Research of Modulation and Control Strategy of Modular Multilevel Inverter

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Abstract: As a new multilevel converter structure, modular multilevel converter (MMC) has many outstanding advantages, such as high degree of modularization and easy cascade expansion, which greatly promotes the development and application of flexible DC transmission technology. In this paper, the modular multilevel inverter is the main research object, its topology and multilevel generation mechanism are analysed, and the capacitor voltage of sub modules is balanced based on the carrier phase shifted PWM strategy. The MMC simulation model is built on the MATLAB/Simulink software platform. According to the simulation results, the feasibility of the modulation and control strategy in reducing the harmonic component of output voltage and maintaining the stability of capacitor voltage is verified.

1. Introduction
In recent years, in the face of the enormous pressure brought by the energy crisis, financial crisis and climate crisis to human society, the new energy with the characteristics of environmental protection and renewable energy has attracted worldwide attention. The new energy has developed unconventionally in the global scope, the investment of various countries in new energy has increased significantly, and the green industry and life modes have been continuously advocated [1].

High power converter plays a key role in the process of transforming the original energy generated by renewable energy into power grid. In order to meet the requirements of high efficiency, high reliability, long life and low cost, classic converters such as DC/AC converter and DC/DC converter are constantly improved or replaced by new topologies. In 2001, R. Marquart and A. Lesnicar in Universität der Bundeswehr München jointly proposed the modular multilevel converter (MMC) topology [2], which greatly promoted the development and application of flexible DC transmission technology.

Considering the practical application of high voltage and high power, the modulation mode of modular multilevel converter is widely studied. [3] used the direct modulation method based on capacitor voltage sequence to modulate the three-phase MMC inverter. [4] concluded that the two schemes are suitable for the modular multilevel inverter in this paper, by comparing the low frequency modulation scheme with the sinusoidal pulse width modulation scheme. [5] described a modified phase-shifted carrier-based pulselength-modulation (PSC-PWM) scheme. [6] compared and analysed three modulation modes, carrier stacked PWM, nearest level modulation and carrier phase shifted PWM, and concluded that carrier phase shifted PWM has the advantages of fixed switching frequency and low loss. In this paper, the carrier phase shifted PWM strategy is adopted, and the capacitor voltage of sub module is balanced according to the relevant theory in [7].
2. Topology and principle analysis of MMC inverter

2.1. Topology of MMC inverter
The basic topology of three-phase MMC is shown in Figure 1. Each phase unit is composed of upper and lower bridge arms, and each bridge arm contains several sub module units and one bridge arm reactor. In the figure, point \( O \) is the zero potential reference point, \( Cell \) is the half bridge sub module unit, \( L_0 \) and \( L_1 \) are the bridge arm reactors, \( U_{dc} \) is the DC bus voltage, \( U_{va}, U_{vb} \) and \( U_{vc} \) are the three-phase output voltage at the AC side, and the lower corner marks \( p \) and \( n \) represent the upper arm and the lower arm respectively.

MMC can realize the expansion of different levels and voltage levels through series connection of sub modules on bridge arms, which can better improve the efficiency of expansion and development in engineering design. Generally, there are two kinds of topology of MMC sub modules, the first is half bridge structure, and the second is full bridge structure, as shown in Figure 2 and 3. Compared with the full bridge structure, the half bridge structure contains fewer switching devices, and the structure is simpler. In practical applications, only one switching device is in the on state. In this paper, half bridge sub module is used to build three-phase MMC model.

The different on-off state of the switch devices and the different current direction of the half bridge sub module will make the sub module in different working modes. See Table 1 for details.
Table 1. Three working states and six working modes of sub module

| State         | Mode | VT₁ | VT₂ | VD₁ | VD₂ | Current direction | Port voltage | Capacitor state |
|---------------|------|-----|-----|-----|-----|-------------------|--------------|-----------------|
| Locking       | 1    | 0   | 0   | 1   | 0   | A→B              | U_c          | Charging        |
| switching on  | 2    | 0   | 0   | 1   | 0   | A→B              | U_c          | Charging        |
| switching off | 3    | 0   | 1   | 0   | 0   | A→B              | 0            | Bypassing       |
| Locking       | 4    | 0   | 0   | 0   | 1   | B→A              | U_c          | Bypassing       |
| switching on  | 5    | 1   | 0   | 0   | 0   | B→A              | U_c          | Discharging     |
| switching off | 6    | 0   | 0   | 0   | 1   | B→A              | 0            | Bypassing       |

Where "0" represents that the power switch is in the off state, "1" represents the on state, and $U_c$ is the capacitor voltage. It can be seen from the table that whether the capacitor $C$ is connected to the bridge arm can be controlled by the switching on and switching off states of the sub module, which is also the basis of MMC multilevel generation mechanism.

