Impact of Strength and Proximity of Receiving AC Systems on Cascaded LCC-MMC Hybrid HVDC System

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Abstract- The cascaded hybrid LCC-MMC inverter is considered as a feasible option to mitigate the commutation failure problem of conventional LCC-HVDC while maintaining bulk power transmission capability. However, the coupling between different types of converters may result in instability when the inverter integrates with weak AC systems. This paper establishes a small-signal model of the cascaded LCC-MMC inverter based hybrid HVDC system and validates the model against PSCAD/EMTDC. Through eigenvalue analysis, the impact of the strength and proximity of receiving AC systems on the small-signal stability is investigated, and the stable zone of the strength of receiving AC systems is identified. Besides, a supplementary coupling mitigation control is proposed to tackle the instability problem under weak AC systems integration. Both analytical results and time-domain simulations demonstrate the validity of the supplementary control.

Index Terms- Cascaded hybrid HVDC, line commutated converter, modular multilevel converter, renewable energy, small-signal stability.

NOMENCLATURE

Variables:

R_{si}, L_{si}	resistance and inductance of AC system i ($i = 1, 2, 3$)
R_{tie}, L_{tie}	resistance and inductance of tie line
L_{T1}, L_{T2}, L_{T3}	leakage inductance of transformers of LCC inverter, MMC and LCC rectifier
L_{dc}	DC current-limiting inductance
$R_{line}, L_{line}, C_{line}$	resistance, inductance and capacitance of DC line
v_{si}, i_{si}	voltage and current of AC system i ($i = 1, 2, 3$)
v_{pcc_i}	voltage of PCC $_i$ ($i = 1, 2, 3$)
i_{tie}	current on tie line
v_{c1}, i_{c1}	AC voltage and current of LCC inverter
v_{c2}, i_{c2}	AC voltage and current of MMC
v_{c3}, i_{c3}	AC voltage and current of LCC rectifier
i_{fr}, i_{fi}	currents injected into filters at PCCs
$v_{chp}^i, v_{c1}^i, v_{c2}^i$	capacitor voltages of filter at PCC $_1$
$i_{lhp}^i, i_{l1}^i, i_{l2}^i$	inductor currents of filter at PCC $_1$
$v_{chp}^r, v_{c1}^r, v_{c2}^r$	capacitor voltages of filter at PCC $_3$
$i_{lhp}^r, i_{l1}^r, i_{l2}^r$	inductor currents of filter at PCC $_3$

$v_{dc}^{LCCi}, v_{dc}^{MMC}, v_{dc}^{LCCr}$	DC voltages of LCC inverter, MMC and LCC rectifier
v_{line1}, v_{line2}	terminal DC voltages of DC line
i_{line}	DC current on DC line
i_{dc1}, i_{dc2}	DC currents of rectifier-side and inverter-side
ω_0	rated angular frequency of AC system
ω, θ_{pll}	tracked angular frequency and output Phase angle of PLL
β_{ord}, β_i	firing-advance angle order and actual firing-advance angle for LCC inverter
α_{ord}, α_r	firing-delay angle order and actual firing-delay angle for LCC rectifier
m, m_2	fundamental-frequency and double-frequency modulation indices
Subscripts:	
x, y	common rotating frame components
x_2, y_2	double-frequency common rotating frame components
d, q	local rotating frame components
d_2, q_2	double-frequency local rotating frame components
m, ref	measured and reference values

I. INTRODUCTION

High voltage direct current (HVDC) transmission technology is widely applied in renewable energy integration, asynchronous power grid interconnection and large-capacity power transmission over long distances [1][2]. Due to the advantages of low cost and bulk power transmission capability, the line commutated converter-based high voltage direct current (LCC-HVDC) is acknowledged to be one of the most mature solutions. In the past decades, more than 100 LCC-HVDC projects have been commissioned world widely [3]. However, with the increasing penetration of large-scale renewable energy, two or more LCC-HVDC links are fed into a regional power grid, resulting in a multi-infeed HVDC system. The LCC inverter is vulnerable to the commutation failure problem, which may lead to a continuous commutation failure of the multi-infeed HVDC system during AC grid faults, putting a severe threat to the safe and stable operation of the receiving AC grid [4].

To address this challenge, the modular multilevel converter (MMC) with self-commutation capability is adopted at the inverter-side [5][6]. Therefore, hybrid LCC-MMC HVDC systems combining the merits of both LCC and MMC are developed rapidly [7]. The hybrid HVDC systems can be classified into three types: (i) The pole-pole hybrid HVDC system with LCC and MMC installed in different poles. For example, the *Skagerrak* HVDC interconnections project adopted the voltage source converter on pole 4 and LCC on

This work is sponsored by the National Natural Science Foundation of China (51907068) (Corresponding author: Wang Xiang).

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poles 1 to 3 [8]. (ii) The station-station hybrid HVDC system with LCC and MMC installed in different stations. The *Kunliulong* HVDC project, which transmits bulk hydropower from *Yunnan* province to load centers in *Guangdong* and *Guangxi* provinces through 1489 km overhead lines, is a practical example [9]. (iii) The in-station hybrid HVDC system with LCC and MMC installed in the same station. According to the connecting method of LCC and MMC, the in-station hybrid HVDC system can be further divided into: (a) The in-station hybrid HVDC system with LCC and MMC in series connection, e.g., the *Baihetan* HVDC project under planning in China. In this project, the inverter-station locating in *Jiangsu* province consists of LCC and MMC in series connection [10]. (b) The in-station hybrid HVDC system with LCC and MMC in parallel connection, which is currently at the academic research level [11].

For the cascaded LCC-MMC hybrid HVDC system, e.g., the *Baihetan* HVDC project, LCC and MMC are usually fed into two receiving AC systems with a certain electrical distance (interconnected by a tie line) to optimize the structure of the receiving power grid [7]. Thus, LCC and MMC are not only connected in series at the DC-side but also interact with each other at the AC-side, indicating that there is a complicated coupling between LCC and MMC. Considering the increasing penetration of renewable energy and power electronics, the AC system tends to weaken gradually [12]. Besides, the tripping of AC transmission lines by scheduled maintenance or occasional AC faults may also result in a temporary decrease of the strength of the AC system [13]. Existing literatures reveal that both LCC-HVDC and MMC-HVDC are subjected to instability issue when integrating with a weak AC system [12]-[14]. Thus, the cascaded LCC-MMC inverter may have a worse stability margin under weak AC systems integration due to the coupling between LCC and MMC. It is significant to identify the stable zone of the strength of the receiving AC systems for the cascaded LCC-MMC inverter to guide the planning and operation of a practical project.

