Impact of control system on the DC impedance characteristics of low-medium frequency bands and stability of modular multilevel converter based HVDC system

Xin Lin\textsuperscript{1*}, Chunyi Guo\textsuperscript{1}, Yanning Wang\textsuperscript{1}, Shuo Yang\textsuperscript{1}, Chunhua Li\textsuperscript{2} and Xu Sun\textsuperscript{2}

\textsuperscript{1} School of Electrical and Electronic Engineering, North China Electric Power University, Beijing 102206, China
\textsuperscript{2} Huaneng Clean Energy Research Institute Co., Ltd., Beijing 102209, China

*Corresponding author’s e-mail: lin970815@163.com

Abstract. The resonance in modular multilevel converter based high voltage direct current (MMC-HVDC) system poses a potential threat to the safe and stable operation of the power grid. The mechanism of the resonance phenomenon is complicated, which is closely related to the impedance characteristics of MMC system. By establishing the DC impedance model of MMC-HVDC system at both ends, the influence of parameters of control system in converter stations on the DC impedance characteristics of MMC system was analyzed, revealing the main influencing frequency bands and effect of each control parameter. The DC impedance characteristics of low and medium frequency bands could be shaped in a targeted manner by adjusting the control parameters, the stability margin of the system will be improved as well. The correctness of the results was verified by time domain simulation. The analysis results of this article can provide reference for the selection of the parameters of control system and the improvement of stability margin of MMC-HVDC system.

1. Introduction
Modular multilevel converter based high voltage direct current (MMC-HVDC) technology is widely used in asynchronous interconnection, cross-regional long-distance power transmission, and new energy scale delivery, etc, because of its advantages such as with high waveform quality, flexible structure, and no problem of phase change failure\textsuperscript{[1-3]}. Engineering experience and existing studies have shown that MMC may bring stability problems to the grid when they are put into operation. The mechanism of resonance in flexible DC transmission systems is complex, and factors on both AC and DC sides may lead to oscillation phenomena\textsuperscript{[3-5]}. Therefore, it is necessary to study the oscillation mechanism of MMC-HVDC system in depth to provide theoretical support for the improvement of the safe and stable operation of the system, and a basis for the suppression measures of resonance.

The impedance-based stability analysis method has been widely used in the analysis of stability problems and oscillation mechanisms. Based on the reasonable selection of the port location, the establishment of AC impedance or DC impedance models, and the analysis of the interaction between the impedance characteristics of two independent subsystems, this method could reflect the stability margin of the system, and reveal the oscillation mechanism\textsuperscript{[6]}. In the application of this method, the analysis of impedance characteristics is crucial.
For the study of impedance characteristics of MMC, most of the literature has been conducted from AC side, revealing the effect of control system, delay links, and AC grid on the impedance characteristics of AC side and stability of the system[729]. For the DC impedance characteristics, reference [10] established an analytical model of the DC impedance of MMC-HVDC system, revealing the effect of the circulating current suppression control on the value of the equivalent R-L-C branch, as well as the suppression of the resonance between the DC cable and the converter station. Reference [11] established a flexible DC transmission system including the control system, and mainly studied the influence of transmission power, DC cables, and capacitors. In the reference [12], the DC impedance model of back-to-back MMC system containing internal dynamic characteristics and control system was established by harmonic transfer function, revealing the influence of DC voltage controller and circulating current suppression controller on the DC impedance characteristics and stability of the system. On this basis, reference [13] established the DC impedance model considering wind farm access, and determined the influencing factors of the impedance characteristics. Part of the DC impedance models established above contain the complete control system, however, none of them involves a comprehensive detailed analysis of the influence of the control parameters on the DC impedance characteristics and stability of MMC-HVDC.

Based on the detailed DC impedance model of the MMC-HVDC system, this paper analyzes the effect of control parameters on the DC impedance characteristics of MMC, clarifies the main influencing frequency bands and effects of each control parameter, and reshapes the DC impedance characteristics of low-medium frequency bands in a targeted manner by adjusting the control parameters to improve the stability margin of the system. Finally, the correctness of the results is verified by time-domain simulation.

