Study on Capacitor Voltage Balancing Control of Modular Multilevel Converter at Low Frequency

Guowei Liu, Qirong Jiang, and Yingdong Wei

***Abstract*—This paper describes a control method and the operating performances of Modular Multilevel Converter (MMC) for high-voltage motor drive. The magnitude of capacitor voltage ripples increases when operating frequency decreases. To deal with the significant voltage fluctuation under low frequency conditions, theoretical analysis is presented in this paper, and a new capacitor voltage balancing control strategy is proposed, which is based on carrier phase-shifted sinusoidal pulse width modulation (CPS-SPWM). The simulation results show that MMC works well and capacitor voltages are balanced with the control strategy at low frequency.**

***Index Terms*—At low frequency, capacitor voltage balancing control, CPS-SPWM, high-voltage motor drive, MMC.**

I. Introduction

High-voltage AC-AC power converters have been widely used in industry, because of the wide speed range, quick response and good performances. In the field of high-voltage AC-AC power conversion, traditional "high-low-high" two-level AC-AC converters with introduction of transformers have the disadvantages of large volume, high cost and low efficiency, and high-voltage AC-AC converters based on power electronic devices in series are hard to achieve. Contrast to the drawbacks of traditional AC-AC converters mentioned above, the multilevel converter technology has the advantages of low harmonic component, small dV/dt, high power factor, and it has developed rapidly in the last few years [1]-[3]. However, the AC-AC converters using neutral-point-clamped multilevel converters and flying-capacitor multilevel converters have the disadvantages such as the complex topology structure and the identical specification. The cascaded H-bridge multilevel converter is widely used recently because it is easy to install and to develop to higher voltage. However, it needs many more switch devices and it doesn't have the ability of four-quadrant operation.

Since Modular Multilevel Converter (MMC) was proposed by Marquardt R and Lesnicar A in 2001 [4], it has attracted more and more attention [5]-[7]. MMC has the advantages of easy assembling and flexible converter design and it can provide for the two-way flow of power. Attention has been paid to high-voltage motor drive since 2009. Reference [8] compares MMC with existing high-voltage converter topologies and puts forward the application of MMC in high-voltage motor drive. Reference [9] introduces the operating performance of MMC for motor drive and comes up with a control method based on modified voltage reference. The performance of this method is restricted to the motor current. However, they haven't taken capacitor voltage balancing control into account. The performance of MMCs at low frequency remains to be improved.

This paper analyzes the imbalance mechanics and presents a voltage balancing control strategy. This control strategy is based on carrier phase-shifted sinusoidal pulse width modulation (CPS-SPWM) and combines energy-averaging control and individual-balancing control. Simulations are carried out using PSCAD/EMTDC and the effectiveness of this control strategy is proved.

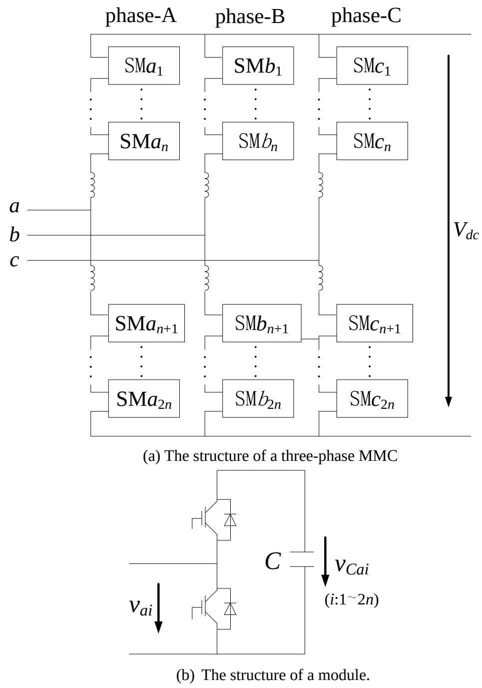

Fig. 1. Configuration of a three-phase MMC and a module.