The small-signal stability analysis of LCC-HVDC and MMC-HVDC has been well studied in recent years. References [15]-[18] developed the dynamic model of LCC based on the quasi-steady-state equations. But the transition of the valve current of LCC is assumed to be linear, which is not accurate. References [19]-[24] established sound small-signal models of MMC, in which the internal harmonics of MMC, including the submodule capacitor voltage ripples and internal circulating currents, are considered. However, researches on the small-signal stability of the hybrid HVDC systems are at the preliminary stage. Only [25]-[27] conducted related studies on

the station-station hybrid HVDC systems, revealing that interactions between different types of converters may induce instability of the system. Therefore, it is necessary to implement an investigation into the small-signal stability of the in-station hybrid HVDC system.

To overcome this challenge, a small-signal model of the cascaded LCC-MMC inverter based hybrid HVDC system is developed in this paper. Based on the eigenvalue analysis [28], the impact of the strength of the receiving AC systems quantified by short circuit ratio (SCR) and the proximity of the receiving AC systems on the small-signal stability of the system is investigated. The contributions of this paper are as follows:

- 1) A comprehensive small-signal model of the cascaded LCC-MMC hybrid HVDC system is established, in which a modified model of LCC, considering the actual sinusoidal variation of the valve current, is incorporated;
- 2) The feasible region of SCR to maintain the system stable under different tie line lengths is identified;
- 3) A supplementary coupling mitigation control is proposed to improve the stability of the system under weak AC systems integration.

The reminder of this paper is organized as follows: Section II describes the studied system. Section III establishes the small-signal model of the system, which is verified in Section IV. Eigenvalue analysis is carried out in Section V. Section VI proposes the supplementary control and a conclusion is conducted in Section VII.

II. CASCADED LCC-MMC INVERTER BASED HYBRID HVDC SYSTEM

A. Main Circuit of HVDC system

The schematic diagram of the cascaded LCC-MMC inverter based hybrid HVDC system studied in this paper is depicted in Fig. 1. The system adopts a traditional LCC based converter in the rectifier-station and the cascaded LCC-MMC converter in the inverter-station, where two sub-converters are connected to two receiving AC systems at points of common coupling (PCCs) joined via a tie line.

Fig. 1. Layout of the cascaded LCC-MMC inverter based hybrid HVDC system.

Fig. 2. Single line diagram of the cascaded LCC-MMC inverter based hybrid HVDC system.

The single line diagram of the cascaded LCC-MMC inverter based hybrid HVDC system is illustrated in Fig. 2. The AC systems are modelled using *Thevenin's* equivalent circuit, i.e., voltage source with series inductance and resistance. A π -type equivalent circuit is used to represent the DC line. The tie line between PCC₁ and PCC₂ is represented by series inductance and resistance. The interfaced transformers of converters are represented by their leakage inductance. The structure of the filter at PCC₁ is shown below the DC line in Fig. 2, which consists of a fixed capacitor, a high pass filter, and a dual-tuned filter. Since the structure of the filter at PCC₃ is the same as that at PCC₁, it is not shown in Fig. 2.

B. Layout of Control System

The control system is comprised of PLLs and controllers of LCC and MMC.

Fig. 3 depicts the conventional structure of PLL, which is used to provide a phase angle reference to the controllers of LCC and MMC, in order to remain LCC and MMC synchronized with AC systems.

Fig. 3. Schematic diagram of PLL.

The schematic diagram of the controller of LCC inverter is depicted in Fig. 4, which employs a constant DC voltage control strategy to remain the DC voltage of LCC inverter constant in steady-state.

Fig. 4. Schematic diagram of the controller of LCC inverter.

Fig. 5 illustrates the controller of LCC rectifier, which maintains a constant rectifier-side DC current by a proportional-integral control strategy.

Fig. 5 Schematic diagram of controller of LCC in the rectifier-station.

Fig. 6 shows the controller of MMC, consisting of a traditional double closed-loop vector control and a circulating current suppression control, as illustrated in Fig. 6(a) and (b), respectively. The vector control comprises an outer voltage/power control loop and an inner AC current control loop. The outer loop control is utilized to regulate the DC voltage of MMC and AC voltage of PCC₂. The inner control tracks the current reference value generated by the outer loop control and allows for the ability to suppress the DC fault current. The circulating current suppression control is exploited to eliminate the internal circulating current.

(a) Double closed-loop vector control

(b) Circulating current suppression control

Fig. 6. Schematic diagram of MMC controllers.

III. LINEARIZED SMALL-SIGNAL MODEL

A. Description for Modelling Approach

For the modelling of an MMC based DC grid, the interfaced equivalent circuit of MMC is usually used to facilitate the linking of MMC with the AC system and DC network [21]. Similar to this method, the interfaced equivalent circuits of both LCC and MMC will be deduced to address the interconnection between them.

B. Interfaced Equivalent Circuit of LCC

1) Inverter Mode

The structure diagram of a six-pulse LCC inverter is shown in Fig. 7(a), where VT_1 to VT_6 are transistor valves. In a practical project, LCC inverter is usually comprised of multiple six-pulse units, and a six-pulse LCC inverter is displayed here for simplicity. Fig. 7(b) depicts the interfaced equivalent circuit of LCC inverter. From Fig. 7(b), LCC inverter is regarded as a controlled voltage source e_{dc}^{LCCi} in series with resistance R_{dc}^{LCCi} and inductance L_{dc}^{LCCi} from the DC-side, whereas it is considered as a controlled current source from the AC-side.

(a) Structure diagram of the six-pulse LCC inverter

(b) Interfaced equivalent circuit diagram of the LCC inverter

Fig. 7. Schematic diagram of LCC inverter.

The interfaced equivalent circuit of LCC inverter will be derived below. The DC voltage of LCC inverter v_{dc}^{LCCI} can be represented by [29]:

$$v_{dc}^{LCCI} = N_{bi} \left[\frac{3\sqrt{3}}{\pi} v_{pcc1} \cos \beta_i + \frac{3}{\pi} X_{T1} i_{dc2} + \left(2 - \frac{3\mu_i}{2\pi} \right) L_{T1} \frac{di_{dc2}}{dt} \right] \quad (1)$$

$$= e_{dc}^{LCCI} + R_{dc}^{LCCI} i_{dc2} + L_{dc}^{LCCI} \frac{di_{dc2}}{dt}$$

where N_{bi} is the number of six-pulse units making up LCC inverter; μ_i is the commutation overlap angle of LCC inverter, and it is calculated by:

$$\mu_i = \beta_i - \cos^{-1} \left(\cos \beta_i + \frac{2X_{T1} i_{dc2}}{\sqrt{3} v_{pcc1}} \right) \quad (2)$$

Besides, from (1) we can get that $e_{dc}^{LCCI} = (3\sqrt{3}/\pi) N_{bi} v_{pcc1} \cos \beta_i$, $R_{dc}^{LCCI} = (3/\pi) N_{bi} X_{T1}$, $L_{dc}^{LCCI} = [2 - 3\mu_i/(2\pi)] N_{bi} L_{T1}$.

Where e_{dc}^{LCCI} is the ideal no-load DC voltage, R_{dc}^{LCCI} is the equivalent commutation resistance, and L_{dc}^{LCCI} is the converter transformer's equivalent DC inductance.

