

# ***Comprehensive Analysis on the Modulation and Control Schemes for Modular Multilevel Converters***

**Yuyang Wang<sup>1,a,\*</sup>**

<sup>1</sup> *School of Engineering, University of Warwick, Coventry CV4 7AL, UK*

*a. Wang-Yuyang.Wang@warwick.ac.uk*

*\*corresponding author*

**Abstract:** The energy transition is thoroughly conducted worldwide, with a significant shift from fossil fuels to renewable sources. The most essential benefit of utilizing clean energy is environmental sustainability, which reduces greenhouse gas emissions. The technology of multilevel converters is of great significance for converting high-voltage and large-capacity electric energy and improving power consumption efficiency. Compared with traditional topology, modular multilevel converter (MMC) adopts a modular design, and each module is composed of independent sub-modules, which is highly flexible and scalable. This design allows the number of sub-modules to be increased or reduced according to actual needs, adapting to different voltages and power levels. However, its distinct characteristics, such as submodules, circulating currents, and parameter sensitivity, require a sophisticated control system to manage the external and internal variables with high dynamical performance. This paper analyzes the basic principle and topology of the modular multilevel converter; the existing research protocols are reviewed and summarized for these three challenges, respectively. Finally, prospect the future development trends and technical challenges.

**Keywords:** Modular Multilevel Converter, Modulation Schemes, Control strategies.

## **1. Introduction**

The energy transition is thoroughly conducted worldwide, with a significant shift from fossil fuels to renewable sources. The most essential benefit of utilizing clean energy is environmental sustainability, which reduces greenhouse gas emissions. Also, natural disasters like fuel spills and natural gas leaks can be eliminated by using renewable energy because it protects the world's natural resources [1]. Therefore, the world now invests almost much more in clean energy than fossil fuels, almost twice. In 2023, global investment in clean energy is 2003 billion USD, and fossil fuel is 1116 billion USD. While the investment in solar PV (503 billion) now surpasses all other generation technologies combined due to its abundance, scalability, low maintenance, less intermittence and versatility [2]. Solar energy can also be harnessed in remote or off-grid locations, providing energy independence to regions that might not have access to other renewable energy sources like hydro or geothermal.

Moreover, inverters are required to convert direct current (DC) from the solar panels into altering current (AC) for solar energy appliances. It must be sized according to the maximum expected load and the solar panel array output. Modular multilevel converter (MMC) is designed for it. Compared with traditional topology, MMC adopts a modular design, and each module is composed of independent sub-modules, which is highly flexible and scalable. This design allows the number of

sub-modules to be increased or reduced according to actual needs, adapting to different voltages and power levels [3]. Also, most of MMC's sub-modules operate at low switching frequencies, significantly reducing switching losses. Compared with traditional high-frequency switching converters, MMC has efficiency advantages, especially in high-power scenarios [4, 5].

However, due to its complexity, some issues and challenges about MMC still need to be solved. Most of the research is about the optimization of control strategies. This paper focus on three aspects of it. The first section is about modulation schemes of MMC, such as phase-shifted carrier modulation and staircase modulation. The second part is about control systems and methods. Including Proportional-Integral (PI) control and Model Predictive Control. At last, this paper analyzes ongoing research challenges in model predictive control, introduces several solutions, such as building simpler mathematical models and using a machine learning toolbox. This paper analyzes the basic principle and topology of modular multilevel converters. It reviews and summarizes the existing research protocols for its modulation schemes and control strategies. Finally, it presents prospects for future development trends and technical challenges, which provide a reference for follow-up research.

