Modeling and Analysis of High-Frequency MMC Impedance Considering Different Control Modes and Voltage Feedforward

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ABSTRACT The sequence impedance of modular multilevel converters (MMC) is the premise to analyze the stability of MMC-based high voltage direct current (HVDC) system. However, few papers have modeled MMC impedance with comprehensive consideration of different control modes and voltage feedforward, the high-frequency impedance characteristics of the MMC have not been intensively studied, either. In fact, the voltage feedforward has an important influence on the high-frequency impedance characteristics of the MMC, which can not be ignored. This article proposes a sequence impedance for MMC considering complete control loops. Not only current inner-loop, circulating current control loop and phase-locked loop (PLL) are considered, but also different control modes including power control, DC voltage control and AC voltage control are considered. It is worth mentioning that especially the voltage feedforward and time delay are taken into account. Based on this impedance model, the characteristics of the MMC are thoroughly analyzed, and the analysis shows that the voltage feedforward and time delay will greatly affect the high-frequency characteristics, which will deeply affect the stability of the system. Meanwhile, the influences of PLL dynamics, outer-loop control, circulating current control and parameters of controller on the sequence impedance are also analyzed in detail.

INDEX TERMS Modular multilevel converter (MMC), voltage feedforward, impedance model, time delay, high frequency.

I. INTRODUCTION

Modular multilevel converters (MMC) are very suitable for renewable energy system and have been widely applied in high-voltage direct current (HVDC) transmission system due to its advantages of modularity, low switching frequency and low distortion output voltage waveforms [1]–[6]. However, with the completion and operation of many MMC-HVDC projects, its stability problems have attracted extensive attention. The oscillation phenomenon and resonance issue were reported in practical MMC-HVDC projects [7], [8]. To deal with the oscillation stability problem, the impedance based stability criterion is effective for analyzing the stability of MMC-HVDC [9]. In this approach, the converter-based interconnected system could be regarded as two subsystems including converter and power grid, the stability of the whole system can be determined only if the terminal impedance of each subsystem is known. Therefore, the terminal sequence impedance model of MMC is the essential prerequisite for analyzing the stability of MMC-HVDC based on impedance stability criterion.

The accurate impedance model of MMC is not easy to obtain. On the one hand, due to the complicated internal dynamics and multiple control loops of MMC, its impedance modeling is very complex. In practice, the control strategy of MMC includes inner-loop decoupled current control, outer-loop control and voltage feedforward in direct-quadrature (d-q) frame, the outer-loop control contains three different control modes: active/reactive power control, DC voltage control and AC voltage control.
However, outer-loop control and the voltage feedforward are usually ignored in most papers, which will affect the accuracy of the impedance model. The sequence impedance models of MMC considering its internal dynamics were established by multi-harmonic linearization [10], but the outer-loop control, voltage feedforward loop and time delay were not considered. The harmonic state-space (HSS) modeling method was introduced to build the impedance models of MMC in [11], but the AC voltage outer-loop control and current inner-loop control were not considered at the same time. Time delay is also unavoidable in the practical MMC-HVDC and have a great influence on impedance characteristics. Although time delay is considered during impedance modeling process and the negative damping caused by time delay is pointed out in [12], the influence of voltage feedforward has not been studied. Voltage feedforward is indispensable in MMC control system, but so far, very few papers have discussed the influence of voltage feedforward on the MMC impedance modeling.

On the other hand, at present, the research of MMC impedance characteristics are mostly focused on below 1000Hz [10]–[12], however, high-frequency oscillation above 1000Hz in MMC-HVDC projects is constantly reported [13], [14]. In order to solve the problem of high-frequency oscillation of MMC-HVDC, the high-frequency impedance characteristics of the MMC need to be intensively studied. And how the voltage feedforward and time delay affect the high-frequency characteristics of MMC impedance should be analyzed in detail.

Based on the above analysis, a more accurate MMC impedance considering complete control loops including different control modes, time delay and voltage feedforward is necessary to be established, and the corresponding influence of control loops on high-frequency impedance characteristics should be further analyzed.

