring quantitative calculation is established. And in the process of derivation, the influence of background harmonic on electrical and control quantities are not ignored.

As a result, the accuracy of the proposed harmonic transferring calculation method is better.

In addition, in accordance with the frequency-domain impedance model established in [18], this paper defines the transfer impedance which describes the constraint relationship between the harmonic voltage in MMC’s one side and the harmonic current response in the other side. The influence of background harmonic on MMC’s other side can be quickly calculated by transfer impedance compared with the time-domain method.

For the harmonic transferring suppression method, the zero sequence arm output voltage caused by the background harmonic is the medium of harmonic transferring between MMC’s AC and DC side. Therefore, this paper proposes a zero sequence virtual damping suppression method to block the background harmonic. Compared with that based on PR controller [12], the proposed method can suppress the harmonics of wider frequency range.

This paper is organized as follows. Section II describes the basic operating principle of MMC. Section III presents the mechanism of harmonic transferring from MMC’s AC side to its DC side. Section IV presents the mechanism of harmonic transferring inversely. And the harmonic transferring calculation method in frequency-domain is introduced in Section V. Section VI shows the harmonic transferring suppression strategy. The accuracy of proposed harmonic transferring calculation method and effectiveness of proposed harmonic suppression strategy is presented in Section VII. Section VIII is the conclusion.

II. BASIC OPERATING PRINCIPLE OF MMC

The MMC’s main circuit, the structure of control system and the topology of sub-module are shown in Fig. 1 [15], [20], and the current positive reference direction of the upper arm, lower arm and PCC (Point of Common Coupling) are marked with red arrow in MMC’s main circuit respectively. $i_{ku}$ and $i_{kd}$ are the currents flowing through the upper and lower arm of phase $k$ ($k = a, b, c$).

The topology of sub-module is shown at the top right of Fig. 1 where $i_C$ is the capacitor current. $u_C$, $u_0$ and $S_i$ ($i = 1, 2$) are the capacitor voltage, output voltage and the switching function of sub-module. When $S_1 = 1$ and $S_2 = 0$, the sub-module is put into. When $S_1 = 0$ and $S_2 = 1$, the sub-module is cut out. For the $i^{th}$ sub-module in each arm, the relationship between the capacitor current and switching function can be expressed as

$$\begin{cases}
  i_{C_1} = i_{ij}, & S_1 = 1, S_2 = 0 \\
  i_{C_2} = 0, & S_1 = 0, S_2 = 1
\end{cases} \quad (1)$$

where $i_{ij}$ is arm current ($j = u$ for the upper arm and $j = d$ for lower) of phase. The arm current is coupled to the capacitor current because of the switching action of sub-module. In addition, the voltage balancing control strategy (nearest level modulation method) is adopted to ensure the capacitor's voltage of each sub-module are the same during
The reference value of the inner current loop. The transfer obtained by (2).

The voltage and current of PCC are measured, then the dq components of voltage and current are obtained (dq decoupling control strategy, the current is controlled by inner-loop decoupled current control strategy, the voltage, DC voltage and power control mode. The structure of control system under the power control mode is shown in FIGURE 1. MMC system structure and basic control principle.

Each control period. And in practical HVDC projects, HVDC systems usually contains at least two MMCs, except for one MMC working in PQ control mode or AC voltage control mode, there must be one MMC working in DC voltage control mode. The MMC working in DC voltage control mode will keep the DC link voltage as constant and stable. So when studying the MMC under PQ control mode, the DC voltage could be regarded as constant.

The control modes of MMC can be divided into AC voltage, DC voltage and power control mode. The structure of control system under the power control mode is shown on the bottom of Fig. 1 where the control loop is based on the dq decoupling control strategy, the current is controlled by inner-loop decoupled current control strategy, the outer-loop is active/reactive power control (PQ control mode). Firstly, the voltage and current of PCC are measured, then the dq components of voltage and current are obtained by the dq transformation. Furthermore, the actual values of instantaneous active power \( P \) and reactive power \( Q \) can be obtained by (2).

\[
\begin{align*}
\begin{cases} 
p = \frac{3}{2}(u_d i_d + u_q i_q) \\
q = \frac{3}{2}(u_d i_q - u_q i_d)
\end{cases}
\end{align*}
\]

PI controller \( H(s) \) can be expressed as

\[
\begin{align*}
H_p(s) &= H_Q(s) = K_{pp} + K_{pi} s \\
H_i(s) &= K_{ip} + K_{ii} s
\end{align*}
\]

Where \( K_{pp} \) and \( K_{pi} \) are proportional and integral coefficient of the outer loop’s PI controller. \( K_{ip} \) and \( K_{ii} \) are the proportional and integral coefficients of the inner loop PI controller.

III. TRANSFERRING MECHANISM OF MMC’S AC SIDE BACKGROUND HARMONIC

A. INFLUENCE OF AC SIDE BACKGROUND HARMONICS ON CONTROL SYSTEM

When MMC’s AC side contains the background harmonic, the harmonic voltage will affect MMC’s system and electrical system. Therefore, this section will quantitatively analyze the influence of background harmonic on the control system.

The analysis process of background harmonic on control system under different control modes is similar. So in this paper, only the effect of AC background harmonic on MMC’s control system under power control mode is analyzed.

When MMC is not affected by the background harmonic, the steady-state voltage and current of PCC can be expressed as

\[
\begin{align*}
\begin{bmatrix} U_a \\
U_b \\
U_c \end{bmatrix} &= \begin{bmatrix} U_1 \cos(\omega t + \theta_A) \\
U_1 \cos(\omega t + \theta_A - \frac{2}{3}\pi) \\
U_1 \cos(\omega t + \theta_A + \frac{2}{3}\pi) \end{bmatrix} \\
\begin{bmatrix} I_a \\
I_b \\
I_c \end{bmatrix} &= \begin{bmatrix} I_1 \cos(\omega t) \\
I_1 \cos(\omega t - \frac{2}{3}\pi) \\
I_1 \cos(\omega t + \frac{2}{3}\pi) \end{bmatrix}
\end{align*}
\]

Where \( U_1 \) and \( I_1 \) are the amplitude of PCC’s voltage and current. \( \theta_A \) is the phase of PCC’s voltage and \( \omega \) is fundamental angular frequency which is equals to \( 2\pi f_1 \) (\( f_1 = 50 \)).