When calculating the AC current of LCC inverter based on the quasi-steady-state equations, the transition of current between involved valves during the commutation period is approximately considered to be linear. However, the actual current waveform is a sine wave. Thus, taking the actual sinusoidal variation of the valve current into consideration, the AC current of LCC inverter i_{c1} should be expressed as:

$$\begin{cases} i_{c1x} = \frac{2\sqrt{3}}{\pi} N_{bi} i_{dc2} \frac{\cos(\beta_i - \mu_i) + \cos \beta_i}{2} \\ i_{c1y} = \frac{2\sqrt{3}}{\pi} N_{bi} i_{dc2} \frac{\sin[2(\beta_i - \mu_i)] - \sin(2\beta_i) + 2\mu_i}{4[\cos(\beta_i - \mu_i) - \cos \beta_i]} \end{cases} \quad (3)$$

2) Rectifier Mode

The interfaced equivalent circuit of the LCC rectifier is shown in Fig. 8, which is similar to that of the LCC inverter.

Fig. 8. Schematic diagram of LCC rectifier.

Therefore, the DC-side components can be obtained:

$$e_{dc}^{LCCr} = \frac{3\sqrt{3}}{\pi} N_{br} v_{pcc3} \cos \alpha_r, R_{dc}^{LCCr} = \frac{3}{\pi} N_{br} X_{T3}, \quad (4)$$

$$L_{dc}^{LCCr} = \left(2 - \frac{3\mu_r}{2\pi} \right) N_{br} L_{T3}$$

The AC-side components are:

$$\begin{cases} i_{c3x} = \frac{2\sqrt{3}}{\pi} N_{br} i_{dc1} \frac{\cos \alpha_r + \cos(\alpha_r + \mu_r)}{2} \\ i_{c3y} = \frac{2\sqrt{3}}{\pi} N_{br} i_{dc1} \frac{\sin(2\alpha_r) - \sin[2(\alpha_r + \mu_r)] + 2\mu_r}{4[\cos \alpha_r - \cos(\alpha_r + \mu_r)]} \end{cases} \quad (5)$$

where N_{br} is the number of six-pulse units making up LCC rectifier, μ_r is the commutation overlap angle of LCC rectifier, and it is calculated by:

$$\mu_r = -\alpha_r + \cos^{-1} \left(\cos \alpha_r - \frac{2X_{T3} i_{dc1}}{\sqrt{3} v_{pcc3}} \right) \quad (6)$$

C. Interfaced Equivalent Circuit and Internal Dynamics of MMC

Fig. 9(a) shows the structure diagram of MMC. v_{pj} and v_{nj} ($j = a, b, c$) represent the upper and lower arm voltages, respectively. i_{pj} and i_{nj} represent the upper and lower arm currents, respectively. i_{cirj} is the internal circulating current. L_{arm} and R_{arm} are respectively the arm inductance and resistance. v_{pj} is the product of the total capacitor voltage of the upper arm v_{cpj}^Σ and the modulation index of the upper arm m_{pj} , where $m_{pj} = (1 - m_j + m_{2j}) / 2$. v_{nj} is similar to v_{pj} except for $m_{nj} = (1 + m_j + m_{2j}) / 2$. Fig. 9(b) shows the interfaced equivalent circuit diagram of MMC. As illustrated in Fig. 9(b), the DC-side equivalent circuit of MMC is a controlled voltage source e_{dc}^{MMC} in series with resistance R_{dc}^{MMC} and inductance L_{dc}^{MMC} . And its AC-side equivalent circuit is a controlled voltage source e_c in series with resistance R_{eq} and inductance L_{eq} .

According to the internal and external dynamics, the 10-order dynamic model of MMC in [21] is divided into two parts here. The AC current and DC current of MMC are considered as the state variables describing the external dynamics, whereas other variables are considered as those describing the internal dynamics. The detailed description of the internal dynamics of MMC can be referred to Appendix A. Based on the external dynamics of MMC, its interfaced equivalent circuit will be derived.

(a) Structure diagram of MMC

(b) Interfaced equivalent circuit of MMC

Fig. 9. Schematic diagram of MMC.

The external dynamics of MMC can be described as:

$$\frac{2}{3} \frac{L_{arm}}{L_{dc}} \frac{di_{dc2}}{dt} = \frac{m_{2x2} v_{cp2}^\Sigma}{2} + \frac{m_{2y2} v_{cpy2}^\Sigma}{2} + \frac{m_x v_{cp2}^\Sigma}{2} + \frac{m_y v_{cpy2}^\Sigma}{2} \quad (7)$$

$$-v_{cp0}^\Sigma - \frac{2}{3} R_{arm} i_{dc2} + v_{dc}^{MMC}$$

$$\begin{cases} \frac{L_{arm}}{2} \frac{di_{c2x}}{dt} = \frac{m_x v_{cp2}^s}{4} + \frac{m_y v_{cpy2}^s}{4} + \frac{(m_{2x2} - 2)v_{cp2}^s}{4} + \frac{m_{2y2} v_{cp2}^s}{4} \\ \quad + \frac{m_x v_{cp0}^s}{2} - \frac{R_{arm}}{2} i_{c2x} + \omega_0 i_{c2y} - v_{c2x} \\ \frac{L_{arm}}{2} \frac{di_{c2y}}{dt} = -\frac{m_y v_{cp2}^s}{4} + \frac{m_x v_{cp2}^s}{4} + \frac{m_{2y2} v_{cp2}^s}{4} - \frac{(m_{2x2} + 2)v_{cp2}^s}{4} \\ \quad + \frac{m_y v_{cp0}^s}{2} - \frac{R_{arm}}{2} i_{c2y} - \omega_0 i_{c2x} - v_{c2y} \end{cases} \quad (8)$$

Equations (7) and (8) represent the dynamics of DC current and AC current of MMC, respectively. Rearranging (7) and (8) yields:

$$v_{dc}^{MMC} = e_{dc}^{MMC} + R_{dc}^{MMC} i_{dc2} + L_{dc}^{MMC} \frac{d}{dt} i_{dc2} \quad (9)$$

$$\begin{cases} v_{c2x} = e_{cx} - R_{eq} i_{c2x} - L_{eq} \frac{d}{dt} i_{c2x} + \omega_0 i_{c2y} \\ v_{c2y} = e_{cy} - R_{eq} i_{c2y} - L_{eq} \frac{d}{dt} i_{c2y} - \omega_0 i_{c2x} \end{cases} \quad (10)$$

where,

$$e_{dc}^{MMC} = -\frac{m_{2x2} v_{cp2}^s}{2} - \frac{m_{2y2} v_{cpy2}^s}{2} - \frac{m_x v_{cp2}^s}{2} - \frac{m_y v_{cpy2}^s}{2} + v_{cp0}^s, \quad (11)$$

$$R_{dc}^{MMC} = \frac{2}{3} R_{arm}, L_{dc}^{MMC} = \frac{2}{3} L_{arm}$$

$$e_{cx} = \frac{m_x v_{cp2}^s}{4} + \frac{m_y v_{cpy2}^s}{4} + \frac{(m_{2x2} - 2)v_{cp2}^s}{4} + \frac{m_{2y2} v_{cp2}^s}{4} + \frac{m_x v_{cp0}^s}{2},$$

$$e_{cy} = -\frac{m_y v_{cp2}^s}{4} + \frac{m_x v_{cp2}^s}{4} + \frac{m_{2y2} v_{cp2}^s}{4} - \frac{(m_{2x2} + 2)v_{cp2}^s}{4} + \frac{m_y v_{cp0}^s}{2}, \quad (12)$$

$$R_{eq} = \frac{1}{2} R_{arm}, L_{eq} = \frac{1}{2} L_{arm}$$

It is intuitive to obtain the interfaced equivalent circuit of MMC in Fig. 9 (b) from (9) and (10). In addition, L_{eq} in Fig. 9 (b) should be modified as $L_{arm}/2 + L_{T2}$, considering the leakage inductance of the transformer.

