Carrier phase shift modulation and voltage equalization control strategy in modular multilevel converter

Xu Zhiqi¹, Ai Xiancang¹

¹State grid gansu construction company (supervision company), lanzhou 730070, China
719011448@qq.com

Abstract. In order to solve the problem of voltage fluctuation of sub-module capacitors in Modular Multilevel Converter, based on carrier phase-shifted sinusoidal pulse width modulations, this paper analyzes the effect of different carrier phase shift modulation and the number of sub-modules on a single bridge arm on the number of output levels and uses proportional control to make capacitor voltage balance and PI control to suppress bridge arm circulation. The method has a good stability effect on the sub-module capacitor voltage. A 31-level model is built in MATLAB/simulink to analyze the capacitor voltage fluctuation, output current and voltage distortion rate, and bridge arm current of the sub-module. The voltage and circulation fluctuation range is compared when there is no circulation suppression. It is verified that the method is simple and effective.

1. Introduction
With the utilization and development of new energy sources such as offshore wind power, the problem of long-distance large-capacity power transmission needs to be solved urgently. The Modular Multilevel Converter (MMC) has a modular structure. By connecting submodules in series, the voltage level and voltage output quality can be improved, the requirements for the AC-side filter can be reduced, and even no filter is required. This is very suitable for solving the problem of long-distance large-capacity power transmission. Recently, many scholars have done a lot of research on topologies [1], modulation methods [2-4], circulating current suppression [5], MMC combined with energy storage systems [6], voltage equalization, and sequencing algorithms. Since the capacitor voltage fluctuation of the sub-module directly affects the output voltage and current quality of the MMC, the balanced voltage control of the capacitor voltage of the MMC sub-module is extremely important.

Reference [7] proposed distributed voltage equalization control. The capacitor charge and discharge time was adjusted by fine-tuning the pulse delay to achieve voltage equalization. Literature [8] proposed an adaptive voltage equalization method, which used a closed-loop control of the number of sub-module inputs to make a trade-off between switching losses and voltage balance effects. The literature [9] analyzed the root cause of the doubling frequency circulating current when using the nearest level approximation modulation, and proposed a superposition approximation modulation strategy, which can effectively suppress the circulating current, but this method is not suitable for the case of a small number of sub-modules. Reference [10] proposed space vector pulse width modulation technology, eliminating external controllers for bridge arm voltage balancing, which can independently control the three-phase upper and lower bridge arms, using redundant switching vectors to achieve capacitor voltage balance. However, the calculation load of the space vector modulator is...
increased. At the same time, the modulation method becomes extremely complicated with the increase of the number of sub-modules, and is not suitable for a case with a large number of sub-modules.

Many voltage equalization methods are based on the nearest level approximation modulation, which needs to be combined with a sorting algorithm to complete the voltage equalization [11]. However, this type of voltage equalization control will continuously change the sequencing result even under a small voltage deviation, resulting in unnecessary repeated switching of the IGBT, which causes the switching frequency to be too high and the switching loss to increase. Large performance errors make it difficult to achieve circulating current suppression. The voltage equalization control method in this paper is based on carrier phase-shift modulation, which not only has a small switching frequency and good voltage stabilization effect, but also has good modulation wave tracking performance and can be combined with various circulating current suppression methods. In this paper, the proportional control sub-module capacitor voltage is used, and additional circulating current suppression is added. From the aspects of voltage, current distortion rate, and capacitance fluctuation, the situation with and without circulating current suppression and its influencing factors are compared and analyzed. Compared with the voltage sequencing algorithm and common voltage balancing, The method is simpler and more practical.

2. MMC topology
The topology of the modular multilevel converter is shown in Figure 1. It consists of six bridge-arms with \( n \) sub-modules and one inductor each arm. Each sub-module has the same structure and consists of two IGBTs and one capacitor. When \( T_1 \) or \( D_1 \) is turned on, it outputs the voltage \( U_c \) across the output capacitor; when \( T_2 \) or \( D_2 \) is turned on, it outputs 0. The upper and lower IGBT signals are opposite. The inductance each bridge arm has a certain circulation suppression effect.

