Interaction between damping characteristics and the initial-stage short-circuit current of MMC-HVDC transmission systems

Boyu Qin1 | Wansong Liu1,2 | Xingyue Zhou1 | Tao Ding1 | Wei Li3 | Albert Y. Zomaya3

Abstract

This paper studies the interaction between the damping characteristics and the initial-stage short-circuit current of modular multilevel converter based high voltage direct current (MMC-HVDC) transmission system. First, the MMCs’ input–output characteristics are obtained through the operator approach, and the influences of both linear part and nonlinear part are analysed. Second, an input–output characteristics based short-circuit current calculation method is proposed. Third, an eigenvalue-based comprehensive index is proposed to evaluate the damping characteristics of the MMC-HVDC transmission system. Finally, the interaction between the damping characteristics and the initial-stage DC short-circuit current is analysed under different system parameters and DC system structures. The analysis results show that there is a negative correlation between the system damping characteristics and the average rising rate of the short-circuit current. The proposed index $G$ can effectively evaluate the short-circuit current of MMC-HVDC and can provide guidance for the planning of DC system structure, the selection of operation mode and system parameters.

1 INTRODUCTION

With the ability of controlling the direction of the DC power flow without changing the DC voltage polarity, modular multilevel converter based high voltage direct current (MMC-HVDC) is able to construct multi-terminal direct current (MTDC) power grid [1, 2]. However, when a DC short-circuit fault occurs, the submodule capacitors in MMCs discharge rapidly, which leads to excessive rising rate of the short-circuit current during the initial fault period [3]. Moreover, the expansion of DC power grid and the increasing of DC voltage level worsen the short-circuit current dynamics of the MMC-HVDC transmission system.

System damping is an important index to study system dynamics under perturbations. Analysing the damping characteristics of MMC-HVDC transmission system can provide guidance for studying the dynamics of short-circuit current. The existing research mainly focus on the calculation and suppression of short-circuit current in MMC-HVDC transmission system. The equivalent circuit method is widely adopted in MMC-HVDC short-circuit current calculation, where MMCs are regarded to be capacitor-inductor series circuits [4, 5]. However, the internal dynamics of MMCs are ignored through the equivalent circuit methods, and the damping characteristics of the system cannot be displayed. The mainstream of the existing short-circuit current suppression methods for MMC-HVDC are optimising the MMC topology [6] and installing new current limiting devices [7]. The existing researches lack evaluation of the system damping and the short-circuit current to provide guidance for the planning and operation of MMC-HVDC transmission system.

This paper studies the interaction between the damping characteristics of the MMC-HVDC transmission system and it is initial-stage DC short-circuit current. First, the MMCs’...
input–output characteristics are obtained through the operator approach. Second, an MMCs’ input–output characteristics based pole-to-pole initial-stage short-circuit current calculation method is proposed, which can fully consider the dynamics of MMC-HVDC during the initial fault period. Third, to evaluate the system damping of MMC-HVDC transmission systems, a comprehensive index $G$ is defined based on the eigenvalue analysis. Finally, the interaction between the damping characteristics and the initial-stage short-circuit current is analysed under different system parameters and DC system structures.

2 | SHORT-CIRCUIT CURRENT CALCULATION BASED ON THE MMCS’ INPUT–OUTPUT CHARACTERISTICS

2.1 | Estimate of input–output characteristics

According to [8], with the operator approach, any nonlinear system can be decomposed into the series combination of a linear part and a nonlinear part.

Therefore, the system’s input–output characteristics can be formulated as

$$y = Zu \Rightarrow y = N\zeta u$$

(1)

where $L\zeta$ represents the dynamics of the linear part, and $N\zeta$ represents the nonlinear dynamics of the system.

For each MMC, the DC current is selected as the output variable, respectively. The dynamics of the linear part can be represented by the auto-regressive moving average (ARMA) model and the parameters of the linear part are identified through the least squares fit based approach [8].

The nonlinear part $N\zeta$ can be estimated by a group of conic center and conic radius $\{c, r\}$ [8], which satisfies

$$\|y - \alpha\| \leq r\|u\|$$

(2)

Under small perturbations, it is feasible to neglect the dynamics of the nonlinear part $N\zeta$. Therefore, the linear part $L\zeta$ can be identified by injecting small-signal perturbations around a stable operating point. $N\zeta$ can be identified by given a measured set of input and output data under large perturbations. The set $\{c, r\}$ representing the characteristics of the nonlinear part can be calculated by

$$r(c) \geq \sqrt{\frac{\|y - \alpha\|^2}{\|u\|^2}}$$

(3)

From the above discussion, each group of $\{c, r\}$ satisfying Equation (3) can be used to represent the dynamics of the system nonlinear part. Generally, the group of $\{c, r\}$ with the smallest value of $c + r$ is selected to reduce the conservativeness of the system identification.