Fig. 10. Equivalent circuit diagram of cascaded LCC-MMC inverter based hybrid HVDC system.

D. Overall Small-Signal Model

Utilizing the interfaced equivalent circuits of LCC and MMC deduced above, the interconnection between LCC and MMC, and the linking of them with the AC system and DC line are realized, as depicted in Fig. 10.

1) DC-Side Modelling

From Fig. 10, the dynamic of DC current flowing through both LCC inverter and MMC i_{dc2} can be obtained:

$$L_{dc}^{tot} \frac{di_{dc2}}{dt} = v_{line2} - e_{dc}^{LCCI} - e_{dc}^{MMC} - (R_{dc}^{LCCI} + R_{dc}^{MMC}) i_{dc2} \quad (13)$$

where $L_{dc}^{tot} = L_{dc} + L_{dc}^{LCCI} + L_{dc}^{MMC}$.

According to (13), the expressions of DC voltage of LCC inverter can be derived as:

$$v_{dc}^{LCCI} = e_{dc}^{LCCI} + i_{dc2} R_{dc}^{LCCI} + L_{dc}^{LCCI} \frac{di_{dc2}}{dt} = \left[\frac{e_{dc}^{LCCI} + i_{dc2} R_{dc}^{LCCI}}{L_{dc}^{LCCI}} + \frac{v_{line2} - e_{dc}^{MMC} - i_{dc2} R_{dc}^{MMC}}{L_{dc} + L_{dc}^{MMC}} \right] \left/ \left(\frac{1}{L_{dc}^{LCCI}} + \frac{1}{L_{dc} + L_{dc}^{MMC}} \right) \right. \quad (14)$$

When calculating the DC voltage of LCC inverter, existing literatures usually ignore the impact of L_{dc}^{LCCI} , which is only suitable for steady-state analysis [17][18]. The impact of L_{dc}^{LCCI} on the DC voltage of LCC inverter is considered in this paper, as shown in (14).

The DC voltage of MMC v_{dc}^{MMC} can be derived in a similar way and will not be repeated here.

The dynamic behavior of the DC line is described by three state variables, i.e., i_{line} , v_{line1} and v_{line2} . Their dynamic equations are as follows:

$$\begin{cases} L_{line} \frac{di_{line}}{dt} = v_{line1} - v_{line2} - i_{line} R_{line} \\ C_{line} \frac{dv_{line1}}{dt} = i_{dc1} - i_{line} \\ C_{line} \frac{dv_{line2}}{dt} = i_{line} - i_{dc2} \end{cases} \quad (15)$$

The dynamic of rectifier-side DC current i_{dc1} can be represented as:

$$(L_{dc} + L_{dc}^{LCCI}) \frac{di_{dc1}}{dt} = e_{dc}^{LCCI} - R_{dc}^{LCCI} i_{dc1} - v_{line1} \quad (16)$$

2) AC-Side Modelling

From Fig. 10, the dynamic model of the receiving AC system i ($i = 1, 2$) can be expressed as:

$$\begin{cases} L_{si} \frac{di_{six}}{dt} = v_{pccix} - V_{six} - i_{six} R_{si} + \omega_0 L_{si} i_{siy} \\ L_{si} \frac{di_{siy}}{dt} = v_{pcciy} - V_{siy} - i_{siy} R_{si} - \omega_0 L_{si} i_{six} \end{cases} \quad (17)$$

The dynamic model of the tie line can be described as:

$$\begin{cases} L_{tie} \frac{di_{tie}}{dt} = v_{pcc1x} - v_{pcc2x} - i_{tie} R_{tie} + \omega_0 L_{tie} i_{tiey} \\ L_{tie} \frac{di_{tiey}}{dt} = v_{pcc1y} - v_{pcc2y} - i_{tiey} R_{tie} - \omega_0 L_{tie} i_{tie} \end{cases} \quad (18)$$

The dynamic of AC voltage of PCC₁, which is the dynamic of the fixed capacitor in the filter at PCC₁, can be represented as:

$$\begin{cases} C_f^i \frac{dv_{pcc1x}}{dt} = i_{f1x} - i_{lhp}^i - \frac{v_{pcc1x} - v_{chpx}^i}{R_{hp}} - i_{l1x}^i + \omega_0 C_f^i v_{pcc1y} \\ C_f^i \frac{dv_{pcc1y}}{dt} = i_{f1y} - i_{lhp}^i - \frac{v_{pcc1y} - v_{chpy}^i}{R_{hp}} - i_{l1y}^i - \omega_0 C_f^i v_{pcc1x} \end{cases} \quad (19)$$

where $i_{f1} = i_{c1} - i_{s1} - i_{tie}$.

The dynamics of other equipment in the filter at PCC₁, i.e., the high-pass filter and the dual-tuned filter, can be represented by the differential equations of corresponding capacitor voltages and inductor currents, which are left out here.

The AC voltage of PCC₂ v_{pcc2} is the interfaced variable between MMC and the AC-side and its expression is deduced as:

$$v_{pcc2} = e_c - R_{eq} (i_{tie} - i_{s2}) - L_{eq} \frac{d(i_{tie} - i_{s2})}{dt} = \left\{ \frac{v_{pcc1} - i_{tie} R_{tie}}{L_{tie}} + \frac{v_{s2} + i_{s2} R_{s2}}{L_{s2}} + \frac{e_c - (i_{tie} - i_{s2}) R_{eq}}{L_{eq}} \right\} / \left(\frac{1}{L_{tie}} + \frac{1}{L_{s2}} + \frac{1}{L_{eq}} \right) \quad (20)$$

The dynamic behavior of the sending AC system can be expressed as:

$$\begin{cases} L_{s3} \frac{di_{s3x}}{dt} = V_{s3x} - v_{pcc3x} - i_{s3x} R_{s3} + \omega_0 L_{s3} i_{s3y} \\ L_{s3} \frac{di_{s3y}}{dt} = V_{s3y} - v_{pcc3y} - i_{s3y} R_{s3} - \omega_0 L_{s3} i_{s3x} \end{cases} \quad (21)$$

3) Small-Signal Modelling

The detailed modelling on the control system, including PLL, controller of LCC inverter, controller of LCC rectifier and controller of MMC, can be refer to Appendix A.