In this paper, the positive sequence background harmonic is taken as an example to discuss the transferring mechanism of harmonic voltage and current in control loop. When AC grid contains the known \( h^{+\text{th}} \) positive sequence harmonic voltage which is shown as

\[
\begin{align*}
\begin{bmatrix} U_{ah^+} \\
U_{bh^+} \\
U_{ch^+} \end{bmatrix} &= \begin{bmatrix} U_{h^+} \cos(h^+\omega t + \varphi_{h^+}) \\
U_{h^+} \cos(h^+\omega t + \varphi_{h^+} - \frac{2}{3}\pi) \\
U_{h^+} \cos(h^+\omega t + \varphi_{h^+} + \frac{2}{3}\pi) \end{bmatrix}
\end{align*}
\]

Where \( U_{h^+} \) and \( \varphi_{h^+} \) are the amplitude and phase of positive sequence harmonic voltage.

In order to calculate the harmonic current, MMC’s AC side impedance needs to be obtained. The impedance modeling method adopted in this paper is referred to the multi-harmonic linearization [18].
After obtaining the impedance model based on the multi-harmonic linearization method, the background harmonic current can be accurately calculated as

\[
\begin{bmatrix}
I_{ah+} \\
I_{bh+} \\
I_{ch+}
\end{bmatrix} = \begin{bmatrix}
U_{ah+} \\
U_{bh+} \\
U_{ch+}
\end{bmatrix} / Z_{ac}(h^+ \omega)
\]

\[
= \begin{bmatrix}
I_{h^+} \cos(h^+ \omega t + \theta_{h^+}) \\
I_{h^+} \cos(h^+ \omega t + \theta_{h^+} - \frac{2}{3} \pi) \\
I_{h^+} \cos(h^+ \omega t + \theta_{h^+} + \frac{2}{3} \pi)
\end{bmatrix}
\]

(7)

where \(I_{h^+}\) and \(\theta_{h^+}\) are the amplitude and phase of positive sequence harmonic current. \(Z_{ac}(h^+ \omega)\) is MMC’s AC side impedance of frequency \(h^+ \omega\).

After the dq transformation which can be expressed as (8), shown at the bottom of the page, where \(\theta_A\) is the initial phase angle of transformation angle, which is usually equal to the initial phase angle of phase \(a\), the dq steady-state and harmonic components of AC side voltage and current can be obtained which are shown in (9) and (10).

\[
\begin{align*}
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix} &= \begin{bmatrix}
U_1 \\
0
\end{bmatrix} \\
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} &= \begin{bmatrix}
I_1 \cos(\theta_A) \\
I_1 \sin(\theta_A)
\end{bmatrix}
\]

\begin{align*}
\hat{u}_d &= U_{h^+} \cos[(h^+ - 1) \omega t + \varphi_{h^+} - \theta_A] \\
\hat{u}_q &= U_{h^+} \sin[(h^+ - 1) \omega t + \varphi_{h^+} - \theta_A] \\
\hat{i}_d &= I_{h^+} \cos[(h^+ - 1) \omega t + \theta_{h^+} - \theta_A] \\
\hat{i}_q &= I_{h^+} \sin[(h^+ - 1) \omega t + \theta_{h^+} + \theta_{h^+} - \theta_A]
\end{align*}

\]

(9)

(10)

\(u_d\) and \(u_q\) denote the d- and q-axis steady-state PCC voltage respectively. \(i_d\) and \(i_q\) denote the d- and q-axis steady-state PCC current. \(\hat{u}_d\) and \(\hat{u}_q\) denote the d- and q-axis harmonic voltage of grid side. \(\hat{i}_d\) and \(\hat{i}_q\) denote the d- and q-axis harmonic current of grid side respectively. After the dq transformation, the frequency of the dq components compared to its original positive sequence harmonic will be subtracted \(f_1\) while the frequency of the dq components compared to its original negative sequence harmonic will be added \(f_1\).

When MMC is disturbed by the background harmonic, the active and reactive power are affected and their small signals can be expressed as

\[
\begin{bmatrix}
\hat{p} \\
\hat{q}
\end{bmatrix} = \begin{bmatrix}
\frac{3}{2} (\hat{u}_d i_d + \hat{u}_q i_q + u_d i_d + u_q i_q) \\
\frac{3}{2} (\hat{u}_d i_q - \hat{u}_q i_d - u_d i_d - u_q i_q)
\end{bmatrix}
\]

(11)

Substituting the harmonic and steady-state components of the voltage and current in (9) and (10) into (11), the influence of the background harmonic on the three-phase modulation wave shown in (12) can be obtained after the active and reactive power small signal pass through the outer loop’s PI controller, inner loop’s PI controller and dq inverse transformation.

\[
\begin{bmatrix}
\hat{M}_d \\
\hat{M}_q
\end{bmatrix} = T_{abc} H_p \left[ j((h^+ - 1) \omega) H_l \left[ j((h^+ - 1) \omega) \right] \right] \begin{bmatrix}
\hat{p} \\
\hat{q}
\end{bmatrix}
\]

(12)

The expression of dq inverse transformation matrix and the detailed expression of the harmonic modulation wave caused by the outer loop PI controller are in (13) and (14), as shown at the bottom of the page. In (14), \(\hat{M}_a\) contains the positive sequence modulation wave \(\hat{M}_{a1}\) of harmonic order \(h^+\) and the negative sequence modulation wave \(\hat{M}_{a2}\) of harmonic order \((h^+ - 2)\). \(G_{in}\) and \(G_{out}\) are the gains of inner and outer loop controller at the harmonic order \((h^+ - 1)\). \(\theta_{in}\) and \(\theta_{out}\) are the phase delay of the \((h^+ - 1)\)th small signals.
Through the above constraints and the transferring mechanism of harmonic current and voltage in the control loop, the analytical expression of the \( h^+ - 2^{\text{th}} \) harmonic modulation wave is in (15), as shown at the bottom of the page.