II. The Structure and Principle of MMC

Fig. 1 shows the circuit configuration of a three-phase MMC and the structure of a module. MMC is made up of six arms and each arm consists of n modules as depicted in Fig. 1(b) and a coupled inductor. The connection point of upper arm and lower arm is connected to the ac-side, forming the structure of a phase. Each module consists of a dc capacitor and two IGBTs that control the output voltage of a module to be capacitor voltage or zero. Fig. 1(a) produces n+1-level

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PWM waveforms since the number of module per arm is n. The difference between MMC and other voltage source converters is that the storage capacitor is not required at the dc-side of MMC and the energy is distributed to each module.

The equivalent circuit of MMC as a inverter in a high voltage frequency converter is shown in Fig. 2. Phase-A is taken for an example, and v_{ap} and v_{an} are equivalent voltage sources of upper arm and lower arm, respectively, and the resistor R in each arm represents the equivalent loss resistance. P and N are the positive and negative buses of the dc-side of MMC, respectively, and O is the neutral point. The resistor and inductor in each arm are relatively small and the voltage over it can be neglected. v_{ao} is the voltage the output voltage of phase-A relative to the neutral point O. The following relationship can be obtained.

$$v_{ao} = \frac{1}{2}V_{dc} - v_{ap} = v_{an} - \frac{1}{2}V_{dc} \tag{1}$$

The following equation can be obtained from (1).

$$v_{ap} + v_{an} = V_{dc} \tag{2}$$

We can conclude that the output voltage of the ac-side can be determined by the numbers of modules switched on of each arm, and the dc voltage is the sum of the voltages of upper and lower arms. Therefore, the number of the modules switched on must be the same at any time. For an MMC with $2n$ modules in each phase as shown on Fig. 1(a), n modules are switched on at the same time to assure a stable dc voltage; hence it produces n+1-level PWM waveforms.

Because of the symmetry of the three phases and the upper and lower arm, the following current relationship can be obtained.

$$i_{ap} = \frac{1}{3}i_{dc} + \frac{1}{2}i_a \tag{3}$$

$$i_{an} = \frac{1}{3}i_{dc} - \frac{1}{2}i_a \tag{4}$$

where i_{ap} is the current of upper arm and i_{an} the lower, i_{dc} is the input current at the dc-side, i_a is the output current at the ac-side. The positive directions of the currents are shown in Fig. 2.

Because of the symmetry, the principles of the three phases are the same.

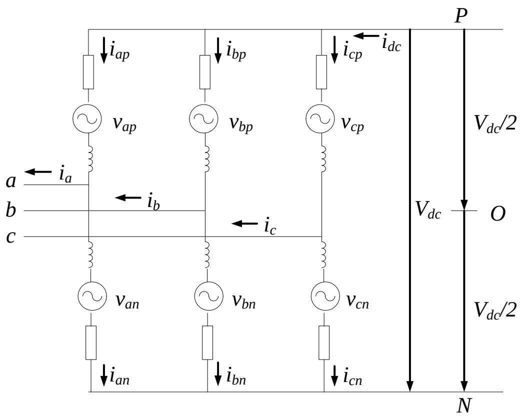


Fig. 2. The equivalent circuit of MMC

III. CPS-SPWM Scheme Suitable for MMC

The capacitor voltage balancing control is based on CPS-SPWM. The CPS-SPWM is the most commonly used modulation strategy for multilevel converter. When CPS-SPWM is applied, the carrier of each module uses determinate frequency, but is phase-shifted. The determinate switching frequency offers convenience to balance the energy in each module and estimate the power loss for real industrial applications. Compared with other modulation strategies, CPS-SPWM has certain advantages in balancing the capacitor voltage. In addition, the CPS-SPWM can reduce the generated harmonic voltages effectively using low switching frequency.

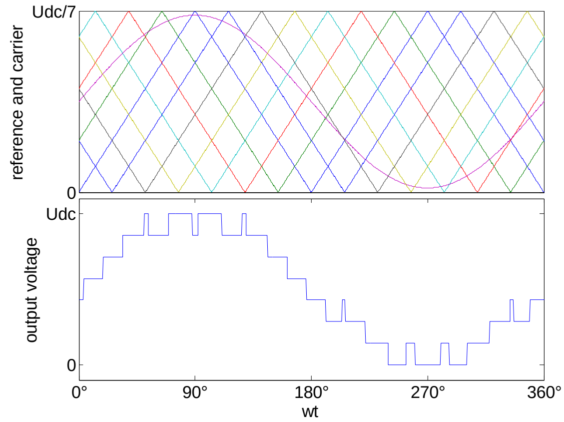


Fig. 3. Principle of carrier phase-shift modulation (8-level).