In this paper, an accurate sequence impedance model of MMC considering complete control loops is derived. Not only current inner-loop and circulating current control loop are considered, but also different control modes (outer-loop control), PLL, time delay and voltage feedforward are considered. Then the correctness of derived analytical impedance model is verified by simulation. Based on this impedance model, the impedance characteristics considering different control modes are described, how the voltage feedforward and time delay affect the high-frequency characteristics of MMC impedance are analyzed in detail, and the resonance peak caused by voltage feedforward and time delay is pointed out and analyzed. Furthermore, the influences of control loops and controller parameters are also discussed.

The main contribution of this paper is summarized as:

1) an accurate impedance model of MMC is established with consideration of complete control loops including different control modes, time delay and PLL, and voltage feedforward is also especially considered;

2) the high frequency characteristics of MMC impedance are analyzed in detail, and in particular, the resonance peak caused by voltage feedforward and time delay is also discussed.

The rest of this paper is organized as follows: Section II presents the small signal model of MMC power stage. Section III derives the small signal mode of control stage. Then the small signal impedance model is validated, and the influences of the voltage feedforward, time delay and other control loops are analyzed in Section IV. Finally, the conclusion is shown in Section V.

II. MMC POWER STAGE SMALL SIGNAL MODEL

MMC power stage small signal model is established based on harmonic linearization in this section.

Fig. 1 shows the circuit diagram of an MMC. In order to apply harmonic linearization to MMC sequence impedance modeling, the first step is to add a sinusoidal voltage perturbation at frequency $f_p$ to the AC side of MMC as shown in Fig. 1 [10].

Phase $a$ voltage with a small voltage perturbation at frequency $f_p$ can be generally written as:

$$v_a(t) = V_a \cos(2\pi f_1 t) + \hat{V}_p \cos(2\pi f_p t + \phi_p)$$  \hspace{1cm} (1)

where $V_a$ is the amplitude of grid voltage in phase $a$, $\hat{V}_p$ and are $\phi_p$ the amplitude and phase of voltage perturbation, $f_p$ is the frequency of voltage perturbation, and $f_1$ is the fundamental frequency of grid voltage. Phase $b$ and $c$ perturbations are defined similarly depending on the sequence of voltage perturbation [15].

In practical MMC-HVDC projects, the number of submodules in per arm of MMC is very large in general, so the equivalent switching frequency is high enough [16]. And the capacitor voltages of all submodules are balanced at all times based on the voltage balancing algorithm [17]. According to the symmetry of MMC, taking the upper arm of phase $a$ as an example, the small signal model of MMC power stage can be obtained by harmonic linearization [18]

$$Z_i \hat{i}_{au} = -\hat{v}_p - M_{au} \hat{u}_{au} - \hat{m}_{au} u_{au}$$  \hspace{1cm} (2)

$$Y_u \hat{u}_{au} = M_{au} \hat{i}_{au} + I_{au} \hat{m}_{au}$$  \hspace{1cm} (3)

where $\hat{i}_{au}$, $\hat{u}_{au}$ and $\hat{m}_{au}$ are small-signal vectors of upper arm current, sum of all submodule capacitor voltages and
modulation index of upper arm respectively in phase \(a\), \(\hat{\nu}_p\) is the vector of small voltage perturbation in phase \(a\), \(\bar{Z}_a\) and \(\bar{Y}_c\) are diagonal matrices which represents the impedance of the arm inductor and the admittance of equivalent module capacitor. Corresponding to small signal variables, \(\hat{I}_{\text{m}}\), \(\hat{u}_{\text{m}}\) and \(\hat{M}_{\text{m}}\) are Toeplitz matrixes of steady-state variables of upper arm current, sum of all submodule capacitor voltages and modulation index of upper arm respectively in phase \(a\).

It is important to note that the given voltage perturbation will lead to a series of small-signal harmonic components at frequency \(f_p\pm k f_1\), \(k = 1, 2 \ldots n\), to balance the accuracy of model and the complexity of mathematical operation, harmonics up to \(f_p\pm 3f_1\) are considered in this paper [19], [20]. The harmonics of small-signal components under voltage perturbation including arm currents, arm capacitor voltages, and arm modulation index have different common-mode or differential-mode relationships. It should be noted that only the differential-mode arm currents will flow to AC side of MMC [12].