Equation (15) is the constraint relationship of modulation waves. It contains two unknown variables, the amplitude \( M_{h^+ - 2} \) and the phase \( \theta_{h^+ - 2} \) of the \( (h^+ - 2)^{\text{th}} \) modulation wave. Therefore, the other constraint relationship is needed to solve the two unknown variables. Fig. 3 shows the MMC’s AC side equivalent circuit where \( V_q \) and \( \varphi_R \) are the amplitude and phase of the AC side voltage. \( V_{\text{conv}} \) and \( \varphi_k \) are the amplitude and phase of the equivalent arm output voltage of MMC which is equal to the half of the difference between the output voltage of the lower arm and that of the upper arm. \( Z_n \) is the equivalent impedance between the equivalent output port of MMC and grid which can be expressed as

\[
Z_n(\omega_n) = \frac{j\omega_n L + R}{2}
\]

where \( L \) and \( R \) are the arm inductor and resistor respectively.

The constraint relationship between the harmonic modulation wave and the harmonic current can be expressed as

\[
I_{h^+ - 2}(\theta_{h^+ - 2}) = \frac{M_{h^+ - 2}(\theta_{M(h^+ - 2)})NU_c}{Z_n(\omega_n)}
\]

where \( N \) is the number of the arm sub-modules. \( U_c \) is DC voltage of the sub-module capacitor. \( I_{h^+ - 2} \) and \( \theta_{h^+ - 2} \) is the amplitude and phase of the \( h^+ - 2^{\text{th}} \) grid side harmonic modulation.

Substituting (17) into (15), the amplitude and phase of the \( (h^+ - 2)^{\text{th}} \) harmonic modulation can be solved.

2) ANALYTICAL CALCULATION OF THE \( h^+ \)-TH MODULATION WAVE

Similarly, the \( h^+ \)-th harmonic modulation wave is the superposition of two parts: (1) the \( h^+ \)-th modulation wave \( \hat{M}_{a1} \) generated by the \( h^+ \)-th harmonic current through the outer power loop; (2) the \( h^+ \)-th modulation wave \( \hat{M}_{a2} \) generated by the \( h^+ \)-th harmonic current through the inner current loop. The generating process is also shown in Fig. 3. Therefore, the influence of AC background harmonic on the control system can be expressed as

\[
\hat{M} = M_{h^+}(\theta_{M(h^+)} + \hat{M}_{a2}(\theta_{M(h^+ - 2)}))
\]

\[
= -\frac{3}{2} G_{\text{out}} G_{\text{in}} I_{h^+} U_1 \sin(h^+\omega t + \theta_{h^+} + \theta_{\text{outer}} + \theta_{\text{inner}}) \to \hat{M}_{a1}
\]

\[
+ I_{h^+} G_{\text{in}} \cos(h^+\omega t + \theta_{h^+} + \theta_{\text{inner}}) + I_{h^+} \omega L/2 \sin(h^+\omega t + \theta_{h^+})
\]

\[
\times \frac{NU_c}{N_{U_c}} \to \hat{M}_{a2}
\]

\[
+ \frac{3}{2} U_1 G_{\text{in}} G_{\text{out}} I_{h^+ - 2} N_{U_c}
\]

\[
\times \cos[(h^+ - 2)\omega t + \theta_{(h^+ - 2)} - \pi/2 + \theta_{\text{outer}} + \theta_{\text{inner}}] \to \hat{M}_{a3}
\]

(15)
\[ \dot{M}_{h+5} + M_{h+2}(\theta_{M(h+5)}) \]  

(18)

Above analysis expressed the effect of small signal disturbance on modulation index, this effect on control system will be coupled with electrical system of MMC and generate corresponding harmonics.

**B. INFLUENCE OF AC SIDE BACKGROUND HARMONICS ON ELECTRICAL SYSTEM**

Taking phase \( a \) as example, when there is the \( h \)-th positive sequence harmonic voltage on MMC’s AC side, MMC’s upper and lower arm current can be expressed as

\[
\begin{aligned}
I_{ad} &= \frac{\sqrt{2}}{2} I_a \sin(\omega t + \varphi) + I_{d0} + I_{d2} \sin(2\omega t + \theta) \\
&\quad - I_{h+2} \sin[(h+2)\omega t + \theta_{h+2}] \\
&\quad - I_{h} \sin(h\omega t + \theta_{h}) \\
I_{ad} &= \frac{\sqrt{2}}{2} I_a \sin(\omega t + \varphi) + I_{d0} + I_{d2} \sin(2\omega t + \theta) \\
&\quad + I_{h+2} \sin[(h+2)\omega t + \theta_{h+2}] \\
&\quad + I_{h} \sin(h\omega t + \theta_{h}) \\
\end{aligned}
\]

(19)

where \( I_a \) and \( \varphi \) are the RMS value and phase of grid side fundamental-frequency current. \( I_{d0} \) is the amplitude of the arm DC current. \( I_{d2} \) and \( \theta \) are the amplitude and phase of the arm circulating current. \( I_{h} \) and \( \theta_{h} \) are the amplitude and phase of the \( h \)-th harmonic current in upper and lower arm. \( I_{h+2} \) and \( \theta_{h+2} \) are the amplitude and phase of the \( (h+2) \)-th harmonic current in upper and lower arm respectively.

According to the average switching function theory, the average switching state of phase \( a \) can be expressed as

\[
\begin{aligned}
S_{au_{av}} &= \frac{1}{2} - \frac{1}{2} M \sin(\omega t) - \frac{1}{2} M h \sin(h\omega t + \theta_{h}) \\
&\quad - \frac{1}{2} M h+2 \sin[(h+2)\omega t + \theta_{h+2}] \\
S_{ad_{av}} &= \frac{1}{2} + \frac{1}{2} M \sin(\omega t) + \frac{1}{2} M h \sin(h\omega t + \theta_{h}) \\
&\quad + \frac{1}{2} M h+2 \sin[(h+2)\omega t + \theta_{h+2}] \\
\end{aligned}
\]

(20)

where \( S_{au_{av}} \) and \( S_{ad_{av}} \) are the average switching state of upper and lower arm respectively. The average capacitive current of upper arm \( i_{ave,u} \) and lower arm \( i_{ave,d} \) can be expressed as

\[
\begin{aligned}
i_{ave,u}(t) &= S_{au_{av}} I_{ad} \\
i_{ave,d}(t) &= S_{ad_{av}} I_{ad}
\end{aligned}
\]

(21)

The specific expression of \( i_{ave,u} \) is shown in appendix. \( i_{ave,d} \) is similar to \( i_{ave,u} \).