2.2 | Pole-to-pole short-circuit current calculation method

To simplify the description, the nodes directly connected to the MMCs are defined as “real nodes” and the nodes without direct connection with MMCs are defined as “virtual nodes”. Consider an MMC-HVDC transmission system with $n$ real nodes and $m$ virtual nodes on the DC side. The DC network equation, the MMCs’ input–output characteristics, and pole-to-pole the short-circuit current of the MMC-HVDC can be presented as

$$\begin{align*}
YU &= I \quad \text{(4a)} \\
I_j - I_{je} &= H_j(U_j - U_{je}), j = 1, 2, 3, 4 \ldots, n \quad \text{(4b)} \\
I_t &= U_t/Z_t \quad \text{(4c)}
\end{align*}$$

where $Y$ is a $s \times s$ matrix which represents admittance matrix of the DC system; $s$ is the total node number of DC system which satisfies $s = n + m + 1$; $U = [U_1, \ldots, U_n, U_{n+1}, \ldots, U_{n+m}]^T$ where $U_k$ is the DC voltage of node $k$; $I = [I_1, \ldots, I_n, I_{n+1}, \ldots, I_{n+m}]^T$ where $I_k$ is the DC current injection of node $k$; $U_j$ and $U_{je}$ denote the $j$th MMC’s actual DC voltage and rated DC voltage, respectively; $I_j$ and $I_{je}$ denote the $j$th MMC’s actual DC current and rated DC current, respectively; $H_j$ represents the $j$th MMC’s input–output characteristic; $I_t$ is the pole-to-pole short-circuit current; $U_t$ is the DC voltage of the short-circuit point; $Z_t$ denotes the short-circuit impedance.

By combing Equations (4b) and (4c), $I$ can be expressed as

$$I = \Theta U + b$$

(5)

where $\Theta$ and $b$ are expressed as follows.

$$\Theta = \text{diag}[H_1, H_2, \ldots, H_n, 0_{(m+1) \times 1}/Z_t], b = \begin{bmatrix} I_{1e} - U_1/H_1 \\ \vdots \\ 0_{(m+1) \times 1} \end{bmatrix}$$

By combining Equations (4a) and (5), the modified DC voltage matrix satisfies

$$(Y - \Theta)U = b$$

(6)

The short-circuit point voltage $U_t$ can be obtained by applying Gauss elimination on Equation (6), then the short-circuit current $I_t$ can be calculated through Equation (4c).

2.3 | Verification of short-circuit current calculation method

To verify the effectiveness of the proposed short-circuit current calculation method, tests are performed on a three-terminal MMC-HVDC transmission system. The structure of the test
FIGURE 1 Structure of three-terminal MMC-HVDC system

TABLE 1 Parameters of three-terminal MMC-HVDC

| System parameter          | Value                      |
|---------------------------|----------------------------|
| DC voltage                | ±320 kV                    |
| Number of submodules      | 200                        |
| Submodule capacitance     | 10,000 μF                  |
| Bridge arm impedance      | 60 mH, 1.5 Ω               |
| Smoothing reactors        | 150 mH                     |
| Equivalent transformer inductance | 25 mH                  |
| AC system equivalent impedance | 35 mH, 2Ω              |
| Rated AC voltage          | 230 kV                     |
| DC line inductance        | 0.82 mH/km                 |
| DC line resistance        | 0.01 Ω/km                  |
| DC line length            | 100 km                     |

system is depicted in Figure 1. MMC_I regulates the DC voltage and reactive power. MMC_II regulates its own active and reactive power, whose reference values are 600 MW and 0 MVar, respectively. MMC_III regulates its own active and reactive power, whose reference values are −200 MW and 0 MVar, respectively. The system parameters are shown in Table 1.

To obtain both MMCs’ input–output characteristics, a DC voltage source is connected to each MMC to provide a stable operating point. The constant-switching-pace symmetric random signal (CSRS), with a maximum amplitude less than 5% of the rated DC voltage is superimposed on DC voltage source as a small-signal perturbation. A sampling frequency of 25,000 Hz and a perturbing frequency of 5000 Hz for the CSRS are selected. 500 sets of the sampling data are recorded.

