Improved voltage equalization control strategy in modular multilevel converter

Jin Hongtao, Luo Yinghong, Pan Shengxiong, Fan Yuheng

(School of Automation and Electrical Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China)

719011448@qq.com

Abstract. In order to solve the problem of traditional carrier phase-shift modulation with multiple ratios or PI controllers and cumbersome tuning parameters, this paper proposes an improved carrier phase-shift method. The control signal is no longer generated by a large number of proportional or PI controllers, but rather by the number of turn-on sub-modules and sorting principles. However, because the method uses a sorting method, the IGBT switching frequency is too high. Therefore, a sorting trigger condition that can effectively reduce the switching frequency is proposed, and the lower switching frequency is realized by reducing the times of sorting. At the same time, the method has better modulation wave following characteristics, and it is easy to achieve the suppression of the circulation. For the circulation problem, the second-frequency negative sequence component is extracted by rotating coordinate transformation, and it is suppressed by PI control. A 21-level MMC model was built in MATLAB / simulink to analyze the sub-module capacitor voltage fluctuation, output current, voltage distortion rate and bridge-arm circulation. It is verified that the modulation method can combine sorting algorithm and circulation suppression method at the same time, and has better voltage equalization and circulation suppression effects.

1. Introduction
Modular Multilevel Converter (MMC) has a modular structure. The sub-module series can increase the voltage level and voltage output quality, reduce the requirements on the AC side filter, and even achieve no filter. MMC is widely used in medium and high voltage power conversion sites [1], offshore wind farm grid-connected, hybrid flexible DC transmission systems and two-terminal, multi-terminal flexible DC transmission systems [2, 3]. Once proposed, many scholars have done a lot of researches on topological structure, modulation [4, 5], circulation suppression [6, 7], voltage equalization [8], and sorting algorithm. Since the sub-module capacitor voltage fluctuation directly affects the MMC output voltage, current quality, and the overcharge and overdischarge of the capacitor affects the capacitor life, the MMC sub-module capacitor voltage equalization control is extremely important.

In [9], the root cause of the double-frequency circulation when using the nearest level modulation is analyzed. The proposed voltage actual value approximation modulation strategy can effectively suppress the circulation, but this method is not suitable for the case of a small number of sub-modules. In [10], the frequency division and equalization control is proposed, so that the sorting frequency is much smaller than the control frequency, and the sorting frequency calculation process is derived, which can reduce the switching frequency and the computational burden. Literature [11] analyzes the necessary and sufficient conditions for the stability of the MMC system under open-loop control, and
achieves voltage equalization by detecting the voltage of each bridge arm and injecting zero-sequence voltage. In [12], a new step-wave modulation method is proposed, which eliminates the need to measure the sub-module capacitance voltage and feedback control, so that the sub-module switch operates at the fundamental frequency and has a lower power loss. Literature [13] proposed a voltage equalization method based on carrier phase shifting, which has a certain weakening effect on the circulation, but the circulation suppression effect is not well and the system cost is large because of the number of controllers is large.

Traditional carrier phase-shift modulation has a large number of proportional or PI controllers and cumbersome parameter adjustment processes, and the system cost is high. The modulation wave following ability of the nearest level modulation is poor when the number of levels is small, so that few circulation suppression methods can be combined with it. In this paper, an improved carrier phase-shift method is proposed, which does not require a large number of proportional or PI controllers, avoids the tedious parameter tuning process, and preserves the modulated wave following characteristics of carrier phase-shift, which is easy to achieve circulation suppression. However, this method makes the switching frequency higher due to the introduction of the sorting method. Therefore, a sorting trigger condition is proposed to reduce unnecessary sorting and achieve a lower switching frequency. In this paper, the principle of voltage equalization for improving carrier phase-shift is introduced in detail. The sequencing trigger condition is introduced to reduce the switching frequency. At the same time, the main component of the circulation is analyzed as the second-frequency negative-sequence property, which is suppressed by PI control and rotating coordinate transformation. Finally, a 21-level MMC model was built in MATLAB/simulink for verification.