2. Structure of MMC-HVDC system
The structure of MMC-HVDC system studied in this paper is shown in figure 1, and the parameters of main circuit and control system are shown in table 1 and table 2. The main circuit of MMC system consists of symmetrical AC system at both ends, converter transformers, MMC converters and DC line. The control system mainly contains the outer and inner loop control boards of classical vector current control (VCC), phase lock loop (PLL) and circulating current suppression control (CCSC). The control system is identified with the rectifier as an example in figure 1, and the same could be obtained for the inverter.

In this system, the rectifier-side MMC adopts fixed active and reactive power control, and the inverter-side MMC adopts fixed DC voltage and reactive power control.

![Figure 1. Diagram of MMC-HVDC system](image-url)
3. DC Impedance model of MMC-HVDC system

The port location shown in figure 1 is chosen to divide the system into 2 separate subsystems, $Z_{rec}$ on the rectifier-side and $Z_{inv}$ on the inverter-side, where the system can be equated to the circuit structure shown as figure 2.

Impedance modeling is performed separately for the above MMC subsystem, and the modeling method is specified as described in the reference [14]. Firstly, the state-space description of the MMC station at both ends is performed separately, where $x$ is the state variable, the input variable $u$ is the...
voltage of the port, and the output variable $y$ is the current of port. The state-space equation and the output equation are obtained as shown in equation (1).

$$\begin{align*}
\begin{bmatrix} g \\
y \end{bmatrix} = & \begin{bmatrix} f(x, u) \\
g(x, u) \end{bmatrix} \\
\end{align*} \quad (1)
$$

Equation (1) can be linearized at the steady-state operating point to obtain the small disturbance dynamic model as shown in equation (2).

$$\begin{align*}
\begin{bmatrix} s\Delta x \end{bmatrix} &= \begin{bmatrix} A\Delta x + B\Delta u \end{bmatrix} \\
\begin{bmatrix} \Delta y \end{bmatrix} &= \begin{bmatrix} C\Delta x + D\Delta u \end{bmatrix} \\
\end{align*} \quad (2)
$$

The DC impedance model of MMC system can be obtained by eliminating the state variables from equation (2), as shown in equation (3), where $Z_{\text{ mmc}}$ refers to $Z_{\text{ rec}}$ and $Z_{\text{ inv}}$ according to different objects. And the detailed expressions are not given here due to space limitation.

$$Z_{\text{ mmc}}(s) = \frac{\Delta u}{\Delta y} = (C(sI - A)^{-1} B + D)^{-1} \quad (3)$$

Based on the impedance-based stability analysis method, the basis for applying the Nyquist criterion to discriminate the stability of system can be expressed as follows: the studied system will be stable when the Nyquist curve of the minimum loop gain $L(s)$ shown in equation (4) does not enclose the (-1, j0) point in ($-\infty$, $+\infty$) frequency range$^{[15]}$.

$$L(s) = \frac{Z_{\text{ inv}}(s)}{Z_{\text{ rec}}(s)} \quad (4)$$

4. Impact of control system parameters on DC impedance characteristics of MMC-HVDC

The oscillatory instability phenomenon of MMC system is related to the negative impedance damping characteristics, whose stability is determined by $Z_{\text{ rec}}$ and $Z_{\text{ inv}}$. To investigate the effect of $Z_{\text{ rec}}$ and $Z_{\text{ inv}}$ DC impedance characteristics of MMC system when control system parameters are changed, this subsection takes the inter loop controller as an example, firstly. The bandwidth of inner loop controller on both sides is modified respectively, and the results are shown in figure 3.