2.2. Working principle of three-phase MMC

It can be seen from the topological structure of the three-phase modular multilevel inverter in Figure 1 that the voltage at the DC side is directly applied to the three-phase bridge arms of MMC. In order to keep the three phases stable, the number of sub modules of any phase that needed to be put into operation at the same time is the same and remains unchanged.

$$u_{p_u} + u_{n_u} = u_{p_b} + u_{n_b} = u_{p_c} + u_{n_c} = U_{dc}$$

(1)

The number of output levels of MMC bridge arm is $N+1$ ($N$ is the number of sub modules of a single bridge arm), and each phase unit of MMC should meet the following requirement at any time:

$$n_{pj} + n_{nj} = N$$

(2)

$n_{pj}$ and $n_{nj}$ represent the number of sub modules required for upper and lower bridge arms of a certain phase respectively. If the MMC system works stably, the capacitor voltage of sub modules should fluctuate near the given value $U_c$. The relationship between the DC voltage value and the given capacitor voltage value of sub modules meets the following equation:

$$U_c = \frac{U_{dc}}{n_{pj} + n_{nj}} = \frac{U_{dc}}{N}$$

(3)

3. Modulation strategy of MMC

In cascaded multilevel inverter, the generation process of PWM control signal of carrier phase shifted pulse width modulation is as follows: the modulation waves signals given by the system is compared with $n$ carrier signals to generate $n$ groups of control signals. It should be noted that the frequency of $n$ carrier signals is the same, and the phase difference between two adjacent carriers is $2\pi / n$ ($n$ is the number of sub modules). In this paper, sine wave is used as modulation wave and triangle wave as carrier wave, namely carrier phase shifted sine pulse width modulation (CPS-SPWM).

For MMC system, different from other multilevel inverters, the upper and lower bridge arms of MMC contain $N$ sub modules, that is, each phase unit contains $2N$ sub modules, so the corresponding triangular carrier phase difference of each sub module is $\pi / N$ in the same phase unit. At the same time, the phase difference between the modulation waves of the lower arm and that of the upper arm is 180 degrees. The phase of b-phase and c-phase modulation wave and that of a-phase modulation wave are staggered by 120 degrees and 240 degrees respectively.

Carrier phase shifted modulation can make the switching frequency of the internal power device in the sub modules consistent with the carrier frequency, the equivalent switching frequency of AC output voltage increased to $2N$ times of carrier frequency. This means that the carrier phase shifted modulation can effectively improve the equivalent switching frequency, reduce the low order harmonics, improve the withstand voltage capability of power devices and enhance the dynamic response.
4. Capacitor voltage balance control method of sub module
DC bus voltage is supported by sub module capacitors in three-phase bridge arms. When the system is running, it is difficult to ensure that the DC voltage in each phase unit is equal. At this time, there will be circulating current between the bridge arms, which will affect the capacitor voltage balance. In this paper, the capacitor voltage balance control strategy is divided into two parts: energy average control and voltage balance control.

4.1. Energy average control
The control content of this part is to make the average value of the capacitor voltage of sub modules track its reference value through the cooperation of two PI regulators, and keep the circulating current value between the bridge arms in the expected range, so as to make the energy in the sub module evenly distributed. Taking phase a as an example, the control block diagram of energy average control is as follows:

\[
C_{av} = \frac{1}{8} \sum_{j=1}^{8} v_{ja}
\]

Where \(C_{av}\) is the average value of capacitor voltage and \(v_{ja}\) is the capacitor voltage of the j-th sub module.

There is a first-order inertia link between the bridge arm circulating current \(i_{za}\) and the sub module capacitor voltage \(v_{ja}\), so the voltage outer loop adopts PI regulator, and its output is the circulating current reference value \(i_{za}^*\). The specific relationship is as follows:

\[
i_{za}^* = K_1 (v_{Cref} - v_{Ca}) + K_2 \int (v_{Cref} - v_{Ca}) dt
\]

Where \(v_{Cref}\) is the reference value of capacitor voltage, \(K_1\) and \(K_2\) are the control proportion and integral constant of PI controller respectively (\(K_3\) and \(K_4\) are synonymous).