III. MMC CONTROL STAGE SMALL SIGNAL MODEL
According to (2) and (3), since the arm current is half of the phase current, so the MMC impedance can be calculated from half of the quotient of small signal disturbance voltage \(\nu_p\) and responding disturbance current \(\hat{I}_{\text{m}}\). Steady state variables of \(\hat{M}_{\text{m}}\), \(\hat{u}_{\text{m}}\) and \(\hat{I}_{\text{m}}\) in (2) and (3) can be calculated from the output power of MMC [21]. To obtain the quotient of small signal \(\nu_p\) and \(\hat{I}_{\text{m}}\), \(\hat{M}_{\text{m}}\) should be represented by \(\nu_p\) and \(\hat{I}_{\text{m}}\). The small signal vector of upper arm modulation index \(\hat{M}_{\text{m}}\) is determined by control loops and controller parameters, which will be derived in this section.

The control modes of MMC include power control, DC voltage control and AC voltage control. The MMC impedance under these three control modes will be derived separately in this section.

A. AC VOLTAGE CONTROL MODE
The control diagram of AC voltage control is shown in Fig.2, including AC voltage outer-loop control, phase current inner-loop control, circulating current control and voltage feedforward. All these control loops have an influence on MMC control stage small signal model.

Influence of each control loop superimposes on the modulation index [10]. Thus the complex vector of arm modulation index can be expressed as:

\[
\hat{m}_{\text{m}} = (Q_i + Q_e)\hat{i}_{\text{m}} + (Q_{\text{ac}} + Q_{\text{feed}})\nu_p
\]

where \(Q_i\), \(Q_e\), \(Q_{\text{ac}}\), and \(Q_{\text{feed}}\) are the coefficient matrices of the phase current control loop, the circulating current control loop, the AC voltage control, and the voltage feedforward respectively. These coefficient matrices represent the influence of each control loop on the modulation index. In this paper, only the harmonics up to third fundamental frequency are considered, so these coefficient matrices are all square matrices of seven order, and the matrix coefficients are related to their control loop structure and controller parameters.

1) PHASE CURRENT CONTROL
The coefficient matrix of the phase current control loop has been derived in [10] as:

\[
Q_i = \text{diag}[0\ a_1\ 0\ a_2\ 0\ 0\ 0]\quad(5)
\]

where the frequencies corresponding to coefficients \(a_1\) and \(a_2\) are \(f_p - 2f_1\) and \(f_p\) respectively.

\[
\begin{align*}
a_1 &= [H_i(2\pi f_p) + j\omega L] \cdot e^{-j2\pi(2f_1)\omega L} \\
a_2 &= [H_i(2\pi f_p - f_1)] - j\omega L] \cdot e^{-j2\pi f_p\omega L}
\end{align*}
\]

where \(H_i\) is the phase current transfer function, and \(t_d\) is the value of time delay in MMC system [12].

2) CIRCULATING CURRENT CONTROL
The coefficient matrix of the circulating current control loop also has been derived in [10] as:

\[
Q_c = \text{diag}[b_1\ 0\ 0\ 0\ b_2\ 0\ b_3]
\]

where the frequencies corresponding to coefficients \(b_1\), \(b_2\) and \(b_3\) are \(f_p - 3f_1\), \(f_p + f_1\), and \(f_p + 3f_1\) respectively.

\[
\begin{align*}
b_1 &= [H_c(2\pi (f_p - f_1)) + 2j\omega L] \cdot e^{-j2\pi(3f_1)\omega L} \\
b_2 &= [H_c(2\pi (f_p - f_1))] - 2j\omega L] \cdot e^{-j2\pi f_p\omega L} \\
b_3 &= [H_c(2\pi (f_p + 5f_1))] + 2j\omega L] \cdot e^{-j2\pi f_p\omega L}
\end{align*}
\]

where \(H_c\) is the circulating-current control transfer function.