The sub-module average capacitor voltage of frequency order \( n \) can be obtained by multiplying the sub-module average capacitor current by the capacitor impedance of the corresponding frequency which can be expressed as

\[ u_{ave(n)} = \frac{i_{ave(n)}}{j\omega C_d} \]

(22)

where \( u_{ave(n)} \) means the \( n \)-th sub-module average capacitor voltage fluctuation. The average capacitor voltage between upper and lower arm is differential mode if \( n \) is odd, while that is common mode if \( n \) is even.

Through the above derivation, the conclusion can be drawn that due to the effect of sub-module’s switching action, the discontinuous state of sub-module’s capacitor current will couple with components of other frequencies in sub-module average capacitor voltage.

**C. ESTABLISHMENT OF MMC ARM EQUIVALENT CIRCUIT**

After adding the output voltage of all sub-modules of upper or lower arm, the output voltage of that arm can be obtained. The output voltage of the upper and lower arm in phase \( a \) are shown in (23) and (24) respectively.

\[
\begin{aligned}
u_{au_{,avo}} &= S_{au_{,av}} \cdot \sum_{n=1}^{n} u_{ave(n)} \\
u_{ad_{,avo}} &= S_{ad_{,av}} \cdot \sum_{n=1}^{n} u_{ave(n)}
\end{aligned}
\]

(23)

(24)

**FIGURE 4. MMC equivalent circuit.**

It can be seen that the MMC’s arm output voltage is super-imposed by multiple components of different frequencies, so the equivalent circuit of MMC is obtained which is shown in Fig. 4. The common mode components of upper and lower arm in phase \( a \) is shown in (25).

\[
\begin{aligned}
u_{au_{,avo,com}} &= u_{au_{,avo}} - \frac{N}{2} \sum_{n=2,4,6...}^{N} u_{ave(n)} \\
\end{aligned}
\]

(25)
The characteristics of arm output voltage at different frequencies can be concluded as follows.

\[
f = \begin{cases} 
  h^+ - 2 & \text{negative sequence} \\
  h^+ - 1 & \text{zero sequence} \\
  h^+ & \text{positive sequence} \\
  h^+ - 2 & \text{differential mode} \\
  h^+ - 1 & \text{common mode} \\
  h^+ & \text{differential mode}
\end{cases}
\]  

(26)

The current generated by the positive or negative sequence arm output voltage will flow among three-phases shown in Fig. 5 (a), and only the current generated by the arm output voltage with common mode and zero sequence property will flow into MMC’s DC side shown in Fig. 5 (b).

To sum up, when the arm current contains the \( h^+ \)th positive sequence harmonic, the \( h^+ - 1 \)th zero sequence common mode output voltage can be expressed as

\[
u_{\text{con}}(h^+ - 1) = \frac{(h^+ + 1)I_{a2}MN \sin[(h^+ - 1)\omega t + \theta_{M(h^+)} + \phi]}{16h^+\omega C_d}
\]

(28)

According to (28), the zero sequence common mode voltage is composed of eight parts where component (1), (3), (4), (5), (6) and (8) containing \( M_{h^+} \) or \( M_{h^+ - 2} \) are relative to the harmonic modulation wave. If the influence of background harmonic on MMC’s control system is ignored, the above items will be neglected. Similarly, component (2) and (7) containing \( I_{h^+ - 2} \) and \( I_{h^+} \) are relative to the harmonic current. If the influence of background harmonic on MMC’s electrical system is ignored, component (2) and (7) will be neglected also. Therefore, the influence of MMC’s electrical system and control system should both be considered separately in order to analyze the harmonic transferring process accurately.

Therefore, the DC side harmonic current generated by the positive sequence background harmonic in (6) can be expressed as

\[
i_{\text{dc}(h^+ - 1)} = \frac{6u_{\text{con}}(h^+ - 1)}{j(h^+ - 1)\omega R + 2L + 2Z_{dc}(h^+ - 1)\omega C_d}
\]

(29)

where \( Z_{dc}(h^+ - 1)\omega \) is the impedance of DC side network of frequency \( (h^+ - 1) \).

Although the above derivation process is based on the characteristic frequency background harmonics such as \( 5f_1 \) (250Hz) or \( 7f_1 \) (350Hz), etc., it is still valid for background harmonic of the non-characteristic frequencies such as 80Hz, etc. For example, \( h^+ \) in (28) is equal to 80/f_1 for 80Hz positive sequence background harmonic.

When there is the \( h^- \)th negative sequence background harmonic on the AC side of MMC, the derivation process is similar.

IV. PROPAGATION MECHANISM OF MMC DC SIDE BACKGROUND HARMONIC

According to the coupling relationship between the MMC’s electrical and control quantities deduced in Section III, the DC side \( h^0 \)th zero sequence harmonic current flowing through three-phases will be coupled with the fundamental frequency modulation wave to produce the \( h - 1 \)th negative sequence and the \( h + 1 \)th positive sequence harmonic voltage in upper and lower arm. Thus, MMC’s AC side will contain the \( h - 1 \)th and the \( h + 1 \)th harmonic current.

When MMC’s AC side contains harmonic current, the current will cause the \( h - 1 \)th and the \( h + 1 \)th harmonic modulation wave through the control loop, which is a second-order small disturbance response. Thus, the neglected harmonic components of modulation wave will not have great impact on the
quantitatively analysis of harmonic transmission. Therefore, only the DC component and the fundamental-frequency component of modulation wave are considered in the following analysis.

Among three-phase arms, the arm output voltage can be divided into positive, negative and zero sequence. The phase sequence relationship of arm output voltage caused by the DC side harmonic can be expressed as

\[
f = \begin{cases} 
  h^0 - 1 & \text{negative sequence} \\
  h^0 & \text{zero sequence} \\
  h^0 + 1 & \text{positive sequence}
\end{cases} \quad h^0 = 3kf_1 \tag{30}
\]

where \(k\) is integer.