The aforementioned nonlinear dynamic model of the cascaded LCC-MMC inverter based hybrid HVDC system can be expressed in the general form of:

$$\frac{dx}{dt} = f(x, u) \quad (22)$$

where x and u are the state and input vectors, respectively; x is a 72×1 vector; $u = [v_{dref}^{LCCI}, I_{dref}, v_{dref}^{MMC}, v_{pcc2ref}]^T$ is a 4×1 vector.

The state variables of the system are summarized in Table I in detail.

TABLE I
STATE VARIABLES

Subsystems	State variables
AC system 1	$i_{s1x}, i_{s1y}, v_{pcc1x}, v_{pcc1y}, v_{chpx}^i, v_{chpy}^i, v_{c1x}^i, v_{c1y}^i, v_{c2x}^i, v_{c2y}^i, i_{lhp}^i, i_{lhp}^i, i_{l1x}^i, i_{l1y}^i, i_{l2x}^i, i_{l2y}^i$
AC system 2	i_{s2x}, i_{s2y}
AC system 3	$i_{s3x}, i_{s3y}, v_{pcc3x}, v_{pcc3y}, v_{chpx}^r, v_{chpy}^r, v_{c1x}^r, v_{c1y}^r, v_{c2x}^r, v_{c2y}^r, i_{lhp}^r, i_{lhp}^r, i_{l1x}^r, i_{l1y}^r, i_{l2x}^r, i_{l2y}^r$
Tie line	i_{tie}, i_{tiey}
DC line	$i_{dc1}, i_{dc2}, i_{line}, v_{line1}, v_{line2}$
MMC	$v_{cp2}^{\Sigma}, v_{cp2}^{\Sigma}, v_{cp2}^{\Sigma}, v_{cp2}^{\Sigma}, v_{cp0}^{\Sigma}, i_{c1x2}, i_{c1y2}$
PLL ₁ /PLL ₂ /PLL ₃	$x_{pll1}, \theta_{pll1}/x_{pll2}, \theta_{pll2}/x_{pll3}, \theta_{pll3}$

Controller of LCC inverter	v_{dcm}^{LCCI}, x_i
Controller of LCC rectifier	i_{dc1m}, x_r
Controller of MMC	$v_{dcm}^{MMC}, v_{pcc2m}, v_{pcc2dm}, v_{pcc2qm}, i_{c2dm}, i_{c2qm}, i_{c1d2m}, i_{c1q2m}, x_{od}, x_{oq}, x_{id}, x_{iq}, x_{cd}, x_{cq}$

By linearizing (22) around the steady-state operating point, the linearized small-signal model can be presented as follow:

$$\frac{d\Delta x}{dt} = A\Delta x + B\Delta u \quad (23)$$

where A and B are the state and input matrices, respectively; A is a 72×72 matrix; B is a 72×4 matrix. The expressions of A and B could be easily generated from the linearization of (22).

IV. SMALL-SIGNAL MODEL VERIFICATION

A detailed electromagnetic transient (EMT) model of the system depicted in Fig. 2 is implemented in PSCAD/EMTDC. The time-domain responses obtained from the linearized small-signal model established in MATLAB/Simulink are then compared with those obtained from the detailed EMT model. System parameters for the verification are listed in Table II and Table III.

TABLE II
MAIN CIRCUIT PARAMETERS

Parameters	Values
Rated DC current of LCC rectifier i_{dc1}	2 kA
Rated DC voltage of LCC inverter v_{dc}^{LCCI}	400 kV
Rated DC voltage of MMC v_{dc}^{MMC}	400 kV
Voltage of AC system $i_{v_{si}}$ ($i = 1, 2, 3$)	500 kV
Resistance and inductance of AC system 1 R_{s1}, L_{s1}	15.5043 Ω , 0.3948 H
Resistance and inductance of AC system 2 R_{s2}, L_{s2}	15.5043 Ω , 0.3948 H
Resistance and inductance of AC system 3 R_{s3}, L_{s3}	7.7522 Ω , 0.1974 H
Tie line resistance R_{tie}	1.4 Ω
Tie line inductance L_{tie}	0.043 H
LCC inverter's transformer leakage inductance L_{T1}	0.18 pu
MMC's transformer leakage inductance L_{T2}	0.1 pu
LCC rectifier's transformer leakage inductance L_{T3}	0.18 pu
Submodule number of MMC N_{sm}	200
Arm resistance of MMC R_{arm}	0.2 Ω
Arm inductance of MMC L_{arm}	0.035 H
Submodule capacitance C_{sm}	13.3 mF
DC current-limiting inductance L_{dc}	0.3 H
DC line resistance R_{line}	10 Ω
DC line inductance L_{line}	1.62 H
DC line capacitance C_{line}	13 μF

TABLE III
CONTROL SYSTEM PARAMETERS

Parameters	Values
PLL ₁	k_{pll1}, k_{ipl1}
PLL ₂	k_{pll2}, k_{ipl2}
PLL ₃	k_{pll3}, k_{ipl3}
Controller of LCC inverter	k_{pi}, k_{ii}
Controller of LCC rectifier	k_{pr}, k_{ir}
Controller of MMC	k_{pod}, k_{iod}
	k_{poq}, k_{ioq}
	k_{pid}, k_{piq}
	k_{piq}, k_{iiq}

k_{pdc}, k_{icd}	0.5, 50
k_{pcq}, k_{icq}	0.5, 50

The parameters of the AC filter & reactive power compensation equipment for LCC and the parameters of feedback filters are detailed in Appendix B.

The comparison of time-domain responses between the EMT and small-signal models is shown in Fig. 11. At $t = 0$ s, the system is operating at the rated operating point ($v_{dcref}^{LCCi} = I_{dcref} = v_{dcref}^{MMC} = v_{pcc2ref} = 1$ pu). At $t = 0.5$ s, a step change from 1 pu to 0.975 pu is imposed on the DC voltage reference value of MMC v_{dcref}^{MMC} . Fig. 11(a)-(f) depict the time-domain responses of the DC voltage of LCC v_{dc}^{LCCi} , DC voltage of MMC v_{dc}^{MMC} , AC voltage of PCC₂ v_{pcc2} , total capacitor voltage of MMC v_{cpa}^s (upper arm of phase a), inner loop d-axis current of MMC, and inner loop q-axis current of MMC, respectively. Where, the legend "EMT" and "SS" in Fig. 11 refer to the EMT model and small-signal model, respectively.

(a) DC voltage of LCC

(b) DC voltage of MMC

(c) AC voltage of PCC₂

(d) Total capacitor voltage of MMC

(e) Inner loop d-axis current of MMC

(f) Inner loop q-axis current of MMC

Fig. 11. Comparison of time-domain responses.