3) VOLTAGE FEED-FORWARD CONTROL
The voltage perturbation will go through abc/dq transformation and add to \(dq\) axis respectively, and then go through \(dq/\text{abc}\) transformation to add to modulation index. So the coefficient matrix of the voltage feedforward can been derived as

\[
Q_{\text{feed}} = \text{diag}[0\ 0\ 0\ e^{-j2\pi f_p\omega L} 0\ 0\ 0]
\]
4) **AC VOLTAGE CONTROL**

Both the outer-loop controller and current inner-loop controller will affect the voltage perturbation, according to Fig. 2, the small signal voltage perturbation will go through the outer-loop controller $G(s)$ and current inner-loop controller $H_i(s)$, then act on the modulation index. So the coefficient matrix of the ac voltage control can be derived as

$$ Q_{ac} = \text{diag}[0 \ 0 \ 0 \ d_3 \ 0 \ 0 \ 0] $$  \hspace{1cm} (10)

where

$$ d_3 = G \left( \frac{2\pi (f_p - f_1)}{f_1} \right) \cdot H_i \left( \frac{2\pi (f_p - f_1)}{f_1} \right) e^{-\frac{2\pi f_p f_1}{f_1}}. $$  \hspace{1cm} (11)

5) **IMPEDELANCE MODEL UNDER AC VOLTAGE CONTROL MODE**

A single matrix equation can be obtained by substituting the power stage small signal model (2) into (3) to eliminate $\hat{\mathbf{m}}_{du}$.

$$ (U + Z_{f}^{-1}M_{du}Y_{c}^{-1}M_{du})\hat{\mathbf{m}}_{du} + Z_{f}^{-1}(u_{du} + M_{du}Y_{c}^{-1}I_{du})\hat{\mathbf{m}}_{du} = 0 $$  \hspace{1cm} (12)

where $U$ is a $7 \times 7$ unity matrix.

Relationship of small signal $\hat{\mathbf{v}}_p$ and $\hat{\mathbf{m}}_{du}$ can be obtained by substituting (4) into (12)

$$ \begin{bmatrix} U + Z_{f}^{-1}M_{du}Y_{c}^{-1}M_{du} \\ Z_{f}^{-1}(u_{du} + M_{du}Y_{c}^{-1}I_{du}) \end{bmatrix} \hat{\mathbf{m}}_{du} + Z_{f}^{-1} \left[ U + (u_{du} + M_{du}Y_{c}^{-1}I_{du})(Q_{ac} + Q_{feed}) \right] \hat{\mathbf{v}}_p = 0 $$  \hspace{1cm} (13)

Based on this, a $7 \times 7$ admittance matrix of small signal upper arm current $\hat{\mathbf{i}}_{du}$ to a perturbation $\hat{\mathbf{v}}_p$ in AC terminal voltage can be modeled as

$$ \mathbf{Y} = \left[ \begin{bmatrix} U + Z_{f}^{-1}M_{du}Y_{c}^{-1}M_{du} \\ Z_{f}^{-1}(u_{du} + M_{du}Y_{c}^{-1}I_{du}) \end{bmatrix} \right]^{-1} \cdot Z_{f}^{-1} \left[ U + (u_{du} + M_{du}Y_{c}^{-1}I_{du})(Q_{ac} + Q_{feed}) \right] $$  \hspace{1cm} (14)

Since the phase current is twice the arm current, the input impedance of MMC at frequency $f_p$ is

$$ Z(f_p) = \frac{1}{2Y(4, 4)} $$  \hspace{1cm} (15)

where $Y(4, 4)$ is the $(4, 4)$th element of $\mathbf{Y}$.

**B. DC VOLTAGE CONTROL MODE**

The control diagram of dc voltage control mode is shown in Fig. 3. Similar to ac voltage control mode, the complex vector of arm modulation index can be expressed as:

$$ \hat{\mathbf{m}}_{du} = (Q_d + Q_c)\hat{\mathbf{i}}_{du} + (Q_{PLL} + + Q_{feed})\hat{\mathbf{v}}_p + Q_{dc}\hat{\mathbf{v}}_{dc} $$  \hspace{1cm} (16)

where $Q_{PLL}$ and $Q_{dc}$ are the coefficient matrix of PLL and dc voltage outer-loop control respectively. The coefficient matrix $Q_d$ and $Q_c$ are the same as derived under ac voltage control mode.