The log (RMS error) of ARMA models with different orders are shown in Table 2. It can be seen that the larger order of the ARMA model results in smaller RMS error. When the order of ARMA model is bigger than 5, the RMS errors tend to level down. Therefore, ARMA models with order greater than 5 do not significantly improve the accuracy of the identification, and the 5th order models are chosen to represent the linear part of the MMCs. The comparison between the 5th order ARMA model and the time-domain simulation are shown in Figure 2(a–c). The mean relative errors of DC current in MMC_I, MMC_II, and MMC_III are 2.0381%, 1.6616% and 1.9302%, which indicate that the DC current response obtained from the 5th order ARMA model are in satisfactory match with negligible errors when compared with the simulation curves.

After identifying the linear part of the MMCs, it is feasible to identify the nonlinear dynamic of the system. To ensure the entire operating region is covered, the switching frequency is selected as 5000 Hz and the maximum CSRS amplitude is selected as the rated DC voltage. Because the linear part and the nonlinear part are connected in series, the output of the linear part, which can be calculated through the ARMA model, are selected as the input of the nonlinear part. Figure 2(d) illustrates the estimated functional relationship between the radius \( r \) and center conic \( c \).

According to Equation (3), \( (c + r) \) represents the input–output gain of the nonlinear part. The closer distance between \( (c + r) \) and 1 indicates less influence of the nonlinear part on the system. Notice that the input–output gains of the three MMCs are very small (less than 2%: for MMC_I, \( c = 0.96, r = 0.0581 \); for MMC_II, \( c = 0.97, r = 0.039 \); for MMC_III, \( c = 0.96, r = 0.05173 \)). When calculating the short-circuit current at the initial period of fault, it is feasible to only consider the linear dynamics of MMCs.

TABLE 2 Log (RMS error) of ARMA with different orders

| Order | MMC_I    | MMC_II   | MMC_III  |
|-------|----------|----------|----------|
| 1     | −2.4633  | −2.5005  | −2.3835  |
| 2     | −2.4738  | −2.5238  | −2.3888  |
| 3     | −2.4862  | −2.5279  | −2.4347  |
| 4     | −2.4961  | −2.5410  | −2.4397  |
| 5     | −2.5475  | −2.5936  | −2.4873  |
| 6     | −2.5485  | −2.5950  | −2.4876  |
| 7     | −2.5623  | −2.5998  | −2.4960  |
FIGURE 2  System identification results of MMCs. (a) Output response comparison MMC$_I$. (b) Output response comparison MMC$_II$. (c) Output response comparison MMC$_{III}$. (d) Conic radius-center conic relationship

FIGURE 3  Short-circuit current comparison

Pole-to-pole short-circuit faults with different resistances are applied at the midpoint of the DC transmission line between MMC$_I$ and MMC$_{III}$. Figure 3 shows the comparison between the short-circuit currents obtained through the proposed method, the equivalent-circuit based method, and simulation under different short circuit resistances.

When the fault resistance is small, the MMCs are blocked due to the protection system. The identification of MMCs’ input–output characteristics is based on the normal operation mode of MMCs. Therefore, the proposed short-circuit current calculation method is effective before blocking. When the fault resistance is large, the short-circuit current is not large enough
to block the MMCs, and the proposed method can accurately reflect the whole process of the fault current.

It can be seen from Figure 3 that both methods can accurately calculate the pole-to-pole short-circuit current of MMC-HVDC transmission system before the MMCs are blocked. Compared with the equivalent-circuit based methods, the proposed input–output characteristic based short-circuit current calculation method considers the internal dynamics of MMCs. It can build the relationship between the system characteristics of MMC-HVDC transmission system and the DC pole-to-pole short-circuit current. The influences of system characteristics on the short-circuit current can be analysed based on the proposed method, which will be discussed in the subsequent sections.

3 INTERACTION BETWEEN SYSTEM DAMPING CHARACTERISTICS AND THE INITIAL-Stage SHORT-CIRCUIT CURRENT

3.1 Index of damping characteristics

To evaluate the damping characteristics of MMC-HVDC, the small signal model needs to be established first. By transforming the input–output characteristics into the state-space matrix form, the small signal model of a single MMC can be obtained as follows

\[
\Delta \dot{x} = A \Delta x + B \Delta u_{de} \tag{7}
\]

where \(\Delta x\) denotes the state variables vector. The order of the state-space model is determined by the order of the ARMA model in system identification. The smoothing reactor is included in the equivalent series inductance of line [9]. The studied system adopts overhead lines and the equivalent model of DC transmission line is established by using resistance inductance series circuit, which is represented by

\[
\frac{dI_{dc}}{dt} = \frac{U_{dc1}}{L_d} - \frac{U_{dc2}}{L_d} - \frac{R_d I_{dc}}{I_{dc}} \tag{8}
\]

where \(U_{dc1}\) and \(U_{dc2}\) are the voltages at both ends of the DC line; \(R_d\) and \(L_d\) are the equivalent impedance of the DC line.