It can be observed from Fig. 11 that the time-domain responses from the small-signal model are in close agreement with those from the EMT model, which indicates that the accuracy of the small-signal model is acceptable. Since the EMT model simulates the switching process, its time-domain responses have additional high-frequency components.

V. INVESTIGATION INTO IMPACT OF STRENGTH AND PROXIMITY OF RECEIVING AC GRIDS

Fig. 12 shows the geographic diagram of the *Baihetan* HVDC project under planning, which will transmit large-capacity hydropower from *Sichuan* province to *Jiangsu* province. With the rapid growth of offshore wind power in *Jiangsu* province, the strength of *Jiangsu* power grid is gradually weakening. Therefore, this section investigates the impact of the strength of the receiving AC grids on the cascaded LCC-MMC inverter based hybrid HVDC system and determines the stable zone of the strength of the receiving AC systems, in order to prevent the HVDC link from being fed into a too weaker AC grid and causing instability. Moreover, the impact of the proximity of the receiving AC grids is also analyzed in this section.

Fig. 12 Geographic diagram of *Baihetan* HVDC project.

A. Strength of Receiving AC Grids

Table IV lists the eigenvalues of the cascaded LCC-MMC inverter based hybrid HVDC system. Only the weak damping modes of the system (damping ratio < 10%) are shown here, and they are arranged in the order of damping ratio from low to

high. It can be concluded from the following analysis that the mode 9 is the dominant mode of the system.

TABLE IV
SYSTEM EIGENVALUES

Mode No.	Eigenvalue	Damping Ratio	Oscillation Frequency
1	$-232.95 \pm 4866.77i$	4.78%	774.57 Hz
2	$-235.89 \pm 4868.59i$	4.84%	774.86 Hz
3	$-29.66 \pm 586.50i$	5.05%	93.34 Hz
4	$-232.67 \pm 4248.68i$	5.47%	676.20 Hz
5	$-237.44 \pm 4252.51i$	5.57%	676.81 Hz
6	$-37.27 \pm 563.81i$	6.60%	89.73 Hz
7	$-114.46 \pm 1579.99i$	7.23%	251.46 Hz
8	$-74.46 \pm 1003.64i$	7.40%	159.73 Hz
9	$-24.83 \pm 321.79i$	7.69%	51.21 Hz
10	$-115.39 \pm 1466.02i$	7.85%	233.32 Hz
11	$-36.88 \pm 421.42i$	8.72%	67.07 Hz

To evaluate the influence of the strength of the receiving AC grids, the following three scenarios are considered: (i) SCR_1 varies and SCR_2 remains constant ($SCR_2 = 2.5$); (ii) SCR_2 varies and SCR_1 remains constant ($SCR_1 = 2.5$); (iii) SCR_1 and SCR_2 vary simultaneously. The length of the tie line is 50 km in the above three scenarios. The root loci of three scenarios are depicted in Fig. 13 (a)-(c).

Fig. 13. Root loci of system with SCR varies (tie length = 50 km).

Fig. 13(a) shows that the dominant mode of the system moves towards the unstable region with the decrease of SCR_1 , resulting in the system instability when $SCR_1 < 1.2$. Similar conclusion is also drawn in Fig. 13(b), i.e., the system gets into an unstable condition when $SCR_2 < 1.14$. It should be noted that despite scenario 1 and scenario 2 are set up symmetrically, the minimum acceptable SCR of AC grid 1 is not the same as that of AC grid 2 due to that they are connected to different types of

converters. The minimum acceptable SCR of AC grid 2 is less than that of AC grid 1, indicating that MMC could tolerate a weaker AC grid than LCC. From Fig. 13(c), with SCR_1 and SCR_2 decreasing simultaneously, the small-signal stability margin of the system also declines, and the system becomes unstable when $SCR < 1.82$.

Fig. 14. Feasible region of SCR (tie length = 50 km)

By setting up more scenarios, the feasible region of SCR to ensure the system stable is determined in Fig. 14. The solid red line in Fig. 14 is referred to as the critical SCR line and represents the minimum acceptable SCR when SCR_1 or SCR_2 vary. For example, points A, B, and C on the line correspond to the minimum acceptable SCR of scenarios 1, 2, and 3, respectively. Note that the critical SCR line is a straight line, indicating there is a linear constraint between the minimum acceptable SCR_1 and SCR_2 . In addition, the slope of the critical SCR line is less than -1 , which also implies MMC allows for the ability to be connected to a weaker AC grid. The critical SCR line divides the entire region of SCR into two. The upper part of the line represents the feasible region of SCR and the lower one represents the unstable region. The HVDC link should be fed into the receiving AC systems which strength is locating in the feasible region, to avoid instability.

B. Proximity of Receiving AC Grids

The root loci of the system with tie line length varying from 1 km to 100 km under three SCR configurations, are shown in Fig. 15(a)-(c), so as to assess the impact of the proximity of the receiving AC grids on the small-signal stability of the system: (i) $SCR_1 = 1.2$ and $SCR_2 = 2.5$; (ii) $SCR_1 = 2.5$ and $SCR_2 = 1.2$; (iii) $SCR_1 = SCR_2 = 1.8$.

Fig. 15. Root loci of system with tie line length varying.

Fig. 15(a)-(c) exhibit similar results, i.e., the decrease of the length of the tie line could cause the system instability, except for that the minimum acceptable length of the tie line is different. For scenario 1 in which $SCR_1 = 1.2$ and $SCR_2 = 2.5$, the minimum acceptable length of the tie line is 56 km, while for scenario 2 ($SCR_1 = 2.5$, $SCR_2 = 1.2$) and scenario 3 ($SCR_1 = SCR_2 = 1.8$), the minimum acceptable length of the tie line is 24 km and 81 km, respectively. It can be seen again that although scenario 1 and scenario 2 are arranged symmetrically, their minimum acceptable tie line lengths are different because AC grids 1 and 2 are connected to different types of converters.

To further study the impact of the proximity of the receiving AC grids on the system, the feasible region of SCR at different tie line lengths is illustrated in Fig. 16.

Fig. 16. Feasible region of SCR under different tie line length.

It can be seen in Fig. 16 that as the length of the tie line increases, the critical SCR line moves towards the lower left and the feasible region of SCR is enlarged. It indicates that the small-signal stability of the system is enhanced; namely, the system under the same SCR configuration may change from an unstable condition to a stable condition with the increase of the tie line length.

To estimate the interaction degree between LCC and MMC, the multi-infeed interaction factor (MIIF) proposed by CIGRE WG B4 is applied [30]. When the interaction is strong, MIIF is high, and vice versa. Fig. 17 shows the MIIF with the length of the tie line varying.

Fig. 17. MIIF with tie length varying

It can be observed in Fig. 17 that as the length of the tie line increases, MIIF decreases, which implies that the interaction between LCC and MMC weakens. According to the previous

results, it is apparent that strong interaction between converters is more likely to cause a small-signal instability in the system. Thus, a longer electrical distance between PCCs is suggested when the HVDC link is fed into the receiving AC grids.