The relationship of phase difference between upper and lower arm can be expressed as

\[
f = \begin{cases} 
  h^0 - 1 & \text{differential mode} \\
  h^0 & \text{common mode} \\
  h^0 + 1 & \text{differential mode}
\end{cases} \quad h^0 = 2kf_1 \tag{31}
\]

The harmonic current arm output voltage of common mode caused by the DC side harmonic will flow among three-phase arms, while the current caused by the differential mode arm output voltage will flow into AC side. The harmonic transferring process is shown in Fig. 6.

![Diagram of harmonic transferring process](image)

FIGURE 6. Process of MMC DC side background harmonic transferring to AC side.

According to the above analysis process, the AC side harmonic current is formed by the coupling of the fundamental-frequency modulation wave with the zero sequence arm current. Firstly, the average capacitor current of the sub-module is calculated according to (32). And \(M_{au}\) and \(i_{au}\) are shown in (33) and (34) respectively.

\[
i_{ave,au} = S_{au,av}i_{au} \tag{32}
\]

\[
S_{au,av} = \frac{1}{2} - \frac{1}{2} M \sin(\omega t) \tag{33}
\]

\[
i_{au} = -\sqrt{2} I_a \sin(\omega t + \phi) + I_{d0} + I_{d2} \sin(2\omega t + \theta) + I_{\phi0} \sin(h^0 \omega t + \theta_{\phi0}) \tag{34}
\]

where \(I_{\phi0}\) and \(\theta_{\phi0}\) are the amplitude and phase of the arm harmonic current in phase \(a\).

In accordance with the analysis above, the differential mode arm output voltage and current caused by the DC side background harmonic will have an impact on the AC side. The differential mode arm output voltage of the phase \(a\) can be expressed as

\[
u_{au,\omega,\text{diff}} = -u_{ad,\omega,\text{diff}} = \frac{N}{2} \sum_{n=1,3,5\ldots} u_{aven}(n) - \frac{N}{2} M \sin(\omega t) \cdot \sum_{n=2,4,6\ldots} u_{aven}(n) \tag{35}
\]

After the above formula is expanded, the positive sequence and negative sequence difference mode arm output voltage can be expressed as

\[
u_{au,dig}(h^0 + 1) = \frac{(2h^0 + 1)I_{d0}MN \sin[\theta_{d0} + (h^0 + 1)\omega t]}{8h^0(h^0 + 1)\omega C_d} \tag{36}
\]

\[
u_{au,dig}(h^0 - 1) = -\frac{(2h^0 - 1)I_{d0}MN \sin[\theta_{d0} + (h^0 - 1)\omega t]}{8h^0(h^0 - 1)\omega C_d} \tag{37}
\]

On the basis of the AC equivalent circuit shown in Fig. 2, AC side positive and negative sequence harmonic current caused by DC side background harmonic can be obtained as

\[
i(h^0 + 1) = \frac{(2h^0 + 1)I_{d0}MN \sin[\theta_{d0} + (h^0 + 1)\omega t]}{8h^0(h^0 + 1)\omega C_d Z_n} \tag{38}
\]

\[
i(h^0 - 1) = -\frac{(2h^0 - 1)I_{d0}MN \sin[\theta_{d0} + (h^0 - 1)\omega t]}{8h^0(h^0 - 1)\omega C_d Z_n} \tag{39}
\]

V. CALCULATION OF HARMONIC TRANSMISSION BASED ON FREQUENCY-DOMAIN METHOD

Section III and IV introduce the mechanism of AC and DC side background harmonic propagating to MMC’s other side. It can be seen that the mechanism of harmonic transmission is extremely complex. So in this section, a harmonic transmission method in frequency-domain is proposed which is suitable for the practical engineering and can be used to calculate quickly the influence of background harmonic on the MMC’s other side.

![Diagram of harmonic propagating](image)

FIGURE 7. Background harmonic propagating in back-to-back MMC.

Fig. 7 shows the process of AC side background harmonic propagating in back-to-back MMCs where MMC1 adopts the power control mode and MMC2 adopts the DC voltage.
control mode. When the AC System 1 contains the positive sequence harmonic voltage, the DC bus will contain zero sequence harmonic current, as shown in process (1) of Fig. 7. Furthermore, DC bus harmonic current will be transferred to the MMC2’s AC side, as shown in process (2) of Fig. 7.

In [18], the relationship between AC side voltage disturbance and current response of upper arm is established which can be expressed as

\[ \hat{I}_u = Y_p \hat{V}_p \] (40)

where \( \hat{I}_u = \begin{bmatrix} \hat{I}_{p-1} e^{j \beta_{p-1}} & \cdots & \hat{I}_{p+n} e^{j \beta_{p+n}} \end{bmatrix}^T \), \( \hat{V}_p = \begin{bmatrix} \hat{V}_{p-1} e^{j \beta_{p-1}} & \cdots & \hat{V}_{p+n} e^{j \beta_{p+n}} \end{bmatrix}^T \) and

\[ Y_p = \begin{bmatrix} Y_{(p-n,n-n)} & \cdots & Y_{(p-n,n+n)} \\ \cdots & \cdots & \cdots \\ Y_{(p+n,n-n)} & \cdots & Y_{(p+n,n+n)} \end{bmatrix} \]

For instance, the elements \( Y_{(p+n,n-n)} \) in \( Y_p \) means the admittance between upper arm current \( \hat{I}_{p+n} e^{j \beta_{p+n}} \) of frequency \( f_p + nf_1 \) and AC side voltage \( \hat{V}_{p-n} e^{j \beta_{p-n}} \) of frequency \( f_p - nf_1 \).

Since the AC side harmonic current \( \hat{I}_p \) of MMC is twice of the upper arm harmonic current \( \hat{I}_u \) which can be expressed as

\[ \hat{I}_p = -2 \hat{I}_u \] (41)

Therefore, the AC side impedance model of MMC can be expressed as

\[ Z_{ac}(f_p) = \frac{\hat{V}_{p(p)}}{\hat{I}_{p(p)}} = -\frac{\hat{V}_{p(p)}}{2 \hat{I}_{u(p)}} = -\frac{1}{2 Y_{(p,p)}} \] (42)

where \( \hat{V}_{p(p)}, \hat{I}_{p(p)} \) and \( \hat{I}_{u(p)} \) are the \((n+1)th\) element of matrix \( \hat{V}_p, \hat{I}_p \) and \( \hat{I}_u \) respectively.