![Figure 3](image-url)

(a) Bode plot of $Z_{\text{ rec}}$ when $f_{\text{ in}, 1}$ changes

(b) Bode plot of $Z_{\text{ inv}}$ when $f_{\text{ in}, 1}$ changes

Figure 3. Influence of $f_{\text{ in}}$ on DC impedance characteristics

It can be seen that the influence of the inner loop bandwidth is mainly concentrated in the frequency band below 100Hz, and the phase angle characteristics of $Z_{\text{ rec}}$ and $Z_{\text{ inv}}$ are basically capacitive before inductive. In the inductive band range, the phase angle curve of $Z_{\text{ rec}}$ on the rectifier side exhibits two inductive troughs with decreasing phase angle followed by increasing one (named “trough 1” and “trough 2” respectively), while the phase angle curve of $Z_{\text{ inv}}$ on the inverter side contains inductive trough in 40–60Hz band range (named “trough 3”).
As shown in figure 3(a), the inner loop control bandwidth \(f_{in,R}\) affects frequency bands involved in two troughs of \(Z_{rec}\), changing the location (frequency band) and depth (inductive intensity) of two troughs on the phase angle curve. As \(f_{in,R}\) increases, the inductance of trough 1 (40-60Hz) decreases; which of trough 2 (60-80Hz) increases, and the location of trough 2 moves toward the positive direction of the real axis of frequency. As shown in figure 3(b), when \(f_{in,1}\) increases, the inductance of trough 3 (40-60Hz) in \(Z_{inv}\) weakens first and followed by increasing, and the location of trough 3 moves toward the positive direction of the real axis of frequency.

Similarly, the main influencing frequency bands and effects of other control parameters on the DC impedance characteristics of MMC subsystem can be obtained, and the results are shown in figure 4 and table 3.

![Phase angle curve](image)

**Figure 4. Main influencing frequency bands of control parameters on DC impedance characteristics**

**Table 3. Main influencing frequency bands and effects of control parameters.**

| Parameters | Main impact frequency bands | The main effect on the phase angle curve |
|------------|-----------------------------|----------------------------------------|
| Inner loop of VCC \(f_{in,R}\) | 40-100Hz | As \(f_{in,R}\) increases, inductance of trough 1 decreases, that of trough 2 increases; the location of trough 2 moves toward the positive direction of the real axis of frequency. |
| Outer loop of PLL \(f_{PLL,R}\) | 60-80Hz | As \(f_{PLL,R}\) increases, inductance of trough 2 increases; the location of trough 2 moves toward the positive direction of the real axis of frequency. |
| Outer loop of CCSC \(f_{CCSC,R}\) | 40-60Hz | As \(f_{CCSC,R}\) increases, inductance of trough 1 slightly increases. |
| Outer loop of \(Z_{inv}\) \(f_{out,1}\) | 40-80Hz | As \(f_{out,1}\) increases, inductance of trough 3 decreases firstly followed by increasing, whose location moves toward the positive direction. |
| Outer loop of \(Z_{inv}\) \(f_{out,Udcl}\) | 0-20Hz / 40-60Hz | As \(f_{out,Udcl}\) increases, inductance of trough 3 decreases, and the phase angle characteristics below 20Hz are affected. |
| Outer loop of VCC \(f_{out,QI}\) | 40-60Hz | As \(f_{out,QI}\) increases, inductance of trough 3 increases, while the location of it moves toward the positive direction. |
| PLL \(f_{PLL,1}\) | 40-60Hz | As \(f_{PLL,1}\) increases, inductance of trough 3 decreases. |
| CCSC \(f_{CCSC,1}\) | 40-60Hz | As \(f_{CCSC,1}\) increases, inductance of trough 3 slightly decreases. |
In summary, the control system parameters mainly affect the phase angle characteristics of the low and medium frequency bands of MMC system. The above law of DC impedance characteristics of MMC system change with control parameters will provides a reference basis for the selection of control parameters and the improvement of system stability margin.

5. Verification of the influencing law of control system parameters on the DC impedance characteristics of MMC-HVDC

In order to verify the correctness of the above conclusions, this subsection takes reducing SCR\_R as an example, analysing the stability of MMC-HVDC system using the impedance-based method, and adjusts the control parameters based on the above-mentioned law of the impact of control system on DC impedance characteristics to stabilize the system. The results will be verified in PSCAD later.