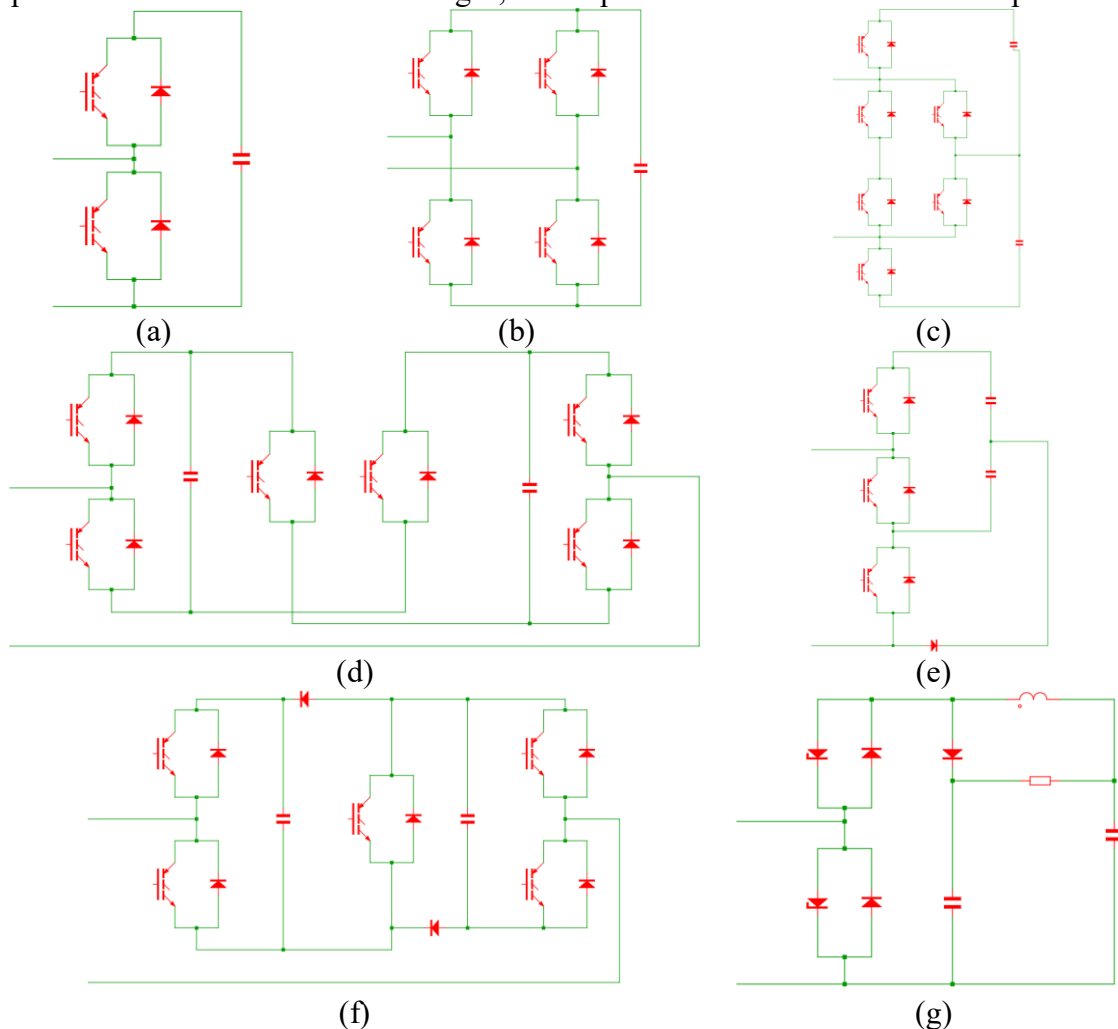


Figure 1: Submodules of MMC [5]

## 2. Basics of Modular Multilevel Converter

The modular multilevel converter consists of several submodules (SMs), as shown in Figure 1. Each submodule has its own strength and application. SM in Figure 1(a) is a half-bridge SM, is simple

cheap and efficiency, suitable for scenarios with low DC fault requirements. SM in Figure 1(b) is a full-bridge SM, complex and costly but flexible. Suitable for more complex application scenarios. SM in Figure 1(c) is a Hybrid-bridge submodule. Through the hybrid design, the high efficiency and low-cost advantages of the half-bridge submodule are retained, while the fault handling capabilities of the full-bridge submodule are enhanced. It is often used in situations where system reliability needs to be improved without significantly increasing costs. SM in Figure 1(d) is five level cross connected submodules and SM in Figure 1(e) is clamp-double SM. they offer improved power quality by reducing total harmonic distortion but the structures are relatively complex, are commonly used in scenarios that require higher output voltage quality or reduced harmonics. SM in Figure 1 (g) is inductor-integrated SM, the inductor helps to smooth out current ripples by acting as a filter. And stores energy in the form of a magnetic field, which can be released gradually. This helps to limit fault currents during abnormal conditions, offering better protection for the MMC and connected equipment.

As Figure 2 illustrates, it is a DC to three-phase configuration which is often used in High Voltage Direct Current applications. The DC system is connected between the upper and lower terminals of the phases, while the central point of each phase connects to the AC system. Both DC and AC system contribute to a controlled voltage at its terminal, producing the required current [5].

By independently controlling each submodule, the MMC can selectively add the capacitive voltage of certain sub-modules to the circuit. By superimposing the voltages of multiple sub-modules, MMC is able to generate a nearly ideal sinusoidal waveform. The number of steps of this waveform depends on the number of sub-modules. The more sub-modules, the closer the output voltage waveform is to an ideal sine wave. The switch control status of each submodule determines whether its capacitor is connected to the circuit. By selectively controlling these switches, the MMC can adjust the magnitude and direction of the output voltage and current at any time.

