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Circulating Current Control Scheme of Modular Multilevel Converters Supplying Passive Networks under Unbalanced Load Conditions

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Abstract

Load imbalances in the supply of passive loads with modular multilevel converter (MMC)-based medium (MVDC) and high voltage (HVDC) dc-links are inevitable. In such applications, the maximum-allowable voltage ripples and peak arm currents define the operating limits of the MMCs. This paper demonstrates the impact of circulating current control in capacitor voltage ripples of sub-modules and peak arm currents under unbalanced load conditions when supplying passive networks, comparing the effects of three circulating current control methods on internal variables of the MMCs. The efficacy of the circulating current control is validated through real-time digital simulations of an 800 MVA benchmark MMC-based HVDC transmission system.

Keywords: modular multilevel converter, MVDC, HVDC, passive network, load imbalance, circulating current, capacitor voltage ripple.

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1. Introduction

Modular multilevel converters (MMCs) [1, 2, 3] have become particularly attractive topologies for high-voltage-direct-current (HVDC) transmission systems [4, 5] and multi-terminal networks [6] due to their modularity and scalability as well as other advantages. Their prevalence in power systems will continue to increase with medium-voltage dc (MVDC) applications reaching commercial maturity [7, 8]. Other potential applications of MMCs include flexible alternating current transmission systems (FACTS) [9], photovoltaic generation [10], wind turbine applications [11], and motor drives [12]. Compared with local power generation, HVDC transmission facilitates integration of remote large scale renewable energy resources contributing to emission reduction targets [13]. Major attention has been drawn to various strategies and technologies for control, protection, and operation of MMC-based HVDC transmission systems, where MMC is interacting with active (strong or weak) ac networks [14, 15]. However, the supply of passive networks with HVDC and MVDC links is also a typical scenario involving transmitting power to isolated or remote load centers [16]. For example, HVDC transmission is the only viable solution for the supply of offshore platforms, due to ac cable charging current issues [17].

Control methods have been reported in the current literature [18] to provide a comprehensive review of operation and control methods applied to MMC-based HVDC systems supplying active networks under grid imbalances caused by faults on the ac network. A control scheme that uses two sets of controllers under the positive and negative synchronous reference frames for improving system performance during unbalanced network conditions is proposed in [19]. An extended limitation method for the converter current of the grid-forming offshore MMC during unbalanced conditions is presented to maximize the injected grid currents in the faulted phases providing better utilization of the converter than the normal limitation method [20]. The relationship between circulating current reference value and sub-module capacitor voltage, modulation index, and arm current under unbalanced grid condition is studied in [21]. Improved strategies based on PR controllers can eliminate both circulating current and dc-line voltage ripples, which greatly enhance the fault ride-through capability of MMC-HVDC without adding extra control cost or increasing the number of controllers. Operating regions of the MMC can be defined depending on multiple control objectives and independent control of active and reactive power. These regions can be used to investigate and quantify the impact of the circulating current control and system control targets on the operation of the converter. [22].

Unlike active networks, either in the form of HVDC links or embedded HVDC systems, in passive networks, the MMC operates in ac voltage and frequency control (VF control) mode where it acts as a constant-frequency, constant-amplitude and balanced voltage source [23]. Unbalanced load conditions are usually inevitable, even during normal operation without faults [24]. It is essential to elaborate on the impact of control methods on capacitor voltage ripples, rms and peak arm currents

as these factors can significantly affect system performance [25] and this is one of the main aims of this work.

On the basis of definite output capacity, effectively reducing sub-module capacitor voltage ripples can lower the system cost and ensure safe operation of the system. A desired second-order [26] or higher-order harmonics [27] may be injected into the circulating currents in order to reduce capacitor ripples. The main demerit of these methods is that they rely on the determination of output current magnitude and phase and use of an extensive lookup table. Circulating current reference based on the instantaneous information [28], only requiring the instantaneous values including output current and the output reference signal of each phase can provide similar performance without any off-line calculations. Such a method of instantaneous information is also reported in [29, 30].

Under unbalanced load conditions, overcurrent may arise on either of the six arm currents resulting in poor converter capacity utilization [31]. One approach to avoid the overcurrent is to control the double-line-frequency circulating currents by injecting double-line-frequency voltages or various harmonic voltages [32]. Under unbalanced conditions, the positive- and zero-sequence double-line-frequency circulating currents may arise, which can also be controlled by injecting corresponding harmonic voltages [33, 34]. Another approach is to control dc component of circulating currents, instead of double-line-frequency component [35]. The advantage of this method is that the dc component has smaller impact on the capacitor voltage ripples.

