DC-LINK CURRENT RIPPLE ELIMINATION & BALANCING OF CAPACITOR VOLTAGE BY USING PHASE SHIFTED CARRIER PWM FOR MODULAR MULTILEVEL CONVERTER

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Abstract—The modular multilevel converter (MMC) is attractive for medium- and high-power applications because of its high modularity, availability, and power quality. In this paper, the current ripple on the dc link of the three-phase MMC derived from the phase-shifted carrier-based pulse-width modulation scheme is analyzed. A control strategy is proposed for the current ripple elimination. Through the regulation of the phase-shifted angles of the carrier waves in the three phases of the MMC, the current ripple on the dc link of the three-phase MMC can be effectively eliminated. Simulations and experimental studies of the MMC were conducted, and the results confirm the effectiveness of the proposed current ripple elimination control.

Index Terms—Capacitor voltage balancing, control strategy, modular multilevel converter (MMC), ripple elimination.

I. INTRODUCTION

MODULAR multilevel converters (MMCs) received increasing attentions in recent years due to the demands of high power and high voltage in industrial applications [1]. The MMC was first proposed by Marquardt and Lesnicar in 2000s and is regarded as one of the next-generation high-voltage multilevel converters without line-frequency transformers [2]. The MMC is composed of a number of half-bridge submodules (SMs) converters, which offers redundancy possibilities for higher reliability. The high number of modules can also produce high-level output voltage and enables a significant reduction in the device’s average switching frequency without compromising the power quality [3]. In addition, the series-connected buffer inductor in each arm can limit the current and protect the system during faults. Due to its modular structure, simple volt-age scaling, the MMC is attractive for medium-voltage drives, high-voltage direct current (HVDC) transmission, and flexible ac transmission systems [4]–[8].

Recently, the MMC has been reported in a few literature works [1]–[25], which focus on pulse width modulation (PWM) method, capacitor voltage balancing control, modeling method, reduction of switching frequency, circulating current-suppressing control, inner energy control, fault detection, loss analysis, system control under unbalanced grid, and so on. Various multicarrier PWM techniques have beenphase-shifted carrier-based (PSC) PWM method are widely used for the control of the MMC [10]–[18]. The capacitor voltage-balancing is an important issue in the MMC. Hagiwara and Akagi [9] proposed a capacitor voltage-balance control for the MMC based on the combination of averaging and balancing control without any external circuit, and the results are verified by simulation and experiment introduced to the MMC, where the phase-disposition (PD) sinusoidal pulse width modulation (SPWM) method and the Saedifard and Iravani [10] proposed a capacitor voltage-balancing control method with PD-SPWM method, where the capacitor voltage can be balanced by sorting and selecting the different SMs to be turned ON in each switching period. Deng and Chen [11] presented the PSC-PWM method for capacitor voltage balancing, where a high-frequency arm current may be generated under the PSC-PWM method, and the capacitor voltage-balance can be real-ized with the generated high-frequency arm current. However, the generated high-frequency arm current under the PSC-PWM method will be injected into the dc link of the MMC and may produce dc-link current ripple, which has not been discussed.

In this paper, the PSC-PWM method for the three-phase MMC is discussed. The produced high-frequency arm current under the PSC-PWM method in the three phases of the MMC is analyzed. A dc-link current ripple elimination control strategy is proposed for the three-phase MMC, where the high-frequency current ripple on the dc link of the MMC can be eliminated by controlling the phase-shift angles of the carrier waves in the three phases.

This paper is organized as follows. In Section II, the basic structure, modulation, and voltage balancing control of the MMC is presented. Section III proposes the current ripple elimination control for three-phase MMCS. The system simulations and experimental tests are described in Sections IV and V, respectively, to show the effectiveness of the proposed current ripple elimination control. Finally, the conclusions are presented in Section VI.