**FIGURE 3. MMC control structure of dc voltage control mode.**

1) **DC VOLTAGE CONTROL**

Based on the dc voltage control diagram, the coefficient matrix of dc voltage control can be expressed as

$$ Q_{dc}\hat{\mathbf{v}}_{dc} = Q_{dc}\hat{\mathbf{i}}_{du} $$

\[= \begin{bmatrix} 0 & k_{dc1} & 0 \\ 0 & k_{dc2} & 0 \\ 0 & 0 & 0 \end{bmatrix} \hat{\mathbf{i}}_{du} \]  \hspace{1cm} (17)

The dc voltage perturbation $\hat{\mathbf{v}}_{dc}$ of MMC dc side is caused by differential-mode arm current flowing to dc side,

$$ k_{dc1} = -\frac{1}{2} G \left( \frac{2\pi (f_p - f_1)}{f_1} \right) H_i \left( \frac{2\pi (f_p - f_1)}{f_1} \right) e^{-\frac{2\pi f_p f_1}{f_1}}Z_{dc} $$

$$ k_{dc2} = \frac{1}{2} G \left( \frac{2\pi (f_p - f_1)}{f_1} \right) H_i \left( \frac{2\pi (f_p - f_1)}{f_1} \right) e^{-\frac{2\pi f_p f_1}{f_1}}Z_{dc} $$

where $Z_{dc}$ is the power load of MMC dc side.

2) **PHASE-LOCKED LOOP**

The ac voltage perturbation will generate PLL dynamics, and the $dq$ transformation and inverse $dq$ transformation will be affected by these PLL dynamics accordingly. To obtain accurate impedance model, the effect of PLL dynamics needs to be considered. This effect has been derived in [10] and [12], which is not repeated in this paper again.

3) **IMPEDELANCE MODEL UNDER DC VOLTAGE CONTROL MODE**

Based on the analysis above, the sequence impedance of MMC is similar to ac voltage control mode impedance (15),

$$ Z(f_p) = \frac{1}{2Y(4, 4)} $$  \hspace{1cm} (18)

but the coefficient matrices are different, where

$$ \mathbf{Y} = \begin{bmatrix} U + Z_{f}^{-1}M_{du}Y_{c}^{-1}M_{du} \\ Z_{f}^{-1}(u_{du} + M_{du}Y_{c}^{-1}I_{du}) \cdot (Q_d + Q_c + Q_{dc}) \end{bmatrix} $$

\[= \begin{bmatrix} 0 & k_{dc1} & 0 \\ 0 & k_{dc2} & 0 \\ 0 & 0 & 0 \end{bmatrix} \hat{\mathbf{i}}_{du} \]  \hspace{1cm} (19)
The control diagram of power control mode is shown in Fig.4, similar to ac voltage control mode, the complex vector of arm modulation index can be expressed as:

\[ \hat{m}_{\text{arm}} = (Q_d + Q_x + Q_{\text{P,j}}) \hat{d}_{\text{arm}} + (Q_{\text{P,u}} + Q_{\text{PLL}} + Q_{\text{feed}}) \hat{v}_p \]  

(20)

where \( Q_{\text{P,j}}, Q_{\text{P,u}} \) are the coefficient matrix of the current effect component of power control loop and the voltage effect component of power control loop respectively.

Detailed derivation has been proposed in [12], so only the results of the coefficient matrix are given here, detailed derivation process is not shown here again. Power control loop is derived here, and other loops \( Q_d, Q_x, Q_{\text{feed}} \) and \( Q_{\text{PLL}} \) have the similar derivation as ac voltage control mode and dc voltage control mode above.

1) POWER CONTROL

The coefficient matrix of power control loop is

\[
Q_{\text{P,j}} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & d_1 & 0 & 0 & 0 \\
0 & 0 & d_2 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

(21)

where

\[
d_1 = \left(1.5U_d + 1.5U_q \cdot e^{j(\frac{\pi}{2})}\right) \cdot G \left(j2\pi(f_p - f_1)\right) \\
\cdot H_1 \left(j2\pi(f_p - f_1)\right) e^{-j2\pi(f_p - 2f_1)\varphi_d}
\]

(22)

\[
d_2 = \left(1.5U_d + 1.5U_q \cdot e^{j\frac{\pi}{2}}\right) \cdot G \left(j2\pi(f_p - 2f_1 + f_1)\right) \\
\cdot H_1 \left(j2\pi(f_p - 2f_1 + f_1)\right) e^{-j2\pi f_p \varphi_d}
\]

(23)

2) IMPEDANCE MODEL UNDER POWER CONTROL MODE

Similar to ac voltage control mode, the sequence impedance of MMC with power control mode is

\[
Z(f_p) = \frac{1}{2Y(4, 4)}
\]