Fig. 3 shows the principle of CPS-SPWM suitable for MMC. For a leg that consists of a stack of n modules, these n modules use n triangular carri ◦ ers whose phases are shifted by $2\pi/n$ from each other. The carriers of positive arm and negative arm are out of phase by π. Without loss of generality, phase-A is taken for an example. The reference voltage of each module is

$$v_{ai}^* = \begin{cases} \frac{1}{n}v_{ap}^* = \frac{1}{2n}V_{dc} - \frac{1}{n}v_a^* & (i = 1 \sim n) \\ \frac{1}{n}v_{an}^* = \frac{1}{2n}V_{dc} + \frac{1}{n}v_a^* & (i = n+1 \sim 2n) \end{cases} \tag{5}$$

where v_{ai}^* is the reference voltage of module a_i and v_a^* is the reference line-to-neutral voltage of MMC ac side.

$$v_a^* = \sqrt{\frac{2}{3}}V \sin \omega t \tag{6}$$

where V is the motor line-to-line rms voltage.

The reference voltage of each module compares with its triangular carrier to produce pulses to drive the IGBTs.

IV. Capacitor Voltage Balancing Control in Low Frequency Condition

A. Capacitor Voltage Imbalance Mechanics

The capacitor in the module is floating. When a module is switched on, current flowing through the capacitor causes charging and discharging and the capacitor voltage fluctuation occurs. Because the switch-on time of each module is different, the capacitor voltage within the same arm becomes imbalanced.

Reference [10] presents the theoretical analysis and mathematical deduction of capacitor voltage fluctuation. The results are as follows.

$$\tilde{v}_{Ca1} = \frac{\sqrt{2}I}{8\pi fC} f(t) \quad (7)$$

$$f(t) = \frac{m^2 \cos\varphi}{2}\cos\omega t - \cos(\omega t - \varphi) + \frac{m}{4}\sin(2\omega t - \varphi) \quad (8)$$

where the modulation index m, related to the ac amplitude of the modulation signal, is given by

$$m = \sqrt{\frac{2}{3}}\frac{2V}{nV_C} \quad (9)$$

where V_C is the dc component of the capacitor voltage.

The following conclusions are obtained from (7), (8) and (9). The magnitude of capacitor voltage fluctuation is proportional to the motor current, and inversely proportional to the motor frequency and the capacitance, and is also affected by the modulation index and the motor power factor. Therefore, the lower the frequency of MMC used for high-voltage motor drive, the larger the capacitor voltage fluctuation. Capacitor voltage control strategy is necessary.

B. Capacitor Voltage Balancing Control

To deal with the obvious capacitor voltage fluctuation of MMC at low frequency, this paper presents a control strategy based on the theory in [10]. The capacitor voltage balancing control is based on CPS-SPWM and consists of energy-averaging control and individual-balancing control.

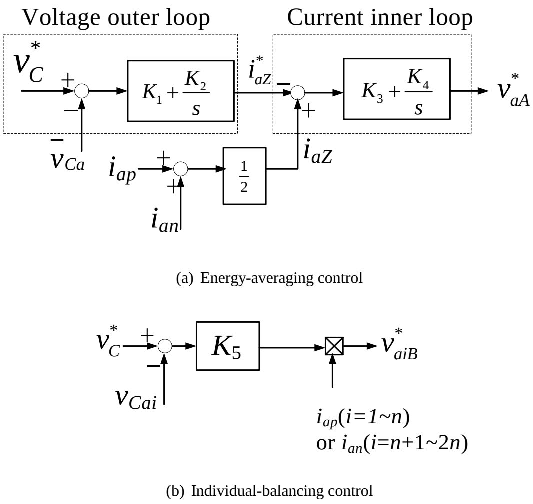


Fig. 4. Block diagram of capacitor voltage balancing control

Fig. 4(a) shows the principle of energy-averaging control which forces the phase-A average voltage $\bar{v}_{Ca}$ to follow capacitor voltage reference v_C^*. Consequently energy is distributed into each module averagely. The phase-A average voltage $\bar{v}_{Ca}$ can be obtained by