![Circuit topology of modular multilevel converter](image)

Figure 1. Circuit topology of modular multilevel converter

3. Control Method
A pulse signal of the \( T_1 \) tube is generated by comparing \( n \) sets of bipolar triangular carriers with a phase shift of \( 2\pi/n \) and a three-phase sinusoidal modulation signal, which are inverted and sent to the \( T_2 \) tube. The sub-modules at the corresponding positions of the upper and lower bridge arms have the same carrier wave, and the modulation waves of the upper and lower bridge arms are inverted. Taking 15 sub-modules of a single bridge arm and a triangular carrier period of 0.003s as an example, the angle of each group of triangular carriers to be staggered is 24º, that is, the delay interval is 0.0002s.
As shown in Figure 2, a deviation is generated by comparing the actual value $U_c$ of the capacitor voltage with the reference value $U_c^*$, and the proportional signal is combined with the current direction of the bridge arm to output a control signal $U_{c,a1}$, which is finally superimposed on the modulation wave. Among them, the bridge arm current direction judgment link, if it is an upper bridge arm sub-module, only needs to determine the $I_{up}$ condition of the corresponding phase; if it is a lower bridge arm sub-module, it determines the $I_{down}$ condition of the corresponding phase. Take the upper arm of phase a as an example. If $I_{up,a} > 0$, output +1; if $I_{up,a} < 0$, output -1.

The voltage balance adjustment amount is

$$U_{c,a1} = \begin{cases} k(U_c^* - U_c), & (I_{up} > 0 \lor I_{down} > 0) \\ -k(U_c^* - U_c), & (I_{up} < 0 \lor I_{down} < 0) \end{cases}$$

(1)

Figure 2. voltage balance control block diagram

When the bridge arm current is positive, the actual capacitor voltage $U_c$ is lower than the set value $U_c^*$. The larger the deviation, the larger the adjustment amount, the longer the capacitor charging time, and the higher the voltage. The larger the adjustment, the smaller the capacitor charging time and the slower the voltage rise. The same can be used to analyze other situations.

As shown in Figure 4, the comparison of the average voltage $U_{c,av}$ of all capacitors on a single bridge arm with the voltage reference $U_{c,av}^*$ produces a difference, which generates the circulating current command value $I_{loop,a}^*$ through the PI controller, and then compares the measured circulating current value Finally, the PI controller generates a circulating current suppression control amount $U_{c,a2}$.

Figure 3. Circulation suppression control block diagram

The modulation wave of a single sub-module of the upper arm is

$$u_{e,up} = U_{up} \frac{U_c^* - U_c}{n} + U_{c,a1} + U_{c,a2}$$

(2)

The modulation wave of a single sub-module of the lower arm is

$$u_{e,up} = U_{up} \frac{U_c^* - U_c}{n} + U_{c,a1} + U_{c,a2}$$

(3)

Among them, $U_c^*$ is a three-phase sinusoidal modulation signal

4. Simulation and analysis
A 31-level MMC model was built in MATLAB / simulink to verify the effect of voltage equalization control using carrier phase shift. The simulation parameters are as follows: DC power supply $U_d/2$ is 1500 V, load resistance $R$ is 22 Ω, load inductance $L$ is 10 mH, bridge arm inductance $L_s$ is 3 mH, sub-module capacitance is 3 mF, and sub-module voltage rating is 200 V.

Figure 4 shows the output voltage and current of phase a when carrier phase shifting is used. The phase-a voltage is stable output 1500 V, and its distortion rate is 5.56% close to 5%. The current
distortion rate is 2.77% <5%. Therefore, the AC output characteristics using carrier phase shifting are good.

Figure 5 shows the sub-module voltage equalization effect with or without circulating current suppression comparison. When there is no circulating current suppression, the capacitor voltage of the sub-module can be stabilized around 200 V, but the fluctuation range is ±15%. After adding circulating current suppression, the voltage balance of the sub-module is more stable, its voltage fluctuation is ± 6% of the reference value, and the voltage waveform is more regular. This is the result of the combined effect of voltage balance and circulating current suppression. Compared with the case where the voltage balance control works alone, the voltage fluctuation after the circulation current suppression is reduced by about 9%.

Figure 6 shows the a-phase double-frequency circulating current with and without circulating current suppression. When there is no circulating current suppression, the doubling frequency circulating current fluctuation range is -60~100A. When circulating current is suppressed, the doubling frequency circulating current fluctuation range is -10~40A. The comparison shows that the circulation suppression waveform becomes more regular and the fluctuation range is reduced. Therefore, the circulation suppression method has a certain suppression effect.

5. Conclusion
In the field of medium and low voltage DC transmission, because the number of sub-modules generally does not exceed 30, carrier phase shift is also a common method in engineering. This paper analyzes in detail the voltage equalization control, circulating current suppression and switching loss under the carrier phase shift method, and draws the following conclusions:
(1) The carrier phase-shifted voltage equalization control used in this paper has a good voltage stabilization effect, low distortion rate of output voltage and current, and has a certain suppression effect on double frequency circulation.

(2) The voltage equalization control signal must not only keep the voltage stable, but also make the control signal small so as not to cause serious distortion of the sinusoidal modulation wave, thereby reducing the voltage and current distortion rates.

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