(24)

where

\[
Y = \left[U + Z_{l}^{-1}M_{\text{arm}}Y_{c}^{-1}M_{\text{arm}}^* + Z_{l}^{-1}(u_{\text{arm}} + M_{\text{arm}}Y_{c}^{-1}I_{\text{arm}}^*)(Q_d + Q_x + Q_{\text{P,j}})\right]^{-1}
\]

(25)

\[
Z_{l}^{-1} = \left[U + (u_{\text{arm}} + M_{\text{arm}}Y_{c}^{-1}I_{\text{arm}})(Q_{\text{P,u}} + Q_{\text{PLL}} + Q_{\text{feed}})\right]
\]

(26)

IV. VALIDATION AND ANALYSIS OF MMC SEQUENCE IMPEDANCE MODEL

The sequence impedance model has been derived analytically based on the analysis above. Impedance simulation models based on sweeping frequency method are established in MATLAB/Simulink to verify the analytical MMC sequence impedance models [22].

A. VERIFICATION OF IMPEDANCE MODEL

The comparison of impedance model and simulation results is shown in Fig. 5, the analytical impedance model derived in this paper matches well with the simulation results, which verifies the correctness of the impedance model proposed above.

These MMC sequence impedance models in Fig. 5 under three different control modes are all with time delay of 300μs. Comparing the impedance models in Fig. 5 under three different control modes, there is a strong similarity of impedance characteristics over 100Hz between dc voltage control mode and power control mode, however, the impedance model under ac voltage control mode is totally different from other two control modes.

The frequency of first resonance peak in Fig. 5(b) (dc voltage control mode) and Fig. 5(c) (power control mode) is about 1/delay, obviously, there is a strong correlation between the delay and the frequency of the resonance peak of the impedance. And the figure shows that this resonance phenomenon occurs periodically in a wide range of frequency. The generation of resonance peak is directly related to the voltage feedforward and time delay, which will be analyzed in the next part.

B. INFLUENCE OF TIME DELAY

Fig. 6 shows the influence of time delay on MMC impedance under power control mode. The purple curve represents the impedance without considering time delay, the other three curves represent the impedance with different time delay. The impedance is significantly different at middle and high frequency when considering delay or not. The impedance changes obviously with the increase of time delay.

When the delay is not considered, the impedance curve has no resonance peak and the phase is always less than 90 degrees in the whole frequency band. As time delay increases, the frequency of first resonance peak decreases, and the frequency of first impedance point whose phase goes up to 90 degrees decreases at the same time. This proves again that the existence of time delay will lead to negative damping of impedance whose phase is larger than 90 degrees, system delay is the root cause of high frequency oscillation.
FIGURE 5. Analytical and simulation results of MMC impedance with (a) ac voltage control mode, (b) dc voltage control mode, (c) power control mode.

FIGURE 6. Impedance with changing time delay under power control mode.

FIGURE 7. Impedance with/without voltage feedforward under power control mode with 300 µs time delay.

C. INFLUENCE OF VOLTAGE FEEDFORWARD

Fig. 7 shows that the impedance characteristics under power control mode are totally different when the voltage feedforward is considered or not. The time delay in Fig. 7 is 300 µs. The impedance characteristics under other control modes have the same conclusion. The existence of feedforward introduces a resonance peak to impedance, the phase of impedance is larger than 90 degrees in a large range below the resonance frequency, which lead to negative damping of impedance. This negative damping means that the probability of high frequency oscillation of MMC-HVDC is greatly increased with the existence of feedforward. From the view of system oscillation risk, both feedforward and delay worsen the stability of the system. But in practical engineering, feedforward is necessary for the need of system dynamic characteristics and fault ride through capability, therefore, how to balance the demand of feedforward and the risk of system oscillation should be an urgent problem to be solved in the future.
FIGURE 8. Impedance with/without outer-loop control. (a) ac voltage control mode. (b) dc voltage control mode. (c) power control mode.

D. INFLUENCE OF OUTER-LOOP

The influence of outer-loop under different control modes with voltage feedforward and time delay is depicted in Fig. 8.

Fig. 8(b) and Fig. 8(c) show that, both MMC impedances under dc voltage control mode and power control mode, the high frequency impedance characteristics are almost the same no matter consider the outer-loop or not. This indicates that the outer-loop only have influence on the impedance characteristics at low frequency range, which is related to its control band loop.