VI. SUPPLEMENTARY COUPLING MITIGATION CONTROL

As mentioned before, a temporary decline in the strength of the AC grid will occur, due to scheduled maintenance or occasional AC faults, which may lead the system to change to an unstable condition from the previous stable condition. Section V has shown that the decreased coupling between converters can help improve stability. Since it is impractical to increase the tie line length to attenuate the coupling between converters for a commissioned project, this paper proposes a supplementary coupling mitigation control (SCMC). It reduces the coupling between converters by virtually increasing the tie line length, and its schematic diagram is depicted in Fig. 18.

Fig. 18. Schematic diagram of supplementary coupling mitigation control.

In Fig. 18, SCMC introduces the product of the tie line current i_{tie} and the virtual resistance R_v into the outer AC voltage control loop of MMC to modify the AC voltage reference value, and to further virtually change the length of the tie line.

To investigate the impact of the virtual resistance R_v on the small-signal stability of the system, the root loci of the system with R_v varying are depicted in Fig. 19 (a)-(c), under the following three SCR configurations: (i) $SCR_1 = 1$ and $SCR_2 = 2.5$; (ii) $SCR_1 = 2.5$ and $SCR_2 = 1$; (iii) $SCR_1 = SCR_2 = 1.8$. To better testify the effect of the supplementary control, a stronger coupling (tie length = 25 km) is considered.

It can be seen in Fig. 19(a) that when $R_v = 0$ pu (SCMC is disabled), the dominant mode of the system lies in the unstable region. With the increase of R_v , the dominant mode of the system moves towards the left and the system restores stability when $R_v > 0.052$ pu. In addition to the difference in the minimum acceptable R_v , similar results could also be observed in Fig. 19(b) and (c). Their minimum acceptable R_v are 0.034 pu and 0.082 pu, respectively.

(a) $SCR_1 = 1$, $SCR_2 = 2.5$

Fig. 19. Root loci of system with R_v varying (tie length = 25 km).

The feasible region of SCR with R_v varying is shown in Fig. 20. From Fig. 20, the increase of R_v can expand the feasible region of SCR. It is noticeable that when $R_v = 0.04$ pu, the critical SCR line is no longer a straight line, but a convex curve.

Fig. 20. Feasible region of SCR with R_v varying (tie length = 25 km).

Fig. 21(a)-(c) show the time-domain simulation results, which correspond to the unstable, critical stable and stable conditions of the system in Fig. 19(a), respectively. They verify the effectiveness of the supplementary coupling mitigation control. The value of the virtual resistance R_v should be reasonably determined. On the one hand, if the value is too small, it will not provide enough damping; On the other hand, if the value is too high, the AC voltage of PCC₂ may seriously deviate the rated value and affect the normal operation of the system.

Fig. 21. Verification of supplementary coupling mitigation control ($SCR_1 = 1$, $SCR_2 = 2.5$, tie length = 25 km).

VII. CONCLUSION

A comprehensive small-signal model of the cascaded LCC-MMC inverter based hybrid HVDC system is established and validated in this paper. The small-signal model is then used to analyze the impact of the strength and proximity of the receiving AC grids. The supplementary coupling mitigation control to improve the stability of the system under weak AC systems integration is also demonstrated by eigenvalue analysis and time-domain simulation.

The results indicate that the decrease of the strength of the receiving AC grids will result in system instability. The minimum acceptable SCRs of two receiving AC grids satisfy a linear constraint and MMC can tolerate a weaker AC grid integration than LCC. As two receiving AC grids are close, the increased coupling between converters will decline the small-signal stability margin of the system, and vice versa. When the HVDC link is fed into the receiving AC grids, the strength of the AC grids should be in the stable zone and a longer tie line is preferable. The value of the virtual resistance should be set reasonably by practical requirement, and too high or small is inappropriate.

APPENDIX A

The internal dynamics of MMC, including the submodule capacitor voltage ripples (v_{cpx2}^s , v_{cpy2}^s , v_{cpx}^s , v_{cpy}^s , v_{cp0}^s) and the internal circulating current (i_{cirx2} , i_{ciry2}), are described by the following equations:

$$\frac{dv_{cpx2}^s}{dt} = 2\omega_0 v_{cpy2}^s + \frac{i_{cirx2}}{2C_{arm}} - \frac{m_{2x2}i_{dc2}}{6C_{arm}} - \frac{m_x i_{c2x}}{8C_{arm}} + \frac{m_y i_{c2y}}{8C_{arm}} \quad (A1)$$

$$\frac{dv_{cpy2}^s}{dt} = -2\omega_0 v_{cpx2}^s + \frac{i_{ciry2}}{2C_{arm}} - \frac{m_{2y2}i_{dc2}}{6C_{arm}} - \frac{m_y i_{c2x}}{8C_{arm}} - \frac{m_x i_{c2y}}{8C_{arm}} \quad (A2)$$

$$\frac{dv_{cpx}^s}{dt} = \omega_0 v_{cpy}^s - \frac{m_x i_{cirx2}}{4C_{arm}} - \frac{m_y i_{ciry2}}{4C_{arm}} - \frac{m_x i_{dc2}}{6C_{arm}} - \frac{(m_{2x2} - 2)i_{c2x}}{8C_{arm}} - \frac{m_{2y2}i_{c2y}}{8C_{arm}} \quad (A3)$$

$$\frac{dv_{cpy}^s}{dt} = -\omega_0 v_{cpx}^s + \frac{m_y i_{cirx2}}{4C_{arm}} - \frac{m_x i_{ciry2}}{4C_{arm}} - \frac{m_y i_{dc2}}{6C_{arm}} - \frac{m_{2y2}i_{c2x}}{8C_{arm}} + \frac{(m_{2x2} + 2)i_{c2y}}{8C_{arm}} \quad (A4)$$

$$\frac{dv_{cp0}^s}{dt} = -\frac{m_{2x2}i_{cirx2}}{4C_{arm}} - \frac{m_{2y2}i_{ciry2}}{4C_{arm}} + \frac{i_{dc2}}{6C_{arm}} - \frac{m_x i_{c2x}}{8C_{arm}} - \frac{m_y i_{c2y}}{8C_{arm}} \quad (A5)$$

$$\frac{di_{cirx2}}{dt} = -\frac{v_{cpy2}^\Sigma}{2L_{arm}} + \frac{m_x v_{cpx}^\Sigma}{4L_{arm}} - \frac{m_y v_{cpy}^\Sigma}{4L_{arm}} + \frac{m_{2x2} v_{cp0}^\Sigma}{2L_{arm}} - \frac{R_{arm}}{L_{arm}} i_{cirx2} + 2\omega_0 i_{ciry2} \quad (A6)$$

$$\frac{di_{ciry2}}{dt} = -\frac{v_{cpy2}^\Sigma}{2L_{arm}} + \frac{m_y v_{cpx}^\Sigma}{4L_{arm}} + \frac{m_x v_{cpy}^\Sigma}{4L_{arm}} + \frac{m_{2y2} v_{cp0}^\Sigma}{2L_{arm}} - 2\omega_0 i_{cirx2} - \frac{R_{arm}}{L_{arm}} i_{ciry2} \quad (A7)$$

where $C_{arm} = C_{sm} / N_{sm}$. C_{sm} is the submodule capacitance. N_{sm} is the number of submodules per arm.