$$\bar{v}_{Ca} = \frac{1}{2n}\sum_{i=1}^{2n} v_{Cai} \quad (10)$$

As is shown in Fig. 4(a), energy-averaging control includes two closed-loops. Both loops adopt proportional-integral control. The voltage loop enables the average voltage to follow its reference and the output is used as current reference of the current loop. The circulating current is adjusted in the current inner loop, the output of which is used as the first additional reference voltage.

The block diagram of individual-balancing control is shown in Fig. 4(b). The individual-balancing control forces the capacitor voltage of each module to follow its reference v_C^*. The difference of capacitor voltage and its reference is used as the input of a proportional controller, then multiplied by the arm current i_{ap}(or i_{an}). The output is the second additional reference voltage.

The additional reference voltage obtained from the individual-balancing control is in the same phase with the arm current. The active power injected into the module depends on the voltage difference and the arm current. The bigger the voltage difference and arm current, the stronger the adjustment ability.

Eventually, two parts of additional reference voltage are added to the arm reference voltage v_{ai}^* to obtain the final reference voltage for the module a_i to realize the capacitor voltage balancing control.

$$v_{airef}^* = v_{ai}^* + v_{aA}^* + v_{aiB}^* \quad (11)$$

V. Simulation Results

To verify the validity of the proposed control strategy, the simulation using the "PSCAD/EMTDC" software package was carried out, where the circuit parameters are summarized in Table I. A high-voltage motor drive system with an 8-level MMC as the inverter was built. The role of the rectifier in the system is to control the active power passing through to guarantee the steadiness of dc-link voltage and it has little to do with the fluctuation of capacitor voltage. So the dc voltage sources are used in the dc side of MMC in the motor drive system.

TABLE I: Circuit Parameters

Rated line-to-line rms voltage	10kV
Rated apparent output	5MVA
Rated dc-link voltage	21kV
Buffer inductance per arm	10mH
DC capacitance per module	8000μF
Rated capacitor dc voltage per module	3kV
Number of modules per arm per phase (n)	7
Carrier frequency per module	2000Hz

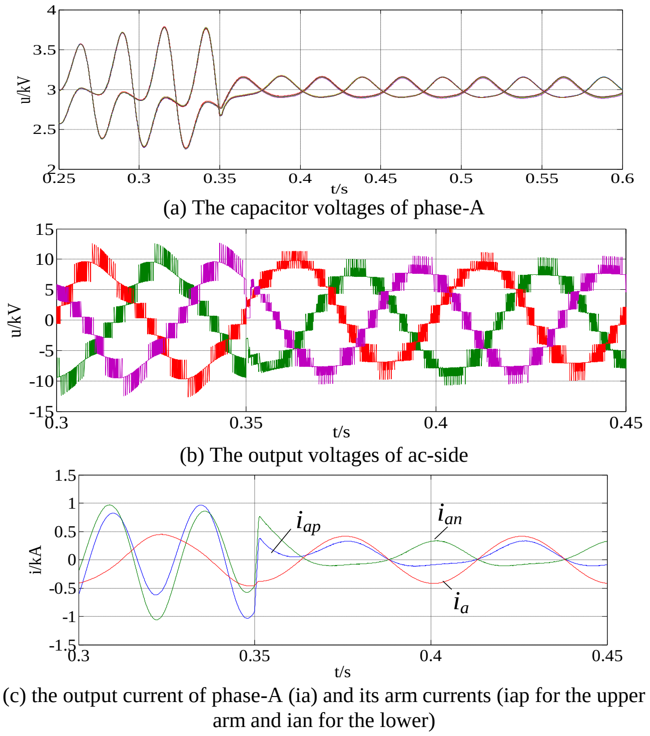
TABLE II: Specifications of the Squirrel Cage Induction Machine

Rated line-to-line rms voltage	10kV
Rated line-to-line rms current	0.5kA
Rated frequency	30Hz

A. Effectiveness of Capacitor Voltage Balancing Control

The MMC ac-side output frequency is set as 20Hz. A 5MVA *R-L* load is used as steady state approximation of a motor, the power factor of which is set as 0.8. The capacitor voltage balancing control strategy is applied at 0.35s. The simulation results are shown in Fig. 5.