It is worth noting that in Fig. 8(a), when the outer-loop is ignored, the high frequency impedance characteristics under ac voltage control is almost the same as that under other two control modes. But when the outer-loop is considered, the high frequency impedance characteristics under ac voltage control is totally different from that under other two control modes. The reason of this phenomenon is that the outer-loop greatly counteracts the feedforward effect under ac voltage control mode. It can be seen from the control diagram in Fig. 2 that the ac voltage control outer-loop and feedforward have similar channels in dealing with voltage perturbation, but the ac voltage control loop is a feedback loop, which is opposite to voltage feedforward to counteract...
the feedforward effect. That’s why when the ac voltage control loop is ignored, the voltage feedforward will not be affected by the outer loop, then its impedance characteristics begin to converge with that under other two control modes.

E. INFLUENCE OF PLL AND CIRCULATING CURRENT CONTROL

As depicted in Fig. 9, the influence of PLL on MMC impedance characteristics is mainly concentrated in the low frequency band, which has little influence on high frequency band, this is because the bandwidth of PLL is usually low. Therefore, the role of PLL can be ignored when studying high frequency oscillation in MMC-HVDC.

It can be seen from Fig. 10 that, the influence of circulating current suppression control on MMC impedance is mainly concentrated below 100Hz, and will not affect the high frequency characteristics of MMC impedance.

F. ANALYSIS OF CONTROLLER PARAMETERS

Taking the impedance under power control mode as an example, the influence of parameters of current loop controller and power controller are shown in Fig.11 and Fig.12 respectively, the impedance under other control modes have the similar results.

It can be seen that both the current loop controller proportional coefficient $K_p_{\text{inner}}$ and outer-loop controller proportional coefficient $K_p_{\text{outer}}$ have great influence on the MMC impedance. As the $K_p$ increases, with the increase of frequency, the transition process of impedance characteristics from capacitive to inductive will be more dramatic. And the frequency point at which the phase exceeds 90$^\circ$ shifts to a lower frequency point as $K_p$ increases, which means that the negative damping frequency band moves to the lower frequency band, which bring negative effect on the stability of the system. Therefore, the proportional coefficient of inner and...
outer control loop controller can not be set too large. On the premise of meeting the sufficient dynamic characteristics of the system, the proportional coefficient should be designed as small as possible.

G. ANALYSIS OF PARAMETERS OF ARM INDUCTANCE AND SUBMODULE CAPACITOR

The influence of arm inductance and submodule capacitor on impedance characteristics are both studied in this paper.

The arm inductance has influence on the impedance characteristics of the whole frequency band as shown in Fig.13(a). With the increase of inductance, the amplitude of impedance characteristic increases gradually in the whole frequency band, but the phase frequency characteristic hardly changes.

The influence of capacitance on the impedance characteristics of the MMC is less obvious than that of inductance as shown in Fig.13(b). The frequency band of capacitance affecting impedance characteristics is mainly in the low frequency band, and has little effect on high frequency characteristics. With the increase of capacitance value, the capacitive characteristics of circuits of impedance is enhanced.

V. CONCLUSION

This paper proposes an accurate sequence impedance model of MMC considering complete control loops and three control modes, especially time delay and voltage feedforward are considered. Based on this impedance model, how the voltage feedforward and time delay affect the high-frequency characteristics of MMC impedance are analyzed in detail. Other factors affecting the impedance are also studied.

The main conclusions are as follows.

1) The impedance characteristics of MMC with ac voltage control mode has its particularity, under the same system parameters, the frequency of the first resonant peak of MMC impedance with ac voltage control is much lower compared with other control modes, so it is more likely to oscillate in MMC-HVDC with ac voltage control.
2) The existence of time delay will lead to negative damping and resonance peak of impedance, system delay is the root cause of high-frequency oscillation in MMC-HVDC.
3) The voltage feedforward has great influence on the high frequency impedance characteristics of MMC, greatly reducing the frequency of the first resonance peak, increasing the risk of oscillation in MMC-HVDC, which should not be ignored.

In summary, time delay is a key factor of affecting the high frequency characteristics of MMC impedance, and the voltage feedforward will enhance this effect. When studying the high-frequency oscillation in MMC-HVDC, the time delay and the voltage feedforward should be seriously considered.

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