The complete small signal model of MMC-HVDC consisting of \(n\) terminals can be obtained as Equation (9) by combing Equations (7) and (8).

\[
\Delta x_{sys} = A_{sys} \Delta x_{sys} \tag{9}
\]

In order to evaluate the damping characteristics of the MMC-HVDC transmission system, both the real part \(\sigma\) and the damping ratio \(\xi\) of the eigenvalues need to be considered. The real parts represent the dynamics of the attenuation modes and damping ratio \(\xi\) represents the dynamics of oscillation modes. The eigenvalue-based comprehensive index \(G\) can be defined as

\[
G = G_a + G_o \tag{10}
\]

where \(G_a\) and \(G_o\) are assessment indices with respect to attenuation modes and oscillation modes.

As the real part \(\sigma\) and the damping ratio \(\xi\) are in different dimensions, they cannot be readily applied in Equation (10). To address this issues, a normalisation method proposed is adopted in this paper. Variables \(f_{\sigma_j}\) and \(f_{\xi_j}\) are introduced to normalise \(\sigma\) and \(\xi\) within the range of 0 to 1, which can be formulated as follows [10].

\[
\begin{align*}
&f_{\sigma_j} = 1 - \frac{1}{\sigma_j - \mu_{0_{\sigma_j}}} \quad \sigma_j \geq \mu_{0_{\sigma_j}} \\
&f_{\xi_j} = 1 - \frac{1}{\xi_j - \mu_{0_{\xi_j}}} \quad \mu \geq \mu_{0_{\xi_j}}
\end{align*}
\tag{11}
\]

where \(f_{\sigma_j}\) and \(f_{\xi_j}\) are the normalisation values for \(\sigma\) and \(\xi\) of mode \(j\); \(\mu_{0_{\sigma_j}}\) and \(\mu_{0_{\xi_j}}\) are the infimum of \(\sigma\) and \(\xi\); \(\tau_{\sigma_j}\) and \(\tau_{\xi_j}\) are the corresponding parameters, which are determined by a pre-specified point \((\mu_\circ, 0.95)\).

Therefore, the comprehensive index \(G\) can be represented as

\[
G = \sum_{i=1}^{\alpha} |p_i| f_{\sigma_i} + \sum_{k=1}^{\beta} |p_k| (f_{\sigma_k} + f_{\xi_k}) \tag{12}
\]

where \(\alpha\) and \(\beta\) are the total number of the attenuation modes and oscillation modes; \(p_i\) and \(p_k\) are the participation factor of attenuation mode \(i\) and oscillation mode \(k\) relative to the DC current.

3.2 Interaction between damping characteristics and the initial-stage short-circuit current

To study the interaction between the damping characteristics and the short-circuit current of MMC-HVDC transmission system, different damping characteristics are selected. The proposed short-circuit current calculation method is applied to calculate the corresponding average rising rate of the pole-to-pole short-circuit currents before blocking with respect to different index \(G\), as shown in Figure 4.

It can be seen from Figure 4 that with the increase of the index \(G\), the average rising rate of the short-circuit current decreases, which indicates that there is a negative correlation between the system damping characteristics and the average rising rate of the short-circuit current.

3.3 Impacts of parameters on system damping characteristics

To investigate the impacts of system parameters on system damping characteristics, different system parameters are applied
FIGURE 4 Interaction between the damping characteristics and the short-circuit current of the studied MMC-HVDC to the studied system and the corresponding index $G$ are calculated. All other parameters are unchanged as shown in Table 1.

Figure 5(a) shows the curve of the index $G$ when the bridge arm inductance and smooth reactors vary. With the increase of the inductance, the damping characteristics of the MMC-HVDC transmission system is dramatically enhanced. Both bridge arm inductance and smooth reactor inductance have great impact the damping characteristics of the MMC-HVDC transmission system.

The bode diagrams of the MMC-HVDC transmission system under different bridge arm inductances are shown in Figure 6. It can be seen that with the increase of bridge arm inductances, the cut-off frequency of the system is gradually reduced, which indicates lower rising rate of the short-circuit current. This trend is consistent with the relationship between the index $G$ and the short-circuit current.

The index $G$ under different submodule capacitances are shown in Figure 5(b). It can be seen from Figure 5(b) that the damping characteristics of the MMC-HVDC transmission system is gradually weaken with the increase of the submodule capacitances. However, compared with the results of different bridge arm inductances, the submodule capacitances have less impact on the index $G$.