APPENDIX B

The dynamic equations of PLL are as follows:

$$\begin{cases} \frac{d}{dt} x_{pll} = k_{ipll} (\theta_{pcc} - \theta_{pll}) \\ \frac{d}{dt} \theta_{pll} = x_{pll} + k_{ppll} (\theta_{pcc} - \theta_{pll}) \end{cases} \quad (B1)$$

where k_{ppll} and k_{ipll} are the proportional and integral gains of PLL, respectively; x_{pll} is the state variable of PLL; θ_{pcc} is the phase angle of PCC, and $\theta_{pcc} = \tan^{-1}(v_{pccy}/v_{pccx})$.

The dynamic of the controller of LCC inverter can be represented as:

$$\begin{cases} \frac{d}{dt} x_i = k_{ii} (v_{dcm}^{LCCI} - V_{dcref}^{LCCI}) \\ \beta_i = x_i + k_{pi} (v_{dcm}^{LCCI} - V_{dcref}^{LCCI}) - (\theta_{pcc1} - \theta_{pll1}) \end{cases} \quad (B2)$$

where k_{pi} and k_{ii} are the proportional and integral gains of the controller of LCC inverter, respectively; x_i is the state variable of the controller of LCC inverter.

The dynamic behavior of the controller of LCC rectifier can be described:

$$\begin{cases} \frac{d}{dt} x_r = k_{ir} (I_{dcref} - i_{dc1m}) \\ \alpha_r = \pi - [x_r + k_{pr} (I_{dcref} - i_{dc1m})] + (\theta_{pcc3} - \theta_{pll3}) \end{cases} \quad (B3)$$

where k_{pr} and k_{ir} are the proportional and integral gains of the controller of LCC rectifier, respectively; x_r is the state variable of the controller of LCC rectifier.

The dynamic equations of the outer voltage/power control loop of MMC are as follows:

$$\begin{cases} \frac{d}{dt} x_{od} = k_{iod} (v_{dcm}^{MMC} - V_{dcref}^{MMC}) \\ i_{c2dref} = x_{od} + k_{pod} (v_{dcm}^{MMC} - V_{dcref}^{MMC}) \end{cases} \quad (B4)$$

$$\begin{cases} \frac{d}{dt} x_{oq} = k_{ioq} (v_{pcc2m} - V_{pcc2ref}) \\ i_{c2qref} = x_{oq} + k_{poq} (v_{pcc2m} - V_{pcc2ref}) \end{cases} \quad (B5)$$

where k_{pod}/k_{poq} and k_{iod}/k_{ioq} are the proportional and integral gains of d -axis/ q -axis outer loop, respectively; x_{od}/x_{oq} is the state variable of d -axis/ q -axis outer loop.

The dynamic equations of inter AC current control loop of MMC are as follows:

$$\begin{cases} \frac{d}{dt} x_{id} = k_{iid} (i_{c2dref} - i_{c2dm}) \\ m_d = v_{pcc2dm} + x_{id} + k_{pid} (i_{c2dref} - i_{c2dm}) - \omega_2 L_{eq} i_{c2qm} \end{cases} \quad (B6)$$

$$\begin{cases} \frac{d}{dt} x_{iq} = k_{iiq} (i_{c2qref} - i_{c2qm}) \\ m_q = v_{pcc2qm} + x_{iq} + k_{piq} (i_{c2qref} - i_{c2qm}) + \omega_2 L_{eq} i_{c2dm} \end{cases} \quad (B7)$$

where k_{pid}/k_{piq} and k_{iid}/k_{iiq} are the proportional and integral gains of d -axis/ q -axis inner loop, respectively; x_{id}/x_{iq} is the state variable of d -axis/ q -axis inner loop.

The dynamic of the circulating current suppression control of MMC can be represented as:

$$\begin{cases} \frac{d}{dt} x_{cd} = k_{icd} (I_{cird2ref} - i_{cird2m}) \\ m_{d2} = -x_{cd} - k_{pcd} (I_{cird2ref} - i_{cird2m}) - 2\omega_2 L_{arm} i_{cird2m} \end{cases} \quad (B8)$$

$$\begin{cases} \frac{d}{dt} x_{cq} = k_{icq} (I_{cirq2ref} - i_{cirq2m}) \\ m_{q2} = -x_{cq} - k_{pcq} (I_{cirq2ref} - i_{cirq2m}) + 2\omega_2 L_{arm} i_{cirq2m} \end{cases} \quad (B9)$$

where k_{pcd}/k_{pcq} and k_{icd}/k_{icq} are the proportional and integral gains of d -axis/ q -axis of circulating current suppression control, respectively; x_{cd}/x_{cq} is the state variable of d -axis/ q -axis of circulating current suppression control.

All measured values are obtained through the first-order feedback filter. The dynamic equation of the first-order feedback filter can be expressed as:

$$\frac{d}{dt} y = \frac{G}{T} x - \frac{1}{T} y \quad (B10)$$

where x and y are the input and output of first-order feedback filter, respectively; G and T are the gain and time constant of first-order feedback filter, respectively.

APPENDIX C

TABLE C I
AC FILTER & VAR COMPENSATION PARAMETERS

Parameters	Values	
	Rectifier-side	Inverter-side
C_f	2.3002 μF	1.1221 μF
C_{hp}	4.6004 μF	2.2441 μF
L_{hp}	0.0056 H	0.0115 H
R_{hp}	49.4228 Ω	101.317 Ω
C_1	4.6004 μF	2.2441 μF
L_1	0.0154 H	0.0316 H
C_2	164.46 μF	80.2264 μF
L_2	0.4308 mH	0.8832 mH
R_2	0.0162 Ω	0.0332 Ω

TABLE C II
FEEDBACK FILTER PARAMETERS

Parameters		Values
v_{dc}^{LCCI} filter	G_{vdi}, T_{vdi}	1, 10 ms
i_{dc1} filter	G_{idr}, T_{idr}	1, 20 ms
v_{dc}^{MMC} filter	G_{vdc}, T_{vdc}	1, 10 ms
v_{pcc2} filter	G_{vs}, T_v	1, 10 ms
v_{pcc2d} filter	G_{vdi}, T_{vdi}	1, 2 ms
v_{pcc2q} filter	G_{vqi}, T_{vqi}	1, 2 ms
i_{c2d} filter	G_{idi}, T_{idi}	1, 1 ms
i_{c2q} filter	G_{iqi}, T_{iqi}	1, 1 ms

i_{cird2} filter	G_{icid}, T_{icid}	1, 2 ms
i_{cird2} filter	G_{icid}, T_{icid}	1, 2 ms

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