II. MODULAR MULTILEVEL CONVERTERS

A. Structure of MMCS

A schematic representation of the three-phase MMC is shown in Fig. 1(a). The MMC consists of six arms where each arm includes n series-connected SMs and a buffer inductor $L_b$. The upper and lower arms in the same phase comprise a phase.
Fig. 1. (a) Block diagram of the three-phase MMC. (b) SM unit.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SM STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM state</td>
<td>Switch S1</td>
</tr>
<tr>
<td>On</td>
<td>ON</td>
</tr>
<tr>
<td>Off</td>
<td>OFF</td>
</tr>
</tbody>
</table>

The capacitor Csm situation in each SM is related to the SM state and the direction of the arm current ism. If the SM state is “On” and the arm current ism is positive, as shown in Fig. 1(b), Csm would be charged and its voltage Vc increased. Conversely, Csm would be discharged and Vc decreased when the SM state is “On” and ism is negative. On the other hand, Csm would be bypassed when the SM state is “Off,” and its voltage Vc remains unchanged [11].

B. Modulation and Voltage-Balancing Control

The PSC-PWM modulation [11], which can produce high voltage level, is applied to the MMC, as shown in Fig. 2 with four SMs for each arm. In the phase A of the MMC with n SMs per arm, the n pulses Sua 1 Sua n and Sia 1 Sia n for the upper and lower arms can be produced by the comparison of the n carrier waves Waur and the reference signal xA and xa, respectively. The carrier wave frequency is fS = 2πfS is the angular frequency of the carrier wave. Each carrier wave is phase-shifted by an angle of θA (0 < θA < 2π/n).

Suppose the carrier wave frequency fS is far higher than that of the reference signal, the generated n upper arm pulses Sua 1 Sua n almost have the same width of θA and the generated n lower arm pulses Sia 1 Sia n almost have the same width of θA, as shown in Fig. 2.

Suppose the capacitor voltages are kept the same and according to [11], a high-frequency component ifsa in the arm currents iua and iia of phase A with a frequency of fS may be generated by the PSC-PWM method, as shown Fig. 2

\[
if_{sa}(t) = \frac{2V_c}{\omega_s f_s^2} \frac{\sin(\theta_A - \theta_s)}{\sin(\theta_A)} \sin(\omega_s t)
\]

1) When the capacitor voltage is low, the pulse with its middle-point close to π/2, as shown in Fig. 2, may be assigned to the corresponding SM. Consequently, the corresponding SM capacitor will absorb more power when the arm current is positive and the capacitor voltage increases more. Or, the corresponding SM capacitor will produce less power when the arm current is negative and the capacitor voltage decreases less.

2) When the capacitor voltage is high, the pulse with its middle-point far from π/2, as shown in Fig. 2, may be assigned to the SM. Consequently, the corresponding SM
TABLE II
SM CAPACITOR VOLTAGE CONTROL

<table>
<thead>
<tr>
<th>SM capacitor voltage</th>
<th>Pulse assignment</th>
<th>Arm current</th>
<th>Capacitor energy transfer</th>
<th>SM capacitor voltage trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Pulse with its middle point close to (\pi/2)</td>
<td>Positive</td>
<td>Absorb more power</td>
<td>Increased more</td>
</tr>
<tr>
<td>High</td>
<td>Pulse with its middle point far away from (\pi/2)</td>
<td>Negative</td>
<td>Produce less power</td>
<td>Decreased less</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>Positive</td>
<td>Absorb less power</td>
<td>Increased less</td>
</tr>
</tbody>
</table>

A capacitor will absorb less power when the arm current is positive and the capacitor voltage increases less. Or, the corresponding SM capacitor will produce more power when the arm current is negative and the capacitor voltage decreases more.

As to the phases B and C, the high-frequency component \(i_f s_b\) and \(i_f s_c\) in the arm currents of phases B and C will lead and lag \(i_f s_a\) by an angle of \(2\pi/3\). According to [11] and Figs. 2 and 3, the generated high-frequency currents \(i_f s_b\) and \(i_f s_c\) in phases B and C can be expressed as

\[
x_a = m \cdot \sin(\omega t + \alpha)
\]

\[
x_b = m \cdot \sin(\omega t + \alpha - 2\pi/3)
\]

\[
x_c = m \cdot \sin(\omega t + \alpha + 2\pi/3)
\]

where \(\theta_{u,b}, \theta_{l,b}, \theta_{u,c}, \theta_{l,c}\) are the upper and lower arm pulse widths of phases B and C, respectively. The three-phase sinusoidal reference signals \(x_a, x_b, x_c\) for the MMC can be defined as

Fig. 3. Block diagram of the PSC waves for phases A, B, and C.