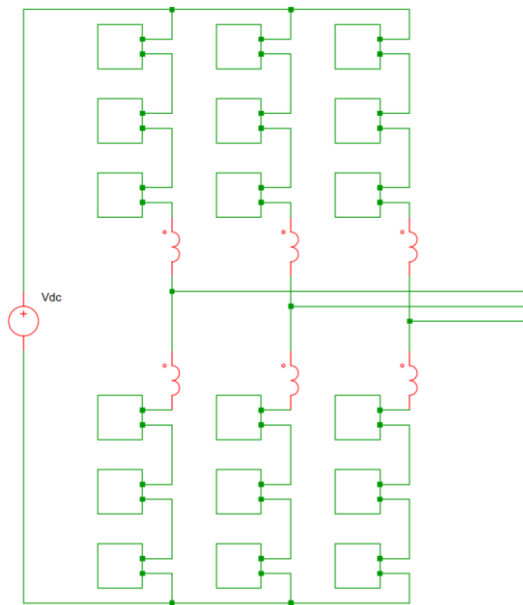


Figure 2: DC to three phase MMC topology [5]

### 3. Modulation Schemes for MMC

There are several Pulse Width Modulation (PWM) schemes of MMC categorized by the switching frequency shown in Figure 3. While Phase-Shifted Carrier Modulation and Staircase Modulation (Nearest-level modulation) are the two most commonly used methods according to their simplicity.

And the choice between this two methods depends on the number of SMs. If the number is relatively smaller, the front choice is more preferable, and vice versa [6].

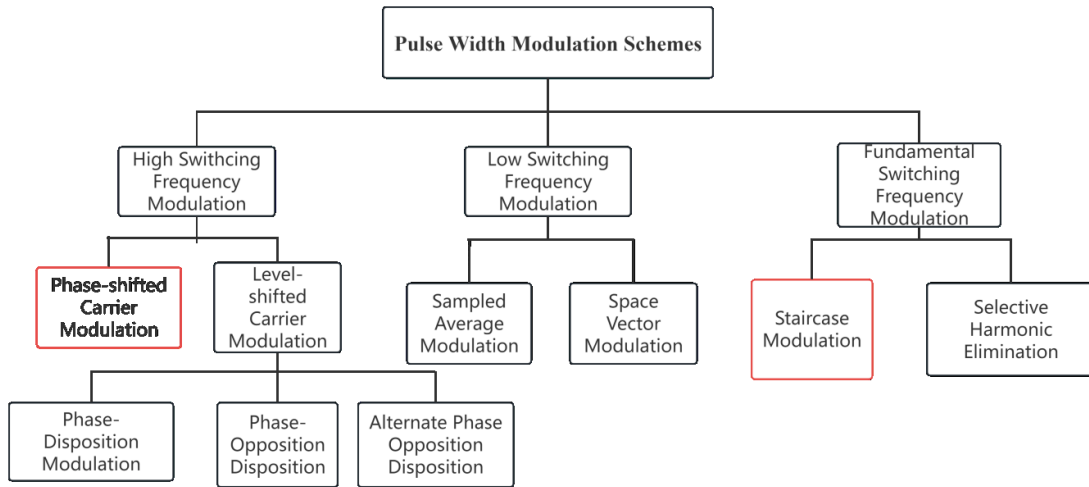


Figure 3: PWM schemes of MMC [6]

### 3.1. Phase-shifted Carrier Modulation

Phase-Shifted Carrier Modulation, as shown in Figure 4 is a Pulse Width Modulation (PWM) technique where each submodule in the MMC uses its own carrier signal, phase-shifted relative to the carriers of other submodules. Each submodule is assigned a triangular or saw-tooth carrier waveform of the same frequency and amplitude but shifted in phase. For an MMC with N submodules per arm, the carriers are phase-shifted by an angle of  $360/N$ . This means the switching events are evenly distributed over one full cycle of the fundamental frequency. And a common sinusoidal reference signal, representing the desired output voltage, is compared with each phase-shifted carrier. The comparison results generate individual PWM signals for each submodule. When the reference signal exceeds the carrier, the submodule is turned on (inserting the capacitor); otherwise, it is turned off (bypassing the capacitor). The combined effect of all submodules switching at different times creates a high-quality voltage waveform with reduced harmonic content.