Since the circulating current exists in MMC and is not affected by external current, an independent current inner loop can be designed. In the inner current loop, PI regulator is used to control the actual value of circulating current to track the reference value, and the voltage command \(v_{av}^*\) is obtained. The expression is as follows:

\[
v_{av}^* = K_3 (i_{za} - i_{za}^*) + K_4 \int (i_{za} - i_{za}^*) dt
\]

4.2. Voltage balance control
The purpose of the control part is to make the capacitor voltage of several sub modules track its reference value. The control block diagram of phase a voltage balance control is shown in the following figure.
As shown in Figure 5, the controller in the voltage loop uses a proportional regulator, and its output $v_{iju}$ is the voltage command of the balance control. At the same time, the polarity of $v_{iju}$ needs to be adjusted according to the current direction of the upper and lower bridge arms. The specific expression is as follows:

$$
v_{iju}^* = \begin{cases} 
K_v (v_{Cref} - v_{Cju}), & i_{pu} \geq 0 \\
-K_v (v_{Cref} - v_{Cju}), & i_{pu} \leq 0
\end{cases} \quad (j = 1, 2, \ldots, 8) \tag{7}
$$

$$
v_{iju}^* = \begin{cases} 
K_v (v_{Cref} - v_{Cju}), & i_{su} \geq 0 \\
-K_v (v_{Cref} - v_{Cju}), & i_{su} \leq 0
\end{cases} \quad (j = 1, 2, \ldots, 8) \tag{8}
$$

4.3. Capacitor voltage balance control combined with CPS-SPWM modulation

According to energy average control and voltage balance control, two voltage commands of phase $a$ are obtained: $v_{iha}^*$ and $v_{iju}^*$, The two voltage commands are added and divided by half of the DC voltage to get the capacitor voltage balance control value $v_{iha}^*$.

As shown in Figure 6, the capacitor voltage balance control quantity is combined with the sinusoidal signal to generate the modulation wave $U_s$. $U_s$ is compared with $N$ triangular carriers with different phases to generate $N$ groups of PWM pulse control signals.

5. Simulation and analysis

In order to verify the effect of the above modulation and control strategy, a three-phase MMC inverter simulation model is built based on MATLAB / Simulink. Select $N=4$, and other simulation data are shown in Table 2.
Table 2. Simulation data of MMC inverter

| Parameter                        | Value |
|----------------------------------|-------|
| DC voltage (V)                   | 8000  |
| Carrier frequency (Hz)           | 750   |
| Rated frequency (Hz)             | 50    |
| Sub module capacitance (mF)      | 3     |
| Bridge arm inductance (mH)       | 5     |
| Initial voltage of capacitor (V) | 2000  |
| Load resistance (Ω)              | 50    |
| Load inductance (mH)             | 10    |

As shown in Figure 7, the output voltage waveform of upper bridge arm of phase a has five levels: $\pm 1/2$ and $\pm 1/4$ of $U_{dc}$ and 0 level, which conforms to 5-level MMC characteristics. Figure 8 shows the load voltage waveform of phase a. It can be seen from the figure that the output voltage waveform is stable and has 9 levels, and each level step value is 1000V. This is because in the process of PWM control signal formation, it is not guaranteed that the number of modules in the state of switching on is always 4 when carrier phase shifting, and the voltage will be divided on the inductance of the bridge arms. Figure 9 shows the FFT analysis of the 9-level output voltage. It can be seen that the equivalent switching frequency of the output voltage is increased to 6000Hz, and its harmonics mainly include harmonics near the equivalent switching frequency (60th) and some low-order harmonics.
Figure 10 (a) and (b) show the voltage waveforms of sub modules before and after adding the capacitor voltage control. It can be seen from figures that the fluctuation range is significantly reduced and the waveform is more regular after adding the capacitor voltage control, which verifies the effectiveness of the sub module capacitor voltage balance control strategy. Figure 11 (a) and (b) show the phase voltage and line current waveforms of MMC inverter respectively, and the waveforms are smooth and stable.

6. Conclusion
In this paper, modular multilevel inverter is taken as the main research object. Based on the topology and working modes of sub module, the working principle of MMC is analysed in detail. The modulation and control strategy of MMC system is designed by combining the principle of CPS-SPWM and capacitor voltage balance control of sub modules. Finally, the feasibility of the system is verified on the Simulink simulation platform.

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