2. MMC topology and basic principles
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 T1 or D1 is turned on, it outputs the voltage $U_c$ across the output capacitor; when T2 or D2 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.

3. Improved carrier phase-shift modulation and voltage equalization
The advantage of the improved carrier phase shift modulation method is that it does not require a large number of ratios or PI controllers, and because of its carrier phase-shift characteristics, its modulation wave tracking performance is better, and it can be freely combined with various circulation suppression methods.
Figure 2 is a flow chart of voltage equalization control with improved carrier phase-shift modulation. Pulse width control signal is generated by comparing \( n \) sets of phase-shifted \( 2\pi/n \) bipolar triangular carriers with a three-phase sinusoidal modulated signal, and \( n \) sets of pulse width control signals are added to obtain the number of a total turn-on sub-module each bridge-arm at a certain time. The number is \( n_{on} \). The sub-module carrier signals of the upper and lower bridge-arms are the same, and the upper and lower bridge-arm modulation waves are inverted. Taking 20 sub-modules of a single bridge-arm and a triangular carrier period of 5ms as an example, the angle at which each group of triangular carriers is staggered is 18º, that is, the delay interval is 0.25ms.

![Flow chart of voltage equalization control](image)

Among them, the average deviation limit judgment link has the effect of reducing the switching frequency of the sub-module. The method compares the voltage average with the actual value and sets an error tolerance range. If the limit is exceeded, the enable pulse lead in reordering, otherwise the original IGBT signal is maintained. This method can make the sub-modules that have been turned on preferentially turn on, reduce the number of times of reordering and the switching frequency. The judgment condition is as shown in equation (1), \( U_{ci} \) is the sub-module capacitor voltage, \( U_{avg} \) is the average value of the capacitor voltage each bridge-arm, and \( i \) is the capacitance label each bridge-arm, and the value is 1, ..., \( n \), \( c \) is the set allowable error range.

\[
\max \left\{ \left| U_{ci} - U_{avg} \right| \right\} > c
\]  

The difference between the actual value of the sub-module voltage and the average value is judged whether the limit is exceeded and whether the number of the turn-on sub-modules is changed. If one of the two conditions is satisfied, the sub-module capacitor voltage is reordered by the sorting algorithm. Finally, a control signal is generated according to the voltage sorting result and the current polarity, and the pulse signal is sent to the \( T_1 \) tube and the pulse signal of the \( T_2 \) tube is inverted. The voltage equalization process is analyzed by taking the a-phase upper arm as an example. \( I_{up,a} \) is the a-phase upper arm current. If \( I_{up,a} > 0 \), the sub-modules of the bridge-arm are in a charging state, and the \( n_{on} \) sub-modules with low voltage after the sorting are turned on. If \( I_{up,a} < 0 \), the sub-modules of the bridge-arm are in a discharging state, and the \( n_{on} \) sub-modules with high voltage after the sorting are turned...
on. The core idea of the voltage equalization method is to preferentially discharge the sub-module with high voltage, and the sub-module with low voltage is preferentially charged.

4. Circulation analysis and suppression method

The voltage equalization control stabilizes the capacitor voltage of each sub-module near the rated value, but there is a slight voltage fluctuation. This causes the sum of the voltages of the upper and lower arms of the phases to be inconsistent with each other, resulting in an internal circulation of the MMC, which flows only in the three-phase bridge arms, and has no effect on the external AC system. However, the double-frequency negative-sequence circulation occupies the capacity of the bridge-arm components and causes system losses.