The objectives of this paper are to analyse and compare the impact of circulating current control schemes of the MMC when supplying passive networks under unbalanced load conditions. A circulating current control method based on instantaneous information that considers overcurrent limitation (CC3) is also proposed. This method achieves simultaneous control of the ac and dc components in the circulating current. The capacitor voltage ripples can be reduced by controlling the ac components and overcurrent limitation can be achieved by balancing the dc components of each arm. The approach offers a compromise between peak arm currents and capacitor voltage ripples. From a modulation perspective, the mathematical expressions of the basic components of capacitor voltage ripples for the three different circulating current control methods are analytically derived.

This paper is organized as follows. Section 2 introduces the basic MMC structure and an analytical mathematical model for passive loads under unbalanced conditions is derived. In Section 3, three control schemes based on circulating current injections are introduced. The calculation of the circulating current reference including dc and ac components is derived. The mathematical expressions of capacitor voltage ripples for the three circulating current control methods are calculated in Section 4. The validity and performance of these schemes is confirmed through real-time digital simulations (RTDS) based on an 800MVA MMC-HVDC transmission system supplying remote passive loads with various unbalance degrees. The results are provided in Section 5 while Section 6 concludes this paper.

2. MMC Structure and Mathematical Model

Figure 1 shows the single-phase equivalent circuit of a three-phase MMC based on the half-bridge sub-module (HB-SM) structure [36]. Each phase of the three-phase MMC can be divided into two arms, each composed of N series-connected identical SMs and an arm inductor L with an equivalent resistance R . Each SM consists of two IGBTs with anti-parallel diode and a parallel storage capacitor C_{SM} . The output voltage v_{SM} of each SM is equal to its capacitor voltage v_C or zero, depending on the switching states of the switches T_1 and T_2 in each SM.

Figure 1: Single phase equivalent circuit of MMC.

The upper and lower arms of phase x ($x = a, b, c$) are denoted respectively by the subscripts xu and xl . v_{xu} and v_{xl} represent the upper and lower arm voltages, i_{xu} and i_{xl} represent the upper and lower arm currents, respectively. V_{dc} is the dc-link voltage, v_x is the output voltage and i_x the output current of phase x , while i_{xdiff} is the circulating current and v_{xdiff} is the differential voltage of phase x .

The arm currents i_{xu} and i_{xl} can be written as:

$$\begin{cases} i_{xu} = i_{xdiff} + \frac{1}{2}i_x, \text{ and} \\ i_{xl} = i_{xdiff} - \frac{1}{2}i_x. \end{cases} \quad (1)$$

The phase arm voltage v_x can be characterized as:

$$v_x = v_{ex} - \frac{R}{2}i_x - \frac{L}{2}\frac{di_x}{dt}, \quad (2)$$

where v_{ex} is the inner equivalent voltage of phase x generated by the inner loop control that can be expressed as:

$$v_{ex} = \frac{1}{2}(v_{xl} - v_{xu}). \quad (3)$$

If we define v_{xdiff} as the arm differential voltage:

$$v_{xdiff} = L\frac{di_{xdiff}}{dt} + Ri_{xdiff}, \quad (4)$$

Figure 2: Block diagram of MMC-HVDC transmission system.

the references of arm voltages $v_{xu.ref}$ and $v_{xl.ref}$ can be defined as:

$$\begin{cases} v_{xu.ref} = \frac{1}{2}V_{dc} - v_{ex.ref} - v_{xdiff.ref}, and \\ v_{xl.ref} = \frac{1}{2}V_{dc} + v_{ex.ref} - v_{xdiff.ref}. \end{cases} \quad (5)$$

Eqs.(1)-(5) show that the output current of MMC i_x and circulating current i_{xdiff} can be controlled independently, and two independent controllers can be introduced to implement the control objectives of ac output and circulating currents [30].

To investigate the various circulating current control schemes, the circuit diagram of the MMC-HVDC system is shown in Figure 2. The following analysis assumes load imbalance of Station 1, and all derivations are performed for this side of the HVDC system. The ac voltage and frequency (VF) control of MMC1 to ensure the stability of voltage amplitude and frequency of the passive network is shown in Figure 3. When the MMC operates in passive networks with unbalanced load conditions, there is negative sequence voltage and current component [37]. Conventional voltage control cannot adjust the negative sequence component. In the paper, a sequence decomposition control method is adopted to replace the traditional voltage control. The positive and negative sequence components are obtained by coordinate transformation, respectively. Then the positive and negative sequence components are controlled respectively by the PI controllers without static error to obtain the corresponding references, and finally they are superimposed [38].

