Computer Simulation Research of MMC Control in DC Power Network Using RTDS

Yu Xu1, Zhe Liu2, Xiaofei Li3, Suo Lian1,4,*

1Inner Mongolia Electric Power Research Institute, Hohhot, China
2Inner Mongolia EHV Power Supply Bureau, Hohhot, China
3Hohhot Power Supply Bureau, Hohhot, China
4Inner Mongolia Key Laboratory of Electrical Power Conversion, Transmission and Control, Hohhot, China

*Corresponding author: suolian@imut.edu.cn

Abstract. With the development of DC power network, MMC has become an important AC/DC converter. MMC adopts the basic double closed-loop control composed of inner loop current control and outer loop power control. The modulation strategy adopts the nearest level approximation modulation and the capacitor voltage sequence method to ensure the capacitor voltage equalization of the sub-modules. The circulation suppression strategy can suppress the internal circulation of MMC. Finally, the simulation model of MMC was built based on RTDS, and the double closed-loop control strategy and circulation suppression strategy of MMC were verified.

Keywords: MMC, Nearest Level Modulation, Circulation suppression.

1. Introduction

As a hot spot of flexible direct current transmission, MMC adopts modular design, which is easy to adjust the DC voltage level or expand the capacity, and its output is multi-level, harmonic content is low, and the filtering link is reduced. In addition, active power and reactive power can be adjusted independently by outer loop control.

The research of MMC mainly focuses on the coordination of control strategy, topology innovation, circulation suppression, etc. Reference [1] proposed a new large-scale photovoltaic (pv) grid system structure based on MMC, the photovoltaic array, DC-DC converter and MMC of sub modules are combined into one unit, can not only improve the utilization efficiency of photovoltaic solar array, and photovoltaic inverter can meet the requirements of large capacity, high voltage grade and is convenient to adjust capacity and voltage grade. Reference [2] verified the feasibility of using MMC design for a two-stage grid-connected photovoltaic inverter based on double closed-loop control. Aiming at the modulation and voltage equalization problems of MMC, a dynamic direct modulation method and a simplified sequence equalization strategy of sub-module capacitance voltage are proposed to improve the quality of grid-connected power. Reference [3] proposed a step mode MMC applied to photovoltaic grid-connected power generation system, and proposed a step control strategy and capacitor voltage balance control algorithm suitable for this topology. In the Reference [4], its circulation is proposed based on the double frequency injection combined with high frequency.
injection method through direct injection of double frequency lower bridge arm fundamental frequency power, effectively reduce the capacitance voltage fluctuations in the fundamental frequency effect, circulation is combined with high frequency and high frequency output voltage injection methods of fundamental frequency power to offset reduced bridge arm, realize further suppression of capacitance voltage fluctuation. Reference [5] shows that the circulation suppression strategy based on internal model control is more suitable for the steady state operation of the system, and the circulation suppression strategy based on quasi proportional resonance has the strongest anti-interference ability, and is more suitable for the DC voltage or power mutation of the system. In [6], it designed an adaptive circulation suppression controller based on fast global least square subspace rotation invariant (TLS-ESPRIT) and proportional integral-vector proportional integrator (PI-VPI). By changing the MMC modulation function, the bridge arm voltage can be adjusted to follow the DC bus voltage fluctuation, so as to realize the circulation suppression.

In this paper, the topological structure and mathematical model of MMC are analyzed, and a basic double closed loop control strategy is established, in which the outer loop control target can be switched. The modulation strategy of MMC is completed by the nearest level approach modulation, and the circulation suppression strategy of MMC is studied. Finally, the simulation model is built in RTDS.

2. MMC Topological Structure and Mathematical Model

The topological structure of MMC is shown in figure 1-(a) below. There are 6 bridge arms in the three-phase. The upper and lower corresponding bridge arms form a phase unit, and the same number of sub-modules (SM) are connected with each bridge arm through a reactor. Due to the modular design of the MMC, the number of modules can be adjusted according to the needs, which is one of the differences between the MMC and the general VSC. The number of series sub-modules will increase correspondingly when the voltage level is higher.