Fig. 4. Block diagram of the proposed current ripple elimination control for three-phase MMCs.
Fig. 5. Simulated waveforms of the MMC without proposed control under $\theta_a = \theta_b = \theta_c = 22^\circ$. (a) Carrier waves for phase A. (b) Carrier waves for phase A in a small time scale. (c) Carrier waves for phase B. (d) Carrier waves for phase B in a small time scale. (e) Carrier waves for phase C. (f) Carrier waves for phase C in a small time scale. (g) Capacitor voltage of phase A. (h) Upper and lower arm currents $i_{ua}$ and $i_{lb}$ of phase A. (i) Upper arm currents $i_{ua}$, $i_{ub}$, and $i_{uc}$. (j) DC-link current $i_{dc}$. (k) Upper arm currents $i_{ua}$, $i_{ub}$, and $i_{uc}$ in small time scale. (l) DC-link current $i_{dc}$ in small time scale.

Fig. 6. Simulated waveforms of the MMC without proposed control under $\theta_a = \theta_b = \theta_c = 26^\circ$. (a) Upper arm currents $i_{ua}$, $i_{ub}$, and $i_{uc}$. (b) DC-link current $i_{dc}$.

Fig. 7. Simulated waveforms of the MMC without proposed control under $\theta_a = \theta_b = \theta_c = 30^\circ$. (a) Upper arm currents $i_{ua}$, $i_{ub}$, and $i_{uc}$. (b) DC-link current $i_{dc}$.
Fig. 8. Simulated waveforms of the MMC with proposed control under $k = 2$. (a) Carrier waves for phase A. (b) Carrier waves for phase A in a small time scale. (c) Carrier waves for phase B. (d) Carrier waves for phase B in a small time scale. (e) Carrier waves for phase C. (f) Carrier waves for phase C in a small time scale. (g) Capacitor voltage of phase A. (h) Upper and lower arm currents $i_{ua}$ and $i_{lb}$ of phase A. (i) Upper arm currents $i_{ua}$, $i_{ub}$, and $i_{uc}$ in small time scale. (j) DC-link current $i_{dc}$. (k) Upper arm currents $i_{ua}$, $i_{ub}$, and $i_{uc}$ in small time scale. (l) Phase-shift angles $\theta_a$, $\theta_b$, and $\theta_c$. 

where $m$ is modulation index, $\alpha$ is the phase angle. As to the SPWM method with symmetrical regular sampling [26], the produced pulse widths for the upper and lower arms of phases A, B, and C in each period of $2\pi$, as shown in Fig. 2, can be calculated as

$$\theta_{uj} = 2\pi \cdot \frac{1 + x_j}{2}, \quad (j = a, b, c).$$

$$\theta = 2\pi \cdot \frac{1-x_j}{2}.$$
Fig. 9. Simulated waveforms of the MMC with proposed control under $k = 2.5$. (a) Upper arm currents $i_{uA}$, $i_{uB}$, and $i_{uC}$. (b) DC-link current $i_{dc}$. (c) Upper arm currents $i_{uA}$, $i_{uB}$, and $i_{uC}$ in small time scale. (d) Phase-shift angles $\theta_A$, $\theta_B$, and $\theta_C$.

Fig. 11. Cable current $i_{dc}$ of the HVDC system. (a) Without proposed control and $\theta_A = \theta_B = \theta_C = 34^\circ$. (b) Without proposed control and $\theta_A = \theta_B = 32^\circ$. (c) Without proposed control and $\theta_A = \theta_B = \theta_C = 30^\circ$. (d) With proposed control and $k = 2$.

Block diagram of an MMC-HVDC
waves of phases A, B, and C in each period of $2\pi$, respectively, so as to eliminate the high-frequency current

IV. SIMULATION STUDIES

Whose middle-points are phase-shifted by an angle of $2\pi/3$, as shown in Fig. 3. Fig. 5(b), (d), and (f) shows the carrier waves for phases A, B, and C in a small time scale, which contains five periods shown in Fig. 3. In addition, each carrier wave for phases A, B and C is phase-shifted by the same angle of $22^\circ$. The active and reactive power of the MMC system is 500 and 0 kW, respectively. The circulating current suppression method presented in [16] is used in the MMC. The capacitor voltages of phase A are shown in Fig. 5(g), which are kept balanced. The upper and lower arm currents $i_a, i_b$, and $i_c$ are shown in Fig. 5(i). Owing to the PSC-PWM method, the 1.15-kHz high-frequency component in the arm current with the same frequency to that of the carrier wave is generated, as shown in Fig. 5(k). The ratio of the 1.15-kHz high frequency component to the 50-Hz fundamental component in the arm current is 10.1%. On the dc link of the MMC, a 1.15-kHz high-frequency current ripple is caused, as shown in Fig. 5(j). From Fig. 5(i), it can be seen that the peak-to-peak value of the current ripple is approximately 0.18 per unit.