3. Circulating Current Control under Unbalanced Load Conditions

The output voltages v_x and currents i_x of the MMC can be expressed as:

$$\begin{cases} v_x = V_p \cos(\omega t + \varphi_{up} - \theta_x) + V_n \cos(\omega t + \varphi_{un} + \theta_x), and \\ i_x = I_p \cos(\omega t + \varphi_{ip} - \theta_x) + I_n \cos(\omega t + \varphi_{in} + \theta_x). \end{cases} \quad (6)$$

where V_p , V_n are the amplitude of positive-sequence and negative-sequence voltages; I_p , I_n are the amplitude of positive-sequence and negative-sequence currents, respectively. θ_x is $[0, 2\pi/3, -2\pi/3]$.

Figure 3: The block diagram of VF control.

Due to the elimination of negative-sequence voltages (Figure 4), the output voltages are considered to be symmetrical. So, (6) can also be expressed as:

$$\begin{cases} v_x = V \cos(\omega t + \varphi_{ux}), \text{ and} \\ i_x = I_x \cos(\omega t + \varphi_{ix}), \end{cases} \quad (7)$$

where I_x and φ_{ix} are given by:

$$\begin{cases} I_x = I_p \sqrt{1 + \varepsilon^2 + 2\varepsilon \cos(\varphi_{ip} - \varphi_{in} - 2\theta_x)}, \text{ and} \\ \varphi_x = \arcsin \frac{\sin(\varphi_{ip} - \theta_x) + \varepsilon \sin(\varphi_{in} + \theta_x)}{\sqrt{1 + \varepsilon^2 + 2\varepsilon \cos(\varphi_{ip} - \varphi_{in} - 2\theta_x)}}. \end{cases}$$

with ε being the load imbalance degree I_n/I_p .

3.1. AC Component Elimination (CC1)

Elimination of the ac component of the circulating current is the most common method used in the MMC [32, 33]. The circulating current i_{xdiff_CC1} can be expressed as:

$$i_{xdiff_CC1} = i_{xdiff_dc_CC1} + i_{xdiff_ac_CC1} = I_{dx_CC1}. \quad (8)$$

where i_{xdiff_dc} and i_{xdiff_ac} are the dc and ac components of circulating current, respectively. Due to the ac component of circulating current $i_{xdiff_ac_CC1}$ is equal to 0 under this method, so I_{dx_CC1} can be used to describe the circulating current in this case.

The block diagram of the circulating current control of ac component elimination is shown in Figure 4. In this method, there is no need to control the dc component of the circulating current, which can be naturally distributed between the three phases [28].

3.2. Instantaneous Information Reference (CC2)

According to (7), the reference signals v_{xm_CC2} can be expressed as:

$$v_{xm_CC2} = m \cos(\omega t + \varphi_{ux}), \quad (9)$$

Figure 4: Circulating current control of ac component elimination (CC1).

Figure 5: Circulating current control of instantaneous information without overcurrent limitation (CC2).

where $m = 2V/V_{dc}$ ($0 \leq m \leq 1$) being the modulation index.

Appropriate harmonic current injection can optimize the operation of MMC. The ac component reference of circulating current $i_{xdiff_ac_CC2}$ can be derived from the output currents i_x and modulation signal v_{xm} [28] by:

$$i_{xdiff}^* = \frac{i_x v_{xm_CC2}}{2} = \frac{1}{4} m I_x \cos(\varphi_{ux} - \varphi_{ix}) + \underbrace{\frac{1}{4} m I_x \cos(2\omega t + \varphi_{ux} + \varphi_{ix})}_{i_{xdiff_ac_CC2}}. \quad (10)$$

The circulating current i_{xdiff_CC2} can be written as (11), where ac component is equal to $i_{xdiff_ac_CC2}$.

$$\begin{aligned} i_{xdiff_CC2} &= i_{xdiff_dc_CC2} + i_{xdiff_ac_CC2} \\ &= I_{dx_CC2} + \frac{1}{4} m I_x \cos(2\omega t + \varphi_{ux} + \varphi_{ix}). \end{aligned} \quad (11)$$

The block diagram of the circulating current control of instantaneous information reference is shown in Figure 5.

3.3. Instantaneous Information Reference with Overcurrent Limitation (CC3)

Second-order harmonic injection (CC2) increases the rms arm currents and may result in peak arm currents above rated values. To avoid such issues, an overcurrent limitation method should be introduced to the circulating current control. In order not to affect the second-order harmonic injection, control of the dc component of the circulating current to eliminate overcurrent is a suitable method.

To fulfill overcurrent limitation, the peak value of all the arm currents is considered equal ($I_{apk} = I_{bpk} = I_{cpk}$). The sum of peak values of the three-phase arm currents can be calculated by:

$$\sum_{x=a,b,c} I_{xpk} = \sum_{x=a,b,c} I_x/2 + I_{dsum}, \quad (12)$$

where $I_{dsum} = I_{da} + I_{db} + I_{dc}$ is the value of the dc-link current.