Fig. 5 demonstrates the change of capacitor voltage, ac-side output voltage and arm current of before and after the control strategy is applied. As shown in Fig. 5, after the control strategy is applied, the fluctuation of module decreases obviously, from 23% down to 7%, and the ac-side harmonic voltages of MMC are reduced effectively. Because of current inner loop of energy-averaging control, the circulating current between the upper and lower arms decreases, which contributes to reducing losses.



(a) The capacitor voltages of phase-A

(b) The output voltages of ac-side

(c) the output current of phase-A (ia) and its arm currents (iap for the upper arm and ian for the lower)

Fig. 5. The effectiveness of capacitor voltage balancing control

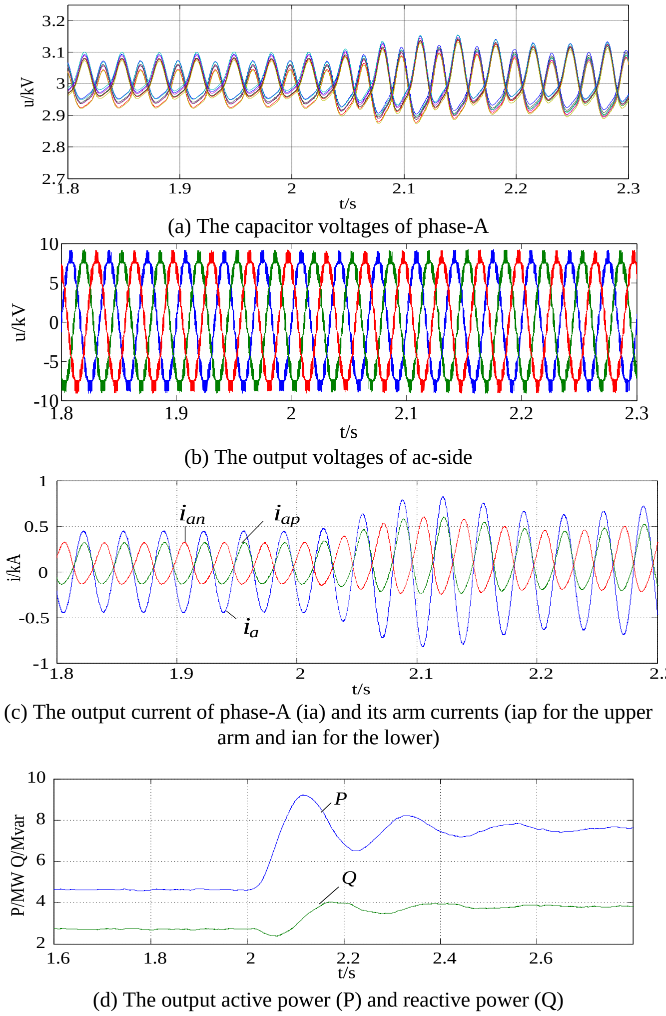
B. Performance Under Dynamic State

The MMC ac-side output frequency is set as 30Hz. A squirrel cage induction machine model is used as a motor, the specifications of which are summarized in Table II. The capacitor voltage balancing control strategy is applied the whole time. The load torque is set as 0.4pu and the system has reached steady-state before 2s, when it increases to 0.6pu. The simulation results are shown in Fig. 6.

As shown in Fig. 6, after the load torque increases, the capacitor voltage doesn't lose its balance. Because of the increase of output power, the ac-side currents and arm currents increase and the fluctuations of capacitor voltages increase to 4%, still in the allowable range. The capacitor voltage balancing control possesses good performance under dynamic state.