Figs. 6(a) and 7(a) show the upper arm currents of the MMC without proposed control under $\theta$ of $26^\circ$ and $30^\circ$, where the ratio of the 1.15-kHz high-frequency component to the 50-Hz fundamental component in the arm current is 7.3% and 4.7%, respectively. A 1.15-kHz high-frequency current ripple is caused in the dc-link current $i_d$, and the peak-to-peak value of the high-frequency current ripple is 0.14 and 0.09 per unit, respectively.

B. MMCs With Proposed Control

The performance of the three-phase MMC with the proposed control is shown in Fig. 8, where the coefficient $k$ is 2. Fig. 8(a), (c), and (e) shows the carrier waves $W_{a1} \sim W_{a10}$, $W_{b1} \sim W_{b10}$, and $W_{c1} \sim W_{c10}$ for phases A, B, and C, whose middle-points are phase-shifted by an angle of $2\pi/3$, as shown in Fig. 3. Fig. 8(b), (d), and (f) shows the carrier waves for phases A, B, and C in a small time scale, which contains five periods shown in Fig. 3. From Fig. 8(a)–(f), it can be seen that the phase-shifted angles of phases A, B, and C vary in different periods. The capacitor voltages of phase A is shown in Fig. 8(g), which is kept balanced. The upper and lower arm currents $i_a, i_b$, and $i_c$ of phase A are shown in Fig. 8(h). Fig. 8(i) shows the upper arm current $i_a, i_b$, and $i_c$. The 1.15-kHz high-frequency component is generated in the arm current, as shown in Fig. 8(k), and the ratio of the 1.15-kHz high-frequency component in the arm current is 7.7%. Owing to the proposed current ripple elimination control, the 1.15-kHz high-frequency current ripple on the dc link of the MMC is almost eliminated, as shown in Fig. 8(j). The phase-shifted angles $\theta_a, \theta_b$, and $\theta_c$ in the proposed current ripple elimination control are shown in Fig. 8(l), which will be sampled in each period and used for control in each period.

Fig. 9 shows the performance of the MMC with the proposed control under $k = 2.5$, where the ratio of the 1.15-kHz high-frequency component to the 50-Hz fundamental component in the arm current is 9.1%. Based on the proposed control, the phase-shifted angles $\theta_a, \theta_b$, and $\theta_c$ are shown in Fig. 9(d), which will be sampled and applied in each period to eliminate the 1.15-kHz high-frequency current ripple on the dc link of the MMC, as shown in Fig. 9(b).

C. Validation With an MMC-Based HVDC System

An MMC-based HVDC system is modeled, as shown in Fig. 10, where the frequency-dependent phase model is applied as the simulation model for cables in PSCAD/EMTDC [27]. The HVDC system parameters and the cable data are listed in the Appendix. In Fig. 10, the MMC 1 is used to keep the dc-link voltage $V_{d1}$ constant as 300 kV, and MMC 2 is used to convert ac to dc and send the power $P_g$ to MMC 1. In the simulation, the HVDC system works at the rated power. Fig. 11(a)–(c) shows the cable current $i_{d1}$ without the proposed control, where the phase-shifted angles are $34^\circ$, $32^\circ$, and $30^\circ$, respectively. On the dc link of the HVDC system, the 500-Hz high-frequency current ripple is caused. From Fig. 11(a)–(c), it can be seen that the peak-to-peak value of the current ripple is approximately 0.15, 0.23, and 0.31 per unit, respectively. Fig. 11(d) shows the cable current $i_{d1}$ with the proposed control and $k = 2$. Obviously, it can be seen that the 500-Hz high-frequency current ripple on the dc link is eliminated with the proposed control.