The circulating components mainly have a direct current component and a double-frequency negative-sequence component. The internal current $I_{\text{loop,j}}$ ($j=a, b, c$) of the three phases $a, b, c$ is as shown in the formula (2). $I_{dc}$ is a DC current, $I_{2f}$ is a double-frequency circulation peak, $\omega_0$ is the fundamental angular frequency, and $\phi_0$ is the initial phase angle.

$$
\begin{align*}
I_{\text{loop,a}} &= \frac{I}{3} + I_{2f} \sin(2\omega_0 t + \phi_0) \\
I_{\text{loop,b}} &= \frac{I}{3} + I_{2f} \sin(2\omega_0 t + \phi_0 + \frac{2\pi}{3}) \\
I_{\text{loop,c}} &= \frac{I}{3} + I_{2f} \sin(2\omega_0 t + \phi_0 - \frac{2\pi}{3})
\end{align*}
$$

The double-frequency negative-sequence circulation is decomposed into two DC quantities by using a rotating coordinate transformation. Circulation suppression structure diagram is shown in Figure 3. $I_{\text{up,j}}$ and $I_{\text{down,j}}$ are the a-phase upper arm current and the lower arm current respectively. The $dq$ component is obtained by the double-frequency negative-sequence rotation coordinate transformation. After comparing with the $dq$ current command value, the $dq$ reference values $u_{\text{diffd_ref}}$ and $u_{\text{diffq_ref}}$ of unbalanced voltage-drop are obtained by the PI and then introducing the feedforward signal, the upper and lower arm voltage reference values $U_{\text{up_jref}}$ and $U_{\text{down_jref}}$ are finally output, and the trigger pulse is generated by using the improved carrier phase-shift modulation to control the turn-on and turn-off of each sub-module.

![Figure 3. Circulation suppression structure](image)

![Figure 4. MMC overall control charts](image)

5. Simulation and results

A 21-level MMC model was built in MATLAB/simulink to verify the voltage equalization and circulation suppression effects with improved carrier phase-shift modulation. The DC power supply $U_{dc}$ is 20kV, the load resistance $R_L$ is 22Ω, the load inductance $L_L$ is 10mH, the bridge arm inductance $L_s$ is 4mH, the bridge-arm resistance is 0.1Ω, the sub-module capacitance is 13mF, and the sub-module voltage rating is 2kV, the circulation suppression controller has a scale factor of 4 and an integral coefficient of 2000.
Set the sub-module capacitor initial voltage value to 2kV. Before 0.3s, only voltage equalization control is performed. After 0.3s, circulation suppression is added. The capacitor voltage of all sub-modules on the a-phase upper arm is shown in Figure 5. When the voltage is equalized, the stable voltage fluctuation is ±60V, which is ±3% of the voltage rating. After the addition of the circulation suppression, the voltage fluctuation is ±40V, which is ±2% of the voltage rating. The comparison shows that after the addition of the circulation suppression, the voltage fluctuation is further reduced and the voltage equalization effect is better. The interaction between voltage equalization and circulation suppression was verified.

Figure 5. Capacitor voltage of sub-modules

Figure 6. A-phase circulation

The d, q axis current command value is set to 0, and the circulation suppression is added after 0.3s. After 0.3 s, the d and q current quickly stabilized around zero. The a-phase circulation waveform and the harmonic analysis are respectively shown in Figure 6 and Figure 7. Before 0.3s, the DC component of the circulation is 220.2A, and the second harmonic component is 84.77%. After the circulation is suppressed, the DC component of the circulation is 221.7A, and the second harmonic component is 4.71%. The comparison shows that the second harmonic is changed from 84.77% to 4.71%, which is 80.06% lower. It is verified that the circulation suppression method has a good effect.

The a-phase AC output voltage and current are shown in Figure 8. After the circulation is suppressed, the voltage distortion rate decreases from 4.29% to 3.73%, and the current distortion rate decreases from 1.52% to 1.23%, which satisfy the condition that the distortion rate is less than 5%. Therefore, it has better AC output characteristics.