As shown in the purple curve in figure 5(a), the impedance characteristic curve of Z\_sec has a capacitive negative damping band and there is a risk of oscillatory instability when SCR\_R=2.0 \((f_{PLL}R=10Hz)\). At the same time, the Nyquist curve of MMC system is shown as the purple curve in figure 5(b), showing that the Nyquist curve of \(L(s)\) surrounds the \((-1, j0)\) point via the second and third quadrants, and the MMC system is judged to be unstable as a result.

To ensure stable operation of MMC system under the weak AC grid condition of the rectifier side, the stability of the system should be enhanced by adjusting the control parameters. From the Bode diagram shown in Fig. 5(a), the main reason for the instability is the capacitive negative damping characteristic of Z\_sec in trough 2 (60–80Hz). By analysis in subsection 4, decreasing \(f_{PLL}R\) of the rectifier-side will significantly improve the impedance characteristics of Z\_sec in this frequency band, making the phase angle curve less capacitive and more inductive. Therefore, the Bode diagram and Nyquist curve at \(f_{PLL}R=7Hz\) under the same operating condition are plotted to compare with the original operating condition, and the results are shown as the blue curve in figure 5. It is easy to know that the capacitance of Z\_sec in above frequency band decreases and it no longer exhibits negative damping characteristics when \(f_{PLL}R\) decreases to 7Hz, and the Nyquist curve of \(L(s)\) stays in the first and fourth quadrants without encircling the \((-1, j0)\) point, at which point MMC system operates stably.

The above conclusions can be verified by time domain simulation, and the results are shown in figure 6. In figure 6, MMC system operates at a steady state with SCR\_R=3.0, \(f_{PLL}R=10Hz\); and SCR\_R changes from 3.0 to 2.0 at 4s, MMC system oscillating and diverging later; \(f_{PLL}R\) step-changes from 10Hz to 7Hz at 6s, with MMC system converging from oscillation and divergence quickly to stable operation, indicating that the stability of MMC system is improved by reducing \(f_{PLL}R\). This conclusion is consistent with the above stability analysis results. At the same time, the oscillation frequency of the system is 65.51Hz under SCR\_R=2.0 and \(f_{PLL}R=10Hz\), which is consistent with the cut-off frequency (the frequency value corresponding to the intersection of Nyquist curve and unit circle) \(\omega_c=65.09Hz\), further verifying the accuracy of the stability analysis.
The case above shows that the control parameters can be adjusted to reshape the DC impedance characteristics of MMC system in the low and medium frequency bands in a targeted manner by applying the law of DC impedance characteristics changing with control parameters, to avoid the destabilizing conditions and improve the stability margin of the system.

6. Conclusions
Based on the detailed DC impedance model of MMC-HVDC, this paper analyses the influence of control parameters of MMC station on the DC impedance characteristics and stability of MMC system, and the main influence frequency bands and effect of each control parameter are determined. The main conclusions are drawn as follows:

(1) For the DC impedance of rectifier-side MMC system, the inner loop control bandwidth and active power control bandwidth mainly affect the phase angle characteristics in the frequency band range of 40–100Hz, the reactive power control bandwidth and phase locked loop bandwidth mainly affect the capacitive- inductive characteristics of the phase angle curve in the frequency band range of 60–80Hz, and the circulating current suppression bandwidth has a limited degree of influence.

(2) For the DC impedance of inverter-side MMC system, the control parameters basically act on the phase angle curve in the frequency range of 40–60Hz. The inner loop control bandwidth mainly changes the location of the trough in this frequency range, and the DC voltage control bandwidth, reactive power control bandwidth and phase locked loop bandwidth mainly affect the capacitive-inductive characteristics, with limited influence of the circulating current suppression bandwidth.

The conclusions above will provide reference for the selection of the parameters of control system, and lay a good foundation for the subsequent research on the improvement method of stability margin and the oscillation suppression measures of the MMC-HVDC system.

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