V. EXPERIMENTAL STUDIES

A three-phase MMC prototype was built in the laboratory, as shown in Fig. 12, where each arm consists of four SMs. The switches and diodes in each cell are the standard IXFK48N60P power MOSFETs. A dc power supply (SM 600–10) is used to support the dc-link voltage. The carrier wave frequency $f_s$ is set as 5 kHz. The experimental circuit parameters are shown in the Appendix.

A. MMCs Without Proposed Control

The operation of the MMC without proposed control is tested, where the middle-points of the carrier waves $W_{a1} \sim W_{a10}$, $W_{b1} \sim W_{b10}$, and $W_{c1} \sim W_{c10}$ for phases A, B, and C are phase-shifted by an angle of $2\pi/3$, as shown in Fig. 3. Each carrier wave for phases A, B, and C is phase-shifted by the same angle of $60^\circ$. Fig. 13(a) shows the voltages $u_a, u_b$, and $u_c$ and the currents $i_a, i_b$, and $i_c$. The currents $i_{a}, i_{b}$, and $i_{c}$ are shown in Fig. 13(b). The capacitor voltages in phases A are shown in Fig. 13(c), which are kept balanced. Owing to the PSC-PWM method, a 5-kHz high-frequency component is generated in the arm current, as shown in Fig. 13(d) and (e). Fig. 13(f) shows three-phase upper arm currents $i_a, i_b$, and $i_c$, and the dc-link current $i_{d1}$ in the small time scale, where the 5-kHz high-frequency component in the arm current is injected into the dc link of the MMC and cause the dc-link current ripple.

Figs. 14–16 show the performance of the MMC under the different phase-shifted angles of $50^\circ$, $45^\circ$, and $40^\circ$, respectively. It can be seen that, along with the reduction of the phase-shifted angle, the fluctuation of the generated high-frequency 5-kHz component in the arm current is increased. A high-frequency 5-kHz current ripple is also caused in the dc-link current $i_{d1}$.
B. MMCs With Proposed Control

The proposed current ripple elimination control is tested. Fig. 17 shows the performance of the MMC under $k = 1$.

The voltage and current of the three-phase MMC are shown in Fig. 17(a) and (b). The capacitor voltages in phase A are shown in Fig. 17(c). The 5-kHz high-frequency component is generated in the arm current of the three-phase MMC, as shown in Fig. 17(d) and (e). Fig. 17(f) shows three-phase upper arm currents $i_u$, $i_v$, and $i_w$ and the dc-link current $i_d$ in the small time scale, where the high-frequency 5-kHz ripple in the dc-link current $i_d$ is eliminated with the proposed control strategy.

Figs. 18 and 19 show the MMC performance under $k = 1.5$ and $k = 2$, respectively. Along with the increase of the coefficient $k$, the fluctuation of the 5-kHz high-frequency component in each arm current is increased. The proposed control strategy can effectively eliminate the 5-kHz high-frequency current ripple in the dc-link current $i_d$.

Dynamic Performances

The dynamic performances of the three-phase MMC under the step change of the modulation index from 0.27 to 0.95 are shown in Fig. 20. Fig. 20(a) shows the results without proposed control and $\theta_a = \theta_b = \theta_c = 40^\circ$. Fig. 20(b) shows the result with the proposed control under $k = 2$. Owing to the application of the proposed control, the 5-kHz high-frequency ripple in the dc-link current $i_d$ is eliminated. In the steady state of Fig. 20(a) and (b), the ripple of the dc-link current $i_d$ is 30% and 9%, respectively.

VI. CONCLUSION

In this paper, a current ripple elimination control strategy is proposed for the three-phase MMC under the PSC PWM scheme. A high-frequency component in the arm current with the same frequency as the carrier wave derived from the PSC PWM scheme is analyzed. The relationship of the generated high-frequency current with the reference signal and the carrier wave’s phase-shifted angle is studied. Through the regulation of the phase-shifted angle of the carrier waves in the three phase of the MMC, the caused high-frequency current ripple on the dc-link of the three-phase MMC can be eliminated. A three-phase MMC system is modeled and simulated with PSCAD/EMTDC, and a small-scale three-phase MMC prototype was built in the laboratory. The simulation and experimental results verify the proposed current ripple elimination control.

REFERENCES


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