Based on the impedance modeling method in [18], the AC side impedance model of MMC1 is established considering the outer control loop, inner control loop, and phase locked loop (PLL).

According to the harmonic transmission characteristics of Section III, the positive sequence background harmonic of frequency \( f_p \) will generate the zero sequence harmonic of frequency \( f_p - f_1 \) on the DC side.

The relationship between the zero sequence harmonic current \( \hat{I}_{u(p-1)} \) of upper arm and the zero sequence harmonic current \( \hat{I}_{dc(p-1)} \) of the DC bus can be expressed as

\[ \hat{I}_{u(p-1)} = \hat{I}_{dc(p-1)} \] (43)

where \( \hat{I}_{u(p-1)} \) is the \(n\)th element of matrix \( \hat{I}_u \).

The ratio of the AC background harmonic voltage \( \hat{V}_{p(p)} \) of the frequency \( f_p \) of MMC1 to the zero sequence harmonic current \( \hat{I}_{dc(p-1)} \) of frequency \( f_p - f_1 \) of DC bus is defined as the transfer impedance \( Z_{MMC1}(f_p) \) of MMC1 which can be expressed as

\[ Z_{MMC1}(f_p) = \frac{\hat{V}_{p(p)}}{\hat{I}_{dc(p-1)}} = \frac{\hat{V}_{p(p)}}{3 \hat{I}_{u(p-1)}} = \frac{1}{3 Y_{(p-1,p)}} \] (44)

Therefore, when AC side background harmonic \( \hat{V}_p \) is known, the zero sequence harmonic current of DC bus can be calculated by transferring impedance (44).

The zero sequence current of DC bus \( \hat{I}_{dc(p-1)} \) will generate the harmonic voltage \( \hat{V}_{dc(p-1)} \) of frequency \( f_p - f_1 \) at the DC port of MMC2. According to the harmonic transferring characteristics that the harmonic voltage of \( \hat{V}_{dc(p-1)} \) will generate the harmonic current response \( \hat{I}_{2,p} \) of frequency \( f_p \) and \( \hat{I}_{2,p-2} \) of frequency \( f_p - 2f_1 \) at the MMC2’s AC side. The ratio of \( \hat{V}_{dc(p-1)} \) to \( \hat{I}_{2,p} \) and \( \hat{I}_{2,p-2} \) can be defined as MMC2’s transfer impedance \( Z_{MMC2}(f_p) \) and \( Z_{MMC2}(f_p - 2f_1) \) respectively which can be expressed as

\[ Z_{MMC2}(f_p) = \frac{\hat{V}_{dc(p-1)}}{\hat{I}_{2(p-1)}} = 2 Y_{(p-1,p)} \] (45)

\[ Z_{MMC2}(f_p - 2f_1) = \frac{\hat{V}_{dc(p-1)}}{\hat{I}_{2(p-2)}} = 2 Y_{(p-1,p-2)} \] (46)

Therefore, when the background harmonic voltage of DC port \( \hat{V}_{dc(p-1)} \) is known, the harmonic current of MMC2’s AC port can be calculated by the transfer impedance. It should be pointed out that the calculation method in frequency-domain is also suitable for the multi-terminal MMC network.

VI. HARMONIC TRANSFERRING SUPPRESSION STRATEGY

Based on the mechanism of harmonic transmission, this paper designs a harmonic suppression strategy to eliminate the propagation of background harmonics through the upper and lower arms.

Because the process of AC background harmonic transferring to DC side or DC background harmonic transferring to AC side will both generate zero sequence harmonic voltage in the upper and lower arm. Therefore, the zero sequence harmonic voltage of the upper and lower arm is the ‘bridge’ of harmonic transmission, so it needs to be blocked. In the proposed method, DC bus harmonic current \( i_{dc} \) is extracted by subtracting DC steady-state current \( P/U_{dc} \) from DC bus current \( i_{dc} \). The DC bus harmonic current \( i_{dc} \) is multiplied by virtual damping coefficient \( R_v \) to generate the additional modulation wave of which magnitude is opposite to the zero sequence arm output voltage so that the transferring path of background harmonic under any frequency can be suppressed. The specific implementing process is shown in Fig. 8.

Comparison to suppression method based on PR controller which only suppresses the background harmonic of the frequency near its resonant frequency [21], [22], the proposed method can suppress the harmonics of a wider frequency range. On the one hand is that introducing a filter will brings
FIGURE 8. Suppressing process of DC bus current.

TABLE 1. Parameters of MMC simulation circuit.

| Parameters               | Values |
|--------------------------|--------|
| DC Bus Voltage           | 500kV  |
| AC line voltage (RMS)    | 260kV  |
| Rated power              | 750MW  |
| Number of Modules Per Arm| 244    |
| Arm Inductance           | 0.05H  |
| Arm Resistance           | 0.1Ω   |
| Capacitance of Sub-module| 14mF   |

an effect on system dynamics, on the other hand is that the parameters of filter will affect the harmonic suppression. In practice, the frequency of background harmonic is unknown, so the filter based on one kind of parameters may doesn’t work when background harmonics change. But with no need of filter in our suppression method, the transferring path of background harmonic under any frequency can be suppressed.

VII. THE EXAMPLE ANALYSIS

In order to verify the proposed analytical method, a simulation model of MMC was established in MATLAB/Simulink. The main parameters of the simulation model under the power control mode are shown in Table 2. In this paper, the 7th positive sequence harmonic and 80Hz non-characteristic background harmonic in MMC’s AC system is taken as example to verify the proposed method.