140 The dc component of the circulating current can be obtained [35] as:

$$I_{dx_CC3} = i_{xdiff_dc_CC3} = \frac{\sum_{x=a,b,c} I_x/2 + I_{dsum}}{3} - \frac{I_x}{2}. \quad (13)$$

By adding a common zero-sequence voltage to the reference voltages, the average active power in each phase can then be regulated, and the arm current can be controlled [35]. The amplitude V_0 and the phase φ_0 can be obtained by Eqs.(14)-(16). The mathematical derivations are provided in detail in [35].

$$\varphi_0 = \arctan \left(-\frac{\cos\varphi_{ia} - k_{pow}\cos\varphi_{ib}}{\sin\varphi_{ia} - k_{pow}\sin\varphi_{ib}} \right), \quad (14)$$

where

$$k_{pow} = \frac{V_{dc}I_{da_CC3} - \frac{VI_a}{2}\cos(\varphi_{ua} - \varphi_{ia})}{V_{dc}I_{db_CC3} - \frac{VI_b}{2}\cos(\varphi_{ub} - \varphi_{ib})} \cdot \frac{I_b}{I_a}.$$

If $[V_{dc}I_{da_CC3} - VI_a\cos(\varphi_{ua} - \varphi_{ia})/2]$ and $\cos(\varphi_0 - \varphi_{ia})$ are neither both positive nor both negative, φ_0 should be

$$\varphi_0 = \pi + \arctan \left(-\frac{\cos\varphi_{ia} - k_{pow}\cos\varphi_{ib}}{\sin\varphi_{ia} - k_{pow}\sin\varphi_{ib}} \right), \text{ and} \quad (15)$$

$$V_0 = \left| \frac{2V_{dc}I_{da_CC3} - VI_a\cos(\varphi_{ua} - \varphi_{ia})}{I_a\cos(\varphi_0 - \varphi_{ia})} \right|. \quad (16)$$

This zero-sequence voltage can be then written as:

$$v_{xdiff_dc_CC3} = V_0\cos(\omega t + \varphi_0). \quad (17)$$

The normalised reference signals v_{xm_CC3} can be expressed as:

$$v_{xm_CC3} = m\cos(\omega t + \varphi_{ux}) + m_0\cos(\omega t + \varphi_0) = m_x\cos(\omega t + \alpha_x), \quad (18)$$

where

$$\begin{cases} m_0 = 2V_0/V_{dc}, \\ m_x = \sqrt{m^2 + m_0^2 + 2m_0m\cos(\varphi_{ux} - \varphi_0)}, \text{ and} \\ \alpha_x = \arcsin \frac{m\sin\varphi_{ux} + m_0\sin\varphi_0}{\sqrt{m^2 + m_0^2 + 2m_0m\cos(\varphi_{ux} - \varphi_0)}}. \end{cases}$$

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Due to $0 \leq m_x \leq 1$, the value of m_0 is limited by m . Considering the model of Fig. 2 as an example, $V = 180kV$, $V_{dc} = 400kV$, and $m = 2V/V_{dc} = 0.9$. The value range of V_0 is shown in Figure 6. The maximum value of V_0 is close to 39kV, when ε is approximately equal to 7.5%.

The ac component reference of circulating current $i_{xdiff_ac_CC3}$ can be derived as CC2:

$$i_{xdiff}^* = \frac{i_x v_{xm_CC3}}{2} = \frac{1}{4}m_x I_x \cos(\alpha_x - \varphi_{ix}) + \underbrace{\frac{1}{4}m_x I_x \cos(2\omega t + \alpha_x + \varphi_{ix})}_{i_{xdiff_ac_CC3}}. \quad (19)$$

The circulating current in this case can be written as:

$$\begin{aligned} i_{xdiff_CC3} &= i_{xdiff_dc_CC3} + i_{xdiff_ac_CC3} \\ &= I_{dx_CC3} + \frac{1}{4}m_x I_x \cos(2\omega t + \alpha_x + \varphi_{ix}). \end{aligned} \quad (20)$$

The block diagram of circulating current control with instantaneous information reference with overcurrent limitation is shown in Figure 7. The dc and ac components can be controlled independently.

4. Analysis of Capacitor Voltage Ripples

Table 1: Parameters of simulated MMC-HVDC system.