![Figure 1. Topological structure and equivalent circuit of MMC.](image)

At present, the more classical SM topology of MMC is generally divided into two types, full bridge and half bridge. Considering economy and low loss, the semi-bridge SM has advantages. The semi-bridge SM contains 2 IGBTs, 2 reverse diodes and 1 capacitor. $U_{SM}$ is the voltage at both ends of the outlet of SM, and a certain amount of $U_{SM}$ of SM jointly maintains the voltage stability of the DC bus. $I_{SM}$ is the current flowing into SM. Since SM adopts a cascade structure, $I_{SM}$ on the same bridge arm is the same. $U_C$ is the capacitance voltage.
According to the equivalent circuit figure 1- (b) of MMC, the three-phase dynamic differential equation on the AC side in the ABC coordinate system is:

\[
\begin{bmatrix}
  u_{sa} \\
  u_{sb} \\
  u_{sc}
\end{bmatrix} = L \frac{d}{dt} \begin{bmatrix}
  i_{sa} \\
  i_{sb} \\
  i_{sc}
\end{bmatrix} + R \begin{bmatrix}
  i_{sa} \\
  i_{sb} \\
  i_{sc}
\end{bmatrix} + \begin{bmatrix}
  u_{ca} \\
  u_{cb} \\
  u_{cc}
\end{bmatrix}
\]

(1)

Use PARK transform to change three-phase coordinate system into coordinate system:

\[
\begin{align*}
    L \frac{di_{sd}}{dt} &= u_{sd} - Ri_{sd} - u_{cd} - \omega L i_{sq} \\
    L \frac{di_{sq}}{dt} &= u_{sq} - Ri_{sq} - u_{cq} + \omega L i_{sd}
\end{align*}
\]

(2)

3. MMC control strategy

3.1. The basic double closed loop control strategy of MMC

The basic control strategy of MMC is double closed loop control, which is composed of inner loop current control and outer loop control based on PI link. This is shown in Figure 2.

![Figure 2. Block diagram of MMC control strategy](image)

![Figure 3. Schematic diagram of NLM](image)
The regulation of active power $P$ and DC voltage $U_{dc}$ is realized through control $i_{sd}$, and the regulation of reactive power $Q$ and AC voltage $U_s$ is realized through control $i_{sq}$. After the reference values $P_{ref}$, $U_{dcref}$, $Q_{ref}$, $U_{sref}$ are given, the two can be independently adjusted.

### 3.2. Modulation strategy for MMC

The inner loop current controller gives the expected output AC voltage waveform of the MMC, and the expected output AC voltage waveform is realized through the control of each bridge arm by the modulation strategy of the MMC, so the appropriate modulation strategy is a necessary condition to ensure the normal operation of the MMC. The commonly used Modulation strategy is Nearest Level Modulation (NLM).

The principle of NLM is shown in Figure 3, where $u_{ref}$ represents the approximate stepped sine wave obtained by modulation, and $u^{*}_{ref}$ represents the modulated wave. By controlling the switching of SM, the capacitor in SM is connected to the circuit. $U_{CAV}$ represents the average capacitance voltage. By controlling the amount of input SM, $u_{ref}$ can approach $u^{*}_{ref}$. The number of SM in input conduction state in the specific bridge arm is determined by $u^{*}_{ref}$. Through Equation (3), we can get $u_{ref}$

$$u_{ref} = \text{round}\left(\frac{u^{*}_{ref}}{U_{CAV}}\right) \cdot U_{CAV} \tag{3}$$

When the input quantity is determined, it is not easy to choose the specified module input quantity. NLM requires the capacitive voltage of each SM on the bridge arm to be in the same range, so the capacitive voltage balance control is adopted to select the modules that need to be invested. First, the capacitance voltages of $N$ sub-modules in the bridge arm are sorted according to their sizes. The modules in the lower order are put in priority when charging, and the modules in the first place are put in priority when discharging. By means of this kind of capacitor voltage sequencing method, the continuous balance control of the capacitor voltage of sub-modules can be maintained.

### 3.3. Circulation suppression of the MMC

Internally by the topology of the MMC, the three-phase unit and connection on the same DC bus, internal modules and MMC runtime capacitance voltage is in fluctuation condition, so the parallel unit of each phase of DC voltage is not strict, 3 phases in the cell can produce circulation, the circulation in the three-phase flow between the units, won’t appear in the inverter outside, that is, independent of external power supply or load. Circulation can cause distortion of bridge arm current, so it is necessary to adopt appropriate control strategy to suppress the circulation.