TABLE 2. Comparison between simulation result and analytical result.

| Electrical Quantity   | Analytical Result | Simulation Result | Error  |
|-----------------------|-------------------|-------------------|--------|
| Output Voltage of Upper Arm(6th) | 309.6 V          | 302.2 V           | 2.45 % |
| Output Voltage of Lower Arm(6th)  | 309.6 V          | 301.6 V           | 2.65 % |
| Current of Upper Arm (6th)         | 1.64 A           | 1.59 A            | 3.14 % |
| Current of Lower Arm (6th)          | 1.64 A           | 1.60 A            | 2.50 % |
| DC-side Current(6th)               | 4.93 A           | 4.79 A            | 2.95 % |

Set MMC’s operating condition as $P = 1000$MW and $Q = 0$MW and control mode as power control mode. MMC’s DC side is connected to an 500kV ideal DC voltage source. The impedance modeling is carried out based on the parameters in Table 2. Amplitude-frequency characteristic and phase-frequency characteristic of impedance are shown in Fig. 9. When there has the 5000 Hz 7th background harmonic voltage on MMC AC side, according to the impedance modeling results, the impedance of 350Hz is $65,084 \angle 53.5^\circ$. The frequency sweeping is carried out in the established simulation model, and impedance value in simulation is $63.884 \angle 53.2^\circ$. So the 7th theoretical grid side harmonic current is $76.834 \angle -53.5^\circ$. Fig. 10 shows the comparison of the theoretical and simulated 7th grid side harmonic current waveform. It is found that the theoretical current value obtained by the impedance modeling is in good agreement with that obtained by simulation.

FIGURE 9. Impedance amplitude-frequency and phase-frequency characteristic curve of MMC AC side.

FIGURE 10. Comparison between MMC the 7th grid side harmonic current analytical result and simulation result.

The phase current is divided equally and flows in opposite directions in upper and lower arm. According to (15) and (17), the theoretical 5th grid side harmonic current can be calculated as $27.74 \angle -0.7^\circ$. After calculating the 5th grid side harmonic current by the impedance modeling, the MMC’s upper and lower arm current can be obtained as

$$i_{ap} = -\frac{\sqrt{2}}{2} I_a \sin(\omega t + \varphi) + I_a 0 + I_{a2} \sin(2\omega t + \theta) - I_5 \sin(5\omega t + \theta_5) - I_7 \sin(7\omega t + \theta_7) \quad (47)$$

$$i_{ad} = +\frac{\sqrt{2}}{2} I_a \sin(\omega t + \varphi) + I_a 0 + I_{a2} \sin(2\omega t + \theta) + I_5 \sin(5\omega t + \theta_5) + I_7 \sin(7\omega t + \theta_7) \quad (48)$$

where $I_5$ and $\theta_5$ are the amplitude and phase of the 5th arm current. $I_7$ and $\theta_7$ are the amplitude and phase of the 7th arm current.
After calculating the amplitude and phase of grid side harmonic current, the method proposed in Section III is used to calculate the influence of background harmonic on modulation wave through the control loop.

According to the conclusion of Section III, the \( h^+ \) positive sequence harmonic can be coupled with the \( h^- - 2^\text{th} \) positive sequence harmonic modulation wave through outer power loop. The theoretical values of the \( 7^\text{th} \), the \( 5^\text{th} \) modulation wave and the \( 5^\text{th} \) harmonic current can be calculated by (15) and (18).

According to the conclusion of Section III, the \( 7^\text{th} \) AC background harmonic will generate the \( 6^\text{th} \) zero sequence common mode voltage in upper and lower arm which can be expressed as

\[
\Delta u_{ph,6}(t) = -\frac{I_{d2}M_5N \cos(6\omega t + \theta_5 + \theta)}{14\omega C_d} - \frac{11I_5N \sin(6\omega t + \theta_5)}{240\omega C_d} - \frac{3I_0M_5N \sin(6\omega t + \theta_{M5})}{20\omega C_d} - \frac{7I_5M_5N \sin(6\omega t + \theta_{M5} + \phi)}{48\sqrt{2}\omega C_d} + \frac{I_{d2}M_7N \cos(6\omega t + \theta_{M7} - \theta)}{20\omega C_d} + \frac{5I_7M_7N \sin(6\omega t + \theta_{M7} - \phi)}{48\sqrt{2}\omega C_d} + \frac{13I_7M_7N \sin(6\omega t + \theta_7)}{336\omega C_d} - \frac{3I_{d0}M_7N \sin(6\omega t + \theta_{M7})}{28\omega C_d} \tag{49}
\]

where \( M_5 \) and \( \theta_{M5} \) are the amplitude and phase of the \( 5^\text{th} \) modulation wave. \( M_7 \) and \( \theta_{M7} \) are the amplitude and phase of the \( 7^\text{th} \) modulation wave.

Equation (49) shows that the harmonic in MMC’s control system \( M_5, M_7 \) and harmonic in MMC’s electrical system \( I_5, I_7 \) have both effect on harmonic transmission. Therefore, if the influence of control system or electrical system is neglected, the calculation result will be inaccurate.

According to (49), the zero sequence common mode arm output voltage is composed of 8 components. Its constituting components in (49) are shown in Fig. 11.

Fig. 12 shows the comparison between the analytical and the simulation result of the zero sequence common mode arm output voltage. The analytical result is consistent with the simulation result, verifying the correctness of (48) and the proposed conclusion. At the same time, the yellow line represents the analytical result that only considers the influence of background harmonic on MMC’s control system neglecting the influence of background harmonic on MMC’s electrical system while the purple line represents the analytical result that only considers the influence of background harmonic on MMC’s electrical system and neglecting the influence of background harmonic on MMC’s control system. Therefore, if the influence of control system or electrical system is ignored, the calculation result of harmonic transmission will be inaccurate, which cannot be used in quantitative analysis of harmonic transmission.

According to the equivalent circuit shown in Fig. 5, the \( 6^\text{th} \) zero sequence common mode current flowing into MMC’s DC side can be calculated. The specific data of analytical result of proposed method and simulation result for this example are shown in Table 3.

In order to verify the effectiveness of the proposed theory for non-characteristic harmonics, the 80Hz background harmonics are taken as example to verify the effect on the output voltage of the bridge arm.