Parameters	Values
Rated power, S	800MVA
Output line-to-line voltage	220kV
dc-link voltage, V_{dc}	± 200 kV
Number of SMs of each arm	200
SM reference voltage, v_c	2kV
SM capacitor, C	10mF
Arm inductors, L	29mH

160 The theoretical analysis of this section is based on the three circulating current control methods introduced in Section 3. Substituting (7), (8), (11) and (20) into (1), the arm currents of MMC under the three circulating current control methods (i_{xu_CCk} , i_{xl_CCk} , $k = 1, 2, 3$) can be expressed

Figure 6: Value range of zero-sequence voltage (CC3).

where v_{cref} is the rated capacitor voltage equal to V_{dc}/N ; λ_{x1} , λ_{x2} and λ_{x3} are the magnitude of the corresponding voltage ripples; and φ_{x1} , φ_{x2} and φ_{x3} are the initial phases. By substituting (25) into (23), λ_{x1} , λ_{x2} and λ_{x3} can be calculated for $CC1$ as:

$$\begin{cases} \lambda_{x1_CC1} = \frac{NI_x \sqrt{1 + \frac{1}{4}m^4 \cos^2(\varphi_{ux} - \varphi_{ix}) - m^2 \cos^2(\varphi_{ux} - \varphi_{ix})}}{4\omega CV_{dc}}, \\ \lambda_{x2_CC1} = \frac{NmI_x}{16\omega CV_{dc}}, \text{ and} \\ \lambda_{x3_CC1} = 0, \end{cases} \quad (26)$$

for $CC2$,

$$\begin{cases} \lambda_{x1_CC2} = \frac{NI_x \sqrt{(1 - \frac{1}{4}m^2)^2 + \frac{1}{2}m^4 \cos^2(\varphi_{ux} - \varphi_{ix}) - m^2 \cos^2(\varphi_{ux} - \varphi_{ix})}}{4\omega CV_{dc}}, \\ \lambda_{x2_CC2} = 0, \text{ and} \\ \lambda_{x3_CC2} = \frac{Nm^2 I_x}{48\omega CV_{dc}}, \end{cases} \quad (27)$$

180 and for $CC3$, as

$$\begin{cases} \lambda_{x1_CC3} = \frac{NI_x \sqrt{(1 - \frac{1}{4}m_x^2)^2 + \frac{1}{2}m_x^4 \cos^2(\alpha_x - \varphi_{ix}) - m_x^2 \cos^2(\alpha_x - \varphi_{ix})}}{4\omega CV_{dc}}, \\ \lambda_{x2_CC3} = 0, \text{ and} \\ \lambda_{x3_CC3} = \frac{Nm_x^2 I_x}{48\omega CV_{dc}}. \end{cases} \quad (28)$$

The unbalanced load condition is set as $\varphi_{ip} - \varphi_{in} = 0^\circ$. Based on the system parameters and previously presented analysis, utilizing the capacitor voltage ripple expressions of (26), (27) and (28), the capacitor voltage ripple magnitude as a function of the output power and imbalance degree are shown in Figure 8. Compared with ac component elimination ($CC1$), instantaneous current injection ($CC2$) can reduce the ripples of capacitor voltage but the peak value of arm currents increases. Compared with $CC2$, instantaneous current injection with overcurrent limitation ($CC3$) can maintain the peak value of arm currents below predetermined limits. However, the capacitor voltage ripples of the phase with the larger power increases, while the other two phases decrease. In this case, $CC3$ offers a compromise solution between $CC1$ and $CC2$. In Figure 9, the peak value for the different circulating current control methods is calculated as $I_{pkm} = \max(I_{apk}, I_{bpk}, I_{cpk})$, and the ratio I_{pkm_CC2}/I_{pkm_CC3} between $CC2$ and $CC3$ is calculated. Based on the results, the effectiveness of $CC3$ in overcurrent limitation due to the injection of the zero-sequence voltage V_0 (shown in Figure 6) is demonstrated. These results depend on the parameters of the system and the available overhead for injection of zero-sequence voltage and in the case of the HVDC system of Table 1, the ratio is approximately equal to 0.91, when ε is over 7.5%.

Figure 8: Capacitor voltage ripple magnitude under the three circulating current control methods ($\varphi_{ip} - \varphi_{in} = 0^\circ$): (a) CC1; (b) CC2; (c) CC3.

Figure 9: Comparison of peak arm currents of $CC2$ and $CC3$.

Figure 10: Hardware requirements of the HVDC transmission real-time simulation.

5. Simulation results

The 800 MVA MMC-HVDC transmission system of Figure 3 and Table 1 is developed and simulated on a real-time platform (RTDS) to verify the SM voltage ripples under the three circulating current control methods. The simulated system requires a total of 7 PB5 processor board cards over two racks, as shown in Figure 10. The MMC is based on a 200-SM per arm average model, considering an equivalent switching frequency. MMC2 in station 2 is connected to an ac grid and functions as the dc-link voltage controller, whereas MMC1 is connected to passive loads and works in voltage and frequency control mode shown in Figure 3. Load imbalances are considered in station 1, and the unbalanced load condition is set as $\varphi_{ip} - \varphi_{in} = 0^\circ$.