The phase $j(a,b,c)$ unbalance current of MMC is $i_{lij}$, which is usually composed of DC component $i_{lij,DC}$ and AC component $i_{lij,AC}$. The AC component is double frequency negative sequence current, while the DC component $i_{lij,DC}$ is equal to $\frac{I_{dc}}{3}$. $i_{lij}$ can be expressed as:

$$\begin{align*}
    i_{lia} &= \frac{I_{dc}}{3} + I_{2f \ sin} \left(2\omega_{s}t + \phi\right) \\
    i_{lib} &= \frac{I_{dc}}{3} + I_{2f \ sin} \left[2 \left(\omega_{s}t - \frac{2}{3}\pi\right) + \phi\right] \\
    i_{lic} &= \frac{I_{dc}}{3} + I_{2f \ sin} \left[2 \left(\omega_{s}t + \frac{2}{3}\pi\right) + \phi\right]
\end{align*} \tag{4}$$
$I_{2f}$ is the maximum of double frequency circulation; $\omega_0$ is the fundamental angular frequency; $\varphi$ is the initial phase angle; $I_{dc}$ is the value of the DC current. The voltage drop generated by the unbalanced current of $i_{cirf}$ is $u_{cirf}$, which can be expressed as:

$$
\begin{bmatrix}
    u_{cira} \\
    u_{circ} \\
    u_{cirb}
\end{bmatrix}
= L_0 \frac{d}{dt} \begin{bmatrix}
    i_{cira} \\
    i_{circ} \\
    i_{cirb}
\end{bmatrix} + R_0 \begin{bmatrix}
    i_{cira} \\
    i_{circ} \\
    i_{cirb}
\end{bmatrix}
$$

(5)

The formula can be obtained by abc/dq transformation:

$$
\begin{bmatrix}
    u_{cird} \\
    u_{cirq}
\end{bmatrix}
= L_0 \frac{d}{dt} \begin{bmatrix}
    i_{2,fd} \\
    i_{2,fq}
\end{bmatrix} + \begin{bmatrix}
    0 & -2\alpha_b L_0 & 0 \\
    2\alpha_b L_0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
    i_{2,fd} \\
    i_{2,fq}
\end{bmatrix} + R_0 \begin{bmatrix}
    i_{2,fd} \\
    i_{2,fq}
\end{bmatrix}
$$

(6)

In summary, a circulation suppressor can be designed to suppress the circulation component and reduce the distortion degree of bridge arm current, as shown in figure 4. By combining the circulation suppressor with the control quantity of the inner and outer loop controller of the MMC, the overall controller of the MMC is obtained, as shown in figure 5.

![Figure 4. Control block diagram of circulation suppressor](image)

![Figure 5. The overall control structure of the MMC includes the CCSC](image)
4. Simulation analysis
The MMC simulation model was built in RTDS to verify the inner and outer loop control strategy of MMC, etc. The MMC is rated for power of 20MW with a DC bus voltage rating of ± 30kV and an AC grid voltage of 110kV. The number of SMs is 50.

![Figure 6. Waveform of grid-connected voltage, current and DC bus voltage under normal operation of MMC](image)

![Figure 7. Capacitance voltage of SM, bridge arm current and circulation waveform when CCSC is started](image)
The grid-connected voltage, grid-connected current and DC bus voltage waveform of MMC is shown in the figure 6 Shown below. The instantaneous values of the three-phase voltage on the AC side of the MMC are $U_a$, $U_b$, $U_c$, and the amplitude gradually stabilizes at about 89kV. The instantaneous value of AC three-phase current of MMC is $I_a$, $I_b$, $I_c$, and the grid-connected current waveform is stable. The DC voltage stabilized at about 60kV.

The circulation suppressor was put into use at 0.04s. The capacitance voltage of SM, bridge arm current and circulation waveform is shown in the figure 7. The ideal value of the sub-module capacitance voltage $U_{c0}$ is 1.2kV. After the system is started, the capacitor voltage of the sub-module will gradually rise to the rated value and fluctuate around the rated value. Before the circulation suppressor is started, the capacitor voltage of the sub-module $U_{c-pa}$ fluctuates greatly, and its value fluctuates within the range of 1.2±0.13kV with a fluctuation rate of 11%. After the circulation suppressor was put in, $U_{c-pa}$ stabilized around 1.2±0.06kV with a fluctuation rate of 5%. The current of the upper bridge arm in phase A is respectively, and its simulation waveform is shown as in figure 7-(b). After the circulation suppressor is put in, the distortion degree of the bridge arm current is significantly reduced. Phase A circulation is significantly inhibited, as shown in figure 7-(c).

5. Conclusions
By establishing the simulation model of MMC in RTDS, the DC bus side voltage can be stabilized under the basic double closed-loop control strategy. The advantage of low harmonic of MMC can be exerted by using NLM, and the circulation suppression strategy can obviously restrain the circulation in the middle phase of MMC.

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