FIGURE 5 Index $G$ under different system parameters (a) Different inductances. (b) Different submodule capacitances. (c) Different bridge arm resistances

FIGURE 6 Bode diagram under different inductances
3.4 Impacts of DC system structure on system damping characteristics

As discussed in 3.2, there is a negative correlation between the system damping characteristics and the average rising rate of the short-circuit current. Therefore, it is feasible to evaluate the short-circuit current of MMC-HVDC system based on index $G$. The index $G$ is only determined by the system properties such as DC system structure, operation modes, and system parameters. The impacts of DC system structure on system damping characteristics and short-circuit current are studied in this section.

For a three-terminal MMC-HVDC transmission system, there are two typical kinds of DC system structures as shown in the Figure 7: Δ-shape and Y-shape. The MMCs adopt the same operation mode with the MMC-HVDC system depicted in Figure 1. The indices $G$ for Δ-shape and Y-shape are calculated as 0.740509 and 0.719506, respectively. The average rising rates of the short-circuits for Δ-shape and Y-shape are 5.009 kA/ms and 5.334 kA/ms, which is consistent with the trend of index $G$.

4 CONCLUSION

This paper studies the interaction between damping characteristics and the initial-stage short-circuit current. The operator approach is applied to model the MMCs’ input–output characteristics. Based on the obtained input–output characteristics, a short-circuit current calculation method for MMC-HVDC is proposed. A comprehensive eigenvalue-based index is proposed to evaluate the damping characteristics of the MMC-HVDC transmission system. The interaction between damping characteristics and initial-stage DC short-circuit current is analysed under different system parameters and DC system structures. The analysis results show that the proposed index $G$ can effectively evaluate the short-circuit current of MMC-HVDC and can provide guidance for the planning of DC system structure, the selection of operation mode and system parameters.

ACKNOWLEDGMENTS

This work is supported by National Key R&D Program of China (2018YFB0904600) and Science and technology project of State Grid Corporation of China (Control Strategy Optimization Technology for Large-Scale Photovoltaic Power Generation on the sending-end and receiving-end of DC power system).

ORCID

Boyu Qin https://orcid.org/0000-0002-2612-7881
Wansong Liu https://orcid.org/0000-0002-3278-5426

REFERENCES

1. Debnath, S., et al.: Operation, control, and applications of the modular multilevel converter: A review. IEEE Trans. Power Electron. 30(1), 37–53 (2015)
2. Zhang, L., et al.: Modeling, control, and protection of modular multilevel converter-based multi-terminal HVDC systems: A review. CSEE J. Power Energy Syst. 3(4), 340–352 (2017)
3. Qin, B., et al.: Review on short-circuit current analysis and suppression techniques for MMC-HVDC transmission systems. Appl. Sci. 10(9), 6769 (2020)
4. Li, C., et al.: A pole-to-pole short-circuit fault current calculation method for dc grids. IEEE Trans. Power Syst. 32(6), 4943–4953 (2017)
5. Liu, Y., et al.: Short-circuit current estimation of modular multilevel converter using discrete-time modeling. IEEE Trans. Power Syst. 34(1), 40–45 (2019)
6. Adam, G.P., et al.: New efficient submodule for a modular multilevel converter in multiterminal HVDC networks. IEEE Trans. Power Syst. 32(6), 4258–4278 (2017)
7. Xin, Y., et al.: Current suppression method for DC side short circuit fault of MMC. In: 2019 4th IEEE Workshop on the Electronic Grid (eGRID), pp. 1-8. IEEE, Piscataway, NJ (2019)
8. Huynh, P., Cho, B.H.: A new methodology for the stability analysis of large-scale power electronics systems. IEEE Trans. Circuits Syst. I: Fundam. Theory Appl. 45(4), 377–385 (1998)
9. Daryabak, M., et al.: Modeling of LCC-HVDC systems using dynamic phasors. IEEE Trans. Power Delivery 29(4), 1989–1998 (2014)
10. Wu, X., Shen, C., Iravani, R.: Feasible range and optimal value of the virtual impedance for droop-based control of microgrids. IEEE Trans. Smart Grid 8(3), 1542–1251 (2017)

How to cite this article: Qin B, Liu W, Zhou X, Ding T, Li W, Zomaya AY. Interaction between damping characteristics and the initial-stage short-circuit current of MMC-HVDC transmission systems. IET Power Electron. 2021;1–8.
https://doi.org/10.1049/pel2.12154