The results of the following sections show the line voltages (v_{ab}, v_{bc}, v_{ca}), phase voltages (v_x), ac output currents (i_x), upper arm currents (i_{xu}), circulating currents (i_{xdiff}) and average SM capacitor voltages of upper and lower arm (v_{xu_avg}, v_{xl_avg}).

5.1. Case 1: $\varepsilon=7\%$, $\varphi_{ip} - \varphi_{in} = 0^\circ$

In the first simulation case, the ac-link average active power $P_{ac.a} = 186.1\text{MW}$, $P_{ac.b} = P_{ac.c} = 167.8\text{MW}$. The total power transmitted is 0.65pu, $\varepsilon=7\%$, $\varphi_{ip} - \varphi_{in} = 0^\circ$. The zero-sequence voltage

injection for $CC3$ is equal to 38.2kV. The output three-phase line and phase voltages and three-phase currents of the converter under $CC1$ are shown in Fig. ???. As the output voltages and currents are not affected by the control of the circulating current, results for the other two methods are omitted. The remaining results are shown in Figure 12. Specific comparison results are shown in Table 2.

Figure 11: Simulation results of circulating current control (Case 1): line voltages, phase voltages v_x , and ac output currents i_x .

The theoretical analysis results of this case according to (26), (27) and (28) are annotated in Figure 9. The comparisons of the theoretical value and the actual value of capacitor voltage ripples are shown in Table 3.

The theoretical and simulation results are closely matched. The main reason for the differences observed between the theoretical and simulated actual value is that in order to control the circulating current, a voltage component is superimposed on the modulation signals of upper and lower arms. Compared with dc voltage, this voltage component is small and has been neglected [33] to simplify the analysis. Although this voltage may cause deviations, it will not affect the analysis in the general trend of capacitor voltage ripples.

In this case, compared with ac component elimination ($CC1$), instantaneous current injection without overcurrent limitation ($CC2$) can reduce capacitor voltage ripples, but the peak value of arm currents increases. Compared with $CC2$, instantaneous current injection with overcurrent limitation ($CC3$) can reduce the peak value of arm currents, but the voltage ripple suppression effect of phase a is worse. However, the effect of voltage ripple suppression of $CC3$ is still better than $CC1$. In this

Figure 12: Simulation results of circulating current control (Case 1): (a) CC1; (b) CC2; (c) CC3. From top to bottom, upper arm currents i_{xu} , circulating currents i_{xdiff} , and average SM capacitor voltages v_{xu_avg} , v_{xl_avg} of upper and lower arm of phase a, b, c.

Table 2: Comparisons under the three control methods (Case 1).

		<i>CC1</i>	<i>CC2</i>	<i>CC3</i>
Peak arm currents	a	1.52kA	1.84kA	1.71kA
	b	1.38kA	1.67kA	1.71kA
	c	1.38kA	1.67kA	1.71kA
Arm currents (RMS)	a	1.20kA	1.23kA	1.13kA
	b	1.08kA	1.11kA	1.16kA
	c	1.08kA	1.11kA	1.16kA
Voltage ripple magnitude	a	0.125kV	0.082kV	0.115kV
	b	0.113kV	0.073kV	0.058kV
	c	0.113kV	0.073kV	0.058kV

Table 3: Comparisons of theoretical value (λ_{th}) and simulated value ($\lambda_{simulated}$) (Case 1).

	<i>CC1</i>		<i>CC2</i>		<i>CC3</i>	
	λ_{th}	λ_{sim}	λ_{th}	λ_{sim}	λ_{th}	λ_{sim}
a	6.75%	6.25%	3.79%	4.20%	5.47%	5.75%
b	6.08%	5.65%	3.41%	3.65%	2.68%	2.90%
c	6.08%	5.65%	3.41%	3.65%	2.68%	2.90%

230 case, compared with *CC2*, peak arm currents drop by about 7.6% under *CC3*.

5.2. Case 2: $\varepsilon=15\%$, $\varphi_{ip} - \varphi_{in} = 0^\circ$

In the second simulation case, the ac-link average active power $P_{ac.a} = 220.4$ MW, $P_{ac.b} = P_{ac.c} = 178.1$ MW. The total power transmitted is 0.72pu, $\varepsilon=15\%$, $\varphi_{ip} - \varphi_{in} = 0^\circ$. In this case, due to the limitation of m , the zero-sequence voltage injection for *CC3* is equal to 39.0kV. The simulation results of Case 2 are shown in Figure 13 and 14. Specific comparison results are shown in Table 4.