C. Performance when a Fault Occurs at Dc-Side

The MMC ac-side output frequency is set as 30Hz and a squirrel cage induction machine model is used as a motor. The capacitor voltage balancing control strategy is applied and the load torque is set as 0.8pu the whole time. The steady-state has been reached before 1s, when the MMC dc-side voltage reference decreases to 18kV from 21kV. The simulation results are shown in Fig. 7.



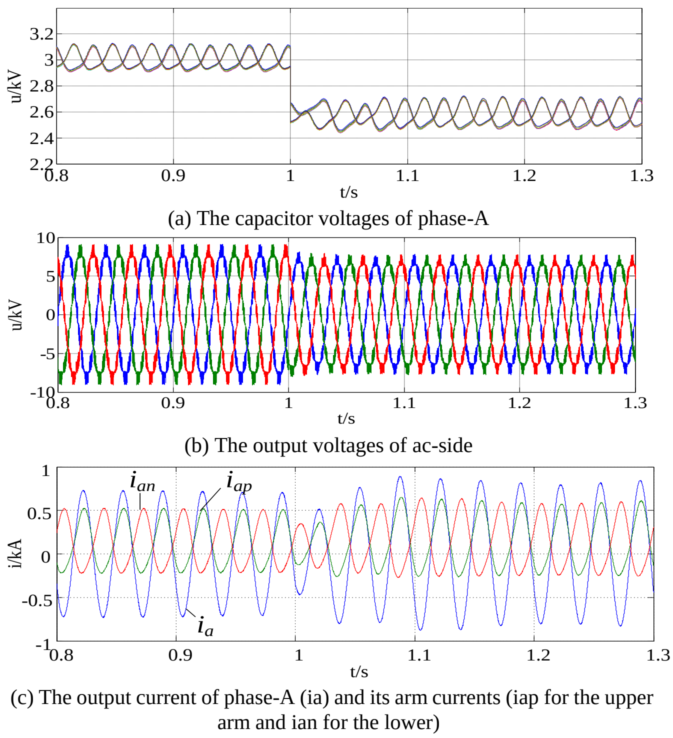
(a) The capacitor voltages of phase-A

(b) The output voltages of ac-side

(c) The output current of phase-A (ia) and its arm currents (iap for the upper arm and ian for the lower)

(d) The output active power (P) and reactive power (Q)

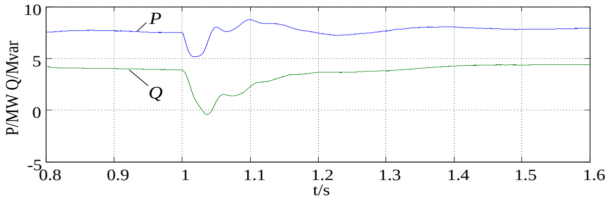
Fig. 6. Performance under dynamic state



(a) The capacitor voltages of phase-A

(b) The output voltages of ac-side

(c) The output current of phase-A (ia) and its arm currents (iap for the upper arm and ian for the lower)



(d) The output active power (P) and reactive power (Q)

Fig. 7. Performance when a fault occurs at dc-side

As shown in Fig. 7, because of the capacitor voltage balancing control, the capacitor voltage keeps its balance and reaches its new steady-state immediately after the dc voltage reference decreases, with the fluctuations about 5%. The control strategy contributes to keeping capacitor voltage balanced when a fault occurs at the dc-side of MMC.

VI. Conclusion

Through theoretically analyzing the imbalance of capacitor voltage, the relation between the voltage fluctuation, ac-side current, frequency and the capacitance is obtained.

To enhance the performance of MMC in low frequency condition, a voltage balancing control strategy based on CPS-SPWM is proposed in this paper. The control strategy combines energy-averaging control and individual-balancing control and it can maintain capacitor voltage balance at low switching frequency.

The simulation of a high-voltage motor drive system with an 8-level MMC as the inverter on the platform of PSCAD/EMTDC was carried out. The simulation results demonstrate that the capacitor voltage balancing control is effective in low frequency condition and possesses good performance under dynamic state.

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