Fig. 13 shows the waveform of arm output voltage when MMC’s AC port contains 80Hz 5000/0° positive sequence background harmonic (THD = 2.35%). It is found that the low-frequency background harmonic has greater impact on MMC than the high-frequency background harmonic. This phenomenon can also be explained by (28). Because the \( h^+ \) in (28) corresponding to the low-frequency background
harmonic is smaller, that is, the denominator is smaller, so the output voltage is larger. Therefore, in engineering, the harm of low-frequency background harmonic to MMC should be paid more attention to.

In order to verify the effectiveness of the frequency-domain method in the calculation of harmonic transmission effects, Fig. 14(a) shows the comparison of DC bus harmonic current between theoretical result calculated by frequency-domain method and simulation result when MMC1’s AC side contains 5000\(\angle 0^\circ\) positive sequence background harmonic at frequency from 1Hz to 1000Hz in MMC AC side (grid side), then study the corresponding current response in MMC DC side. The horizontal axis represents the frequency of AC side background harmonic, and the vertical axis represents the amplitude of DC bus harmonic current. It can be seen from the figure that the frequency-domain method is effective in calculating the harmonic transmission. For example, the simulated and theoretical values of 30 Hz DC bus harmonic current generated by 80 Hz AC side positive sequence background harmonic are 189.9 A and 188.5 A respectively meaning that the low-frequency background harmonic has great influence on MMC’s DC side. In the engineering project, it ought to suppress the harm of the low-frequency background harmonic. This figure shows that the theoretical result matches well with the simulation result, which verifies the correctness of theoretical analysis of harmonic transfer characteristics in our paper.

Fig. 14(b) shows the corresponding current response in MMC DC side under different working conditions and control modes. The blue line shows the DC current response when MMC works under PQ control mode at \(P = 1000\text{MW} Q = 1000\text{MW}\) operating point, the red line shows the DC current response when MMC works under PQ control mode at \(P = 1000\text{MW} Q = -1000\text{MW}\) operating point. The comparison between blue line and red line shows that the operating point almost only has an effect under low frequency, and the higher frequency harmonic transfer characteristics are almost the same. It should be noted that the yellow line shows the DC current response when MMC works under AC voltage control mode. It could be seen that the corresponding current response has a big difference due to the different control modes. So it means that when discussing the harmonic transfer characteristics of MMC, we should pay attention to the different control modes of MMC.

Fig. 14(c) shows the influence of DC bus background harmonic on MMC’s AC port harmonic current when MMC is under the power control mode. It can be seen from the figure that 30Hz background harmonic has great influence on MMC’s AC port.

In order to verify the effectiveness of the proposed zero sequence virtual damping strategy, a four-terminal MMC-based DC grid is shown in Fig. 15 where the DC side is connected to a loop network including four converter stations. In this project, converter stations A and C operate in the AC voltage control mode, whose AC side is connected to island new energy electric field. Converter station B operates in the DC voltage control mode, while converter station D operates in the power control mode.

Converter station B and D is connected to ideal Ac voltage source. To simulate the influence of harmonic voltage caused
TABLE 3. Parameters of MMC-HVDC grid.

| MMC under different control mode | Description                     | Value     |
|----------------------------------|---------------------------------|-----------|
| PQ control mode (MMC-D)          | current loop PI controller      | 0.6~8/s   |
|                                  | PI controller of PQ control     | 0.5~20/s  |
| DC voltage control mode (MMC-B)  | current loop PI controller      | 0.6~8/s   |
|                                  | PI controller of DC voltage control | 5~800/s  |
| AC voltage control mode (MMC-A, MMC-C) | current loop PI controller | 0.6~8/s   |
|                                  | PI controller of AC voltage control | 3~800/s  |

by island power farms, the positive sequence controlled voltage source of the amplitude 5000V and the frequency 70Hz is activated at 2s.

The detailed controller parameters of the four-terminal MMC-based DC grid are shown as below.

By giving the detailed simulation conditions electrical system parameters and controller parameters, it’s easy for other people to confirm and repeat the results in this paper.

The DC port current waveforms of Station A, B, C and D are shown in Fig. 16(a)∼(d) respectively. By observing the DC bus time-domain current waveform of stations A, B, C and D, the harmonic current in DC bus is quickly suppressed after the additional virtual damping control strategy is put into operation at 2.5s, which verifies the effectiveness of the proposed control measures. Since the virtual damping only works on the zero sequence harmonics, it will not affect the fundamental-frequency electric quantities and other steady-state quantities of MMC, the additional strategy will not affect the MMCs’ steady-state characteristic.

Fig. 17 shows AC side current waveforms of Station B and Fig. 18 shows the d- and q-axis modulation wave of Station B.

Fig. 17 indicate that the AC side background harmonic at one terminal of the DC network will affect the whole DC grid and other MMC’s AC ports. After the zero sequence virtual damping strategy is put into use at 2.5s, the harmonic of the whole DC network is suppressed. It can be seen from Fig. 18 that the steady-state modulation wave will not be affected after the zero sequence virtual damping strategy is activated at 2.5s.

VIII. CONCLUSION

This paper proposes a method for quantitative analysis of harmonic transferring mechanism from MMC’s AC or DC side to the other side. Based on the harmonic transferring mechanism, a zero-sequence virtual damping strategy is proposed to suppress the background harmonic transferring. Analytical
expressions for the quantitative calculation of harmonic transferring is derived, which provides a theoretical basis for the steady-state characteristic analysis and the stability analysis for MMC. The main conclusions are as follows:

1. Background harmonics have both impact on MMC control system and electrical system. Quantitative research on its impact is the premise of quantitative analysis of the mechanism of harmonic transferring.

2. There is a coupling relationship between MMC’s control system and the electrical system, and the coupling relationship is finally reflected in the arm output voltage, which is the ‘bridge’ for harmonic transmission.

3. The harmonic modulation waves and the arm harmonic currents of each frequency are important factors of harmonic transferring. That’s why the method only considering the fundamental-frequency modulation wave and the fundamental-frequency arm current but ignoring other frequency components of current and modulation wave, is not precise enough.

4. The low frequency background harmonic has greater influence on MMC’s other side than the high frequency background harmonic. Therefore, in the engineering, its harm to MMC should be paid more attention to.

APPENDIX

See $i_{ave,u}(t)$, as shown at the top of the page.

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