The theoretical analysis results of this case according to (26), (27) and (28) are also annotated in Figure 9. The comparisons of the theoretical value and the actual value of capacitor voltage ripples are shown in Table 5. Similarly to Case 1, slight deviations are a result of neglecting the circulating current control term to simplify the analysis.

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In this case, similar to Case 1, compared with *CC1*, *CC2* can reduce capacitor voltage ripples, but the peak value of arm currents increases. Compared with *CC2*, *CC3* can reduce the peak value of arm currents, but the voltage ripple suppression effect of phase a gets worse. However, the voltage

Figure 13: Simulation results of circulating current control (Case 2): line voltages, phase voltages v_x , and ac output currents i_x .

ripple suppression effect of $CC3$ is still better than $CC1$. In this case, compared with $CC2$, peak arm currents drop by about 10% under $CC3$.

Figure 14: Simulation results of circulating current control (Case 2): (a) CC1; (b) CC2; (c) CC3. From top to bottom, upper arm currents i_{xu} , circulating currents i_{xdiff} , and average SM capacitor voltages v_{xu_avg} , v_{xl_avg} of upper and lower arm of phase a, b, c.

Table 4: Comparisons under the three control methods (Case 2).

		<i>CC1</i>	<i>CC2</i>	<i>CC3</i>
Peak arm currents	a	1.79kA	2.17kA	1.97kA
	b	1.45kA	1.75kA	1.81kA
	c	1.45kA	1.75kA	1.81kA
Arm currents (RMS)	a	1.42kA	1.45kA	1.33kA
	b	1.14kA	1.18kA	1.22kA
	c	1.14kA	1.18kA	1.22kA
Voltage ripple magnitude	a	0.146kV	0.096kV	0.136kV
	b	0.117kV	0.078kV	0.061kV
	c	0.117kV	0.078kV	0.061kV

Table 5: Comparisons of theoretical value (λ_{th}) and simulated value ($\lambda_{simulated}$) (Case 2).

	<i>CC1</i>		<i>CC2</i>		<i>CC3</i>	
	λ_{th}	λ_{sim}	λ_{th}	λ_{sim}	λ_{th}	λ_{ac}
a	7.99%	7.30%	4.48%	4.80%	7.01%	6.80%
b	6.46%	5.85%	3.62%	3.90%	2.84%	3.05%
c	6.46%	5.85%	3.62%	3.90%	2.84%	3.05%

6. Conclusion

This paper presents and compares circulating current control methods MMC operation under unbalanced load conditions in passive networks, introducing a method to eliminate potential over-currents in the arm currents. The mathematical expressions of the SM capacitor voltage ripples and arm currents for the three different circulating current control methods are analytically derived with the provided analysis aligning with the results from an 800 MVA MMC-based HVDC system. The proposed method of controlling both ac and dc components based on instantaneous values and with overcurrent limitation offers a compromise between peak arm currents and capacitor voltage ripples. Considering system parameters and load imbalanced degree, when the peak arm currents are below rated values, *CC2* can be applied to minimize the capacitor voltage ripples. When the peak arm currents are above rated values, *CC3* should be used to reduce the capacitor voltage ripples and eliminate arm overcurrents. If *CC3* cannot make sure peak arm currents below rated values, *CC1* should be applied, and in that case, capacitor voltage ripple suppression effect is worse. So in practical applications, it is necessary to consider capacitor voltage ripples and peak arm currents in combination with the load imbalance degree in order to select the appropriate circulating current

control method.

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Appendix A.

The detailed expressions of (21) are given as:

$$\begin{aligned}
i_{xu_CC1} &= I_{dx_CC1} + \frac{1}{2}I_x \cos(\omega t + \varphi_{ix}), \\
i_{xl_CC1} &= I_{dx_CC1} - \frac{1}{2}I_x \cos(\omega t + \varphi_{ix}), \\
i_{xu_CC2} &= I_{dx_CC2} + \frac{1}{2}I_x \cos(\omega t + \varphi_{ix}) + \frac{1}{4}mI_x \cos(2\omega t + \varphi_{ux} + \varphi_{ix}), \\
i_{xl_CC2} &= I_{dx_CC2} - \frac{1}{2}I_x \cos(\omega t + \varphi_{ix}) + \frac{1}{4}mI_x \cos(2\omega t + \varphi_{ux} + \varphi_{ix}), \\
i_{xu_CC3} &= I_{dx_CC3} + \frac{1}{2}I_x \cos(\omega t + \varphi_{ix}) + \frac{1}{4}m_x I_x \cos(2\omega t + \alpha_x + \varphi_{ix}), \\
i_{xl_CC3} &= I_{dx_CC3} - \frac{1}{2}I_x \cos(\omega t + \varphi_{ix}) + \frac{1}{4}m_x I_x \cos(2\omega t + \alpha_x + \varphi_{ix}).
\end{aligned} \tag{A.1}$$