The switching frequency of the IGBT is measured by triggering the cumulative counting of the rising edge pulse of the IGBT control signal. The IGBT control signals before and after reducing switching frequency are shown in Figure 9. Before the addition of the reducing frequency control, the average switching frequency of the IGBT in the sub-module is measured to be 3553Hz. After adding frequency control, the switching frequency is 614.1Hz, which is 82.7% lower. This verifies the effectiveness of this method in reducing the switching frequency.

Figure 7. Circulation harmonic analysis

Figure 8. A-phase AC output

Figure 9. IGBT control signal
6. Conclusions
In this paper, the improved carrier phase-shift modulation is used, which does not require a large number of proportional or PI controllers, and there is no complicated parameter tuning process. It’s suitable for medium and low voltage flexible DC transmission systems. The method can combine the sorting algorithm and the PI circulation suppression method at the same time, because of its better modulation wave following characteristics. The principle and method of voltage equalization and circulation suppression in this modulation are analyzed. The good effectiveness of voltage equalization and circulation suppression effects and the mutual influence between them are verified. The proposed reordering trigger condition can avoid unnecessary repeated switching of the IGBT and effectively reduce the IGBT switching frequency.

References
[1] Xu Yijia, Luo Yinghong and Shi Tongtong. A new MMC sub-modules with DC fault self-clearing ability and its hybrid topology. Power system protection and control, 2018, vol. 46, no. 7, pp. 129-37.
[2] Guan Minyuan, Xu Zheng and Tu Qingrui. Modulation strategy of modular multilevel converter type DC transmission. Automation of Electric Power Systems, 2010, vol. 34, no. 2, pp. 48-52.
[3] Li Guoqing, Wang Weru and Xin Yechun. Modular multilevel converter submodule packet sequencing modulation strategy. High voltage technology, 2018, vol. 44, no. 7, pp. 2107-14.
[4] Wang Tiezhu, Bu Guangquan and Wang Wei. An improved modulation strategy for improving the robustness of MMC AC voltage. Grid Technology, 2018, vol. 42, no. 3, pp. 797-803.
[5] Yang Xiaofeng, Lin Zhiqin and Zhou Chuyi. Overview of the loop suppression technology of modular multilevel converter MMC. Journal of Power Supply, 2015, vol. 13, no.6, pp. 58-68.
[6] Li Shanying, Wu Tao and Ren Bin. Overview of energy storage systems based on modular multilevel converter. Power System Protection and Control, 2015, vol. 43, no. 16, pp. 139-46.
[7] Li Jianguo, Yang Wenbo and Song Qiang. Distributed equalization control method for modular multilevel converter capacitor voltage. Automation of Electric Power Systems, 2016, vol. 40, no. 17, pp. 197-203.
[8] Su Shiping, Wei Xinwei and Niu Ding. Modular multilevel converter capacitor voltage improved sorting balance method. Chinese Journal of Electrical Engineering, 2017, vol. 37, no. 13, pp. 3874-82.
[9] Zhang Jing, Hao Liangliang and Huang Yinhua. Circulating Harmonic Suppressing Strategy for MMC Based on Superimposed Approach Modulation. Power System Technology, 2017, vol. 41, no. 11, pp. 3539-46.
[10] Hao Liangliang, Zhang Jing and Huang YinhuaXin. Frequency dividing control of capacitor voltage balance for modular multilevel converter. Electric power automation Equipment, 2018, vol. 38, no. 6, pp. 195-223.
[11] Xia Chaoying and Yu Jiali. The Asymptotic Stability and Capacitor Voltage Balancing Control Strategy for MMC. Proceedings of the CSEE, 2018, vol. 38, no. 19, pp. 5812-21.
[12] Ni Shuangwu, Su Jianhu and Zhou Songlin. MMC capacitance voltage balance strange based on fundamental switching frequency. Acta Energiae Solaris Sinica , 2018, vol. 38, no. 2, pp. 293-301.
[13] Ma Shang and Wang Yi. Research on Capacitor Voltage Balancing Control Strategy of Modular Multilevel Converter. Modern electricity, 2015, vol. 34, no. 2, pp. 55-60.