The detailed expressions of (22) are given as:

$$\begin{aligned}
F_{xu_CC1} &= F_{xu_CC2} = \frac{1}{2}[1 - m \cos(\omega t + \varphi_{ux})], \\
F_{xl_CC1} &= F_{xl_CC2} = \frac{1}{2}[1 + m \cos(\omega t + \varphi_{ux})], \\
F_{xu_CC3} &= \frac{1}{2}[1 - m_x \cos(\omega t + \alpha_x)], \\
F_{xl_CC3} &= \frac{1}{2}[1 + m_x \cos(\omega t + \alpha_x)].
\end{aligned} \tag{A.2}$$

The detailed expressions of (23) are given as:

$$\begin{aligned}
C \frac{du_{xcu_CC1}}{dt} &= F_{xu_CC1} i_{xu_CC1} \\
&= \frac{1}{2} I_{dx_CC1} - \frac{1}{8} m I_x \cos(\varphi_{ux} - \varphi_{ix}) \\
&\quad - \frac{1}{2} m I_{dx_CC1} \cos(\omega t + \varphi_{ux}) + \frac{1}{4} I_x \cos(\omega t + \varphi_{ix}) \\
&\quad - \frac{1}{8} m I_x \cos(2\omega t + \varphi_{ux} + \varphi_{ix}), \\
C \frac{du_{xcl_CC1}}{dt} &= F_{xl_CC1} i_{xl_CC1} \\
&= \frac{1}{2} I_{dx_CC1} - \frac{1}{8} m I_x \cos(\varphi_{ux} - \varphi_{ix}) \\
&\quad + \frac{1}{2} m I_{dx_CC1} \cos(\omega t + \varphi_{ux}) - \frac{1}{4} I_x \cos(\omega t + \varphi_{ix}) \\
&\quad - \frac{1}{8} m I_x \cos(2\omega t + \varphi_{ux} + \varphi_{ix}), \\
C \frac{du_{xcu_CC2}}{dt} &= F_{xu_CC2} i_{xu_CC2} \\
&= \frac{1}{2} I_{dx_CC2} - \frac{1}{8} m I_x \cos(\varphi_{ux} - \varphi_{ix}) \\
&\quad - \frac{1}{2} m I_{dx_CC2} \cos(\omega t + \varphi_{ux}) + \left(\frac{1}{4} - \frac{1}{16} m^2 \right) I_x \cos(\omega t + \varphi_{ix}) \\
&\quad - \frac{1}{16} m^2 I_x \cos(3\omega t + 2\varphi_{ux} + \varphi_{ix}), \\
C \frac{du_{xcl_CC2}}{dt} &= F_{xl_CC2} i_{xl_CC2} \\
&= \frac{1}{2} I_{dx_CC2} - \frac{1}{8} m I_x \cos(\varphi_{ux} - \varphi_{ix}) \\
&\quad + \frac{1}{2} m I_{dx_CC2} \cos(\omega t + \varphi_{ux}) - \left(\frac{1}{4} - \frac{1}{16} m^2 \right) I_x \cos(\omega t + \varphi_{ix}) \\
&\quad + \frac{1}{16} m^2 I_x \cos(3\omega t + 2\varphi_{ux} + \varphi_{ix}), \\
C \frac{du_{xcu_CC3}}{dt} &= F_{xu_CC3} i_{xu_CC3} \\
&= \frac{1}{2} I_{dx_CC3} - \frac{1}{8} m_x I_x \cos(\alpha_x - \varphi_{ix}) \\
&\quad - \frac{1}{2} m_x I_{dx_CC3} \cos(\omega t + \alpha_x) + \left(\frac{1}{4} - \frac{1}{16} m_x^2 \right) I_x \cos(\omega t + \varphi_{ix}) \\
&\quad - \frac{1}{16} m_x^2 I_x \cos(3\omega t + 2\alpha_x + \varphi_{ix}), \\
C \frac{du_{xcl_CC3}}{dt} &= F_{xl_CC3} i_{xl_CC3} \\
&= \frac{1}{2} I_{dx_CC3} - \frac{1}{8} m_x I_x \cos(\alpha_x - \varphi_{ix}) \\
&\quad + \frac{1}{2} m_x I_{dx_CC3} \cos(\omega t + \alpha_x) - \left(\frac{1}{4} - \frac{1}{16} m_x^2 \right) I_x \cos(\omega t + \varphi_{ix}) \\
&\quad + \frac{1}{16} m_x^2 I_x \cos(3\omega t + 2\alpha_x + \varphi_{ix}).
\end{aligned} \tag{A.3}$$

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