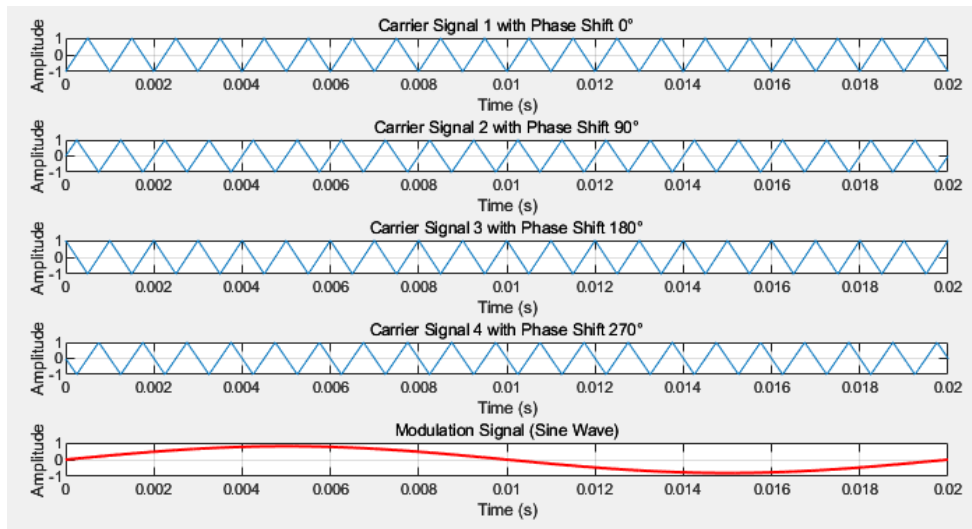


Figure 4: Phase-shifted carrier modulation for MMC

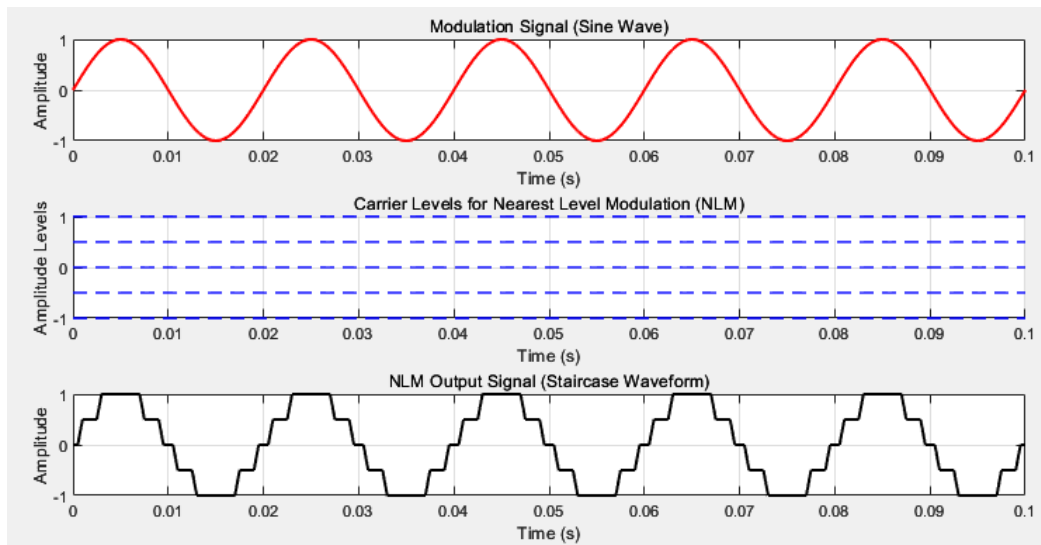


Figure 5: Staircase modulation for MMC

### 3.2. Staircase Modulation

In staircase modulation, as shown in Figure 5, the output voltage waveform is synthesized by controlling the number of active sub-modules at any given time. The output voltage resembles a "staircase" pattern, where each step corresponds to a voltage level determined by the number of sub-modules that are inserted or bypassed. The main goal of staircase modulation is to approximate a sinusoidal waveform by switching sub-modules at specific intervals, generating discrete voltage levels that sum to create the desired output.

The control system decides which sub-modules are turned on or off, depending on the desired voltage level. The staircase waveform can have a low switching frequency compared to other modulation methods, which reduces switching losses. The modulation index controls the amplitude of the output voltage, with each level in the staircase waveform contributing a specific fraction of the overall voltage. In high-voltage applications, this reduces the stress on individual power electronics and allows for better power quality.

## 4. Control Schemes for MMC

The main objectives of the MMC control system are illustrated by Figure 6, and summarized as:

- Capacitor voltage balance: Ensure that the capacitor voltage of each sub-module is maintained within a predetermined range to avoid overvoltage or undervoltage thus ensure the normal operation of the system.
- External control: The external control includes active power control, which controls the active power output by the MMC. By regulating the input signal, the external control can manage the transmitted power level to ensure that the system can provide or absorb active power according to demand. For reactive power control, which controls reactive power to regulate and maintain the voltage level of the grid. MMC can help maintain system stability by adjusting reactive power. Especially when connected to the grid, precise control of reactive power can be achieved by adjusting the phase angle.
- Internal control: DC and AC current control. And it includes a special feature of MMC, circulating current. There is a potential difference between arm voltage and  $V_{dc}$ , thus cause a circulating flow

in the internal loop. This control need to control the circulating current as it will occupy the circulation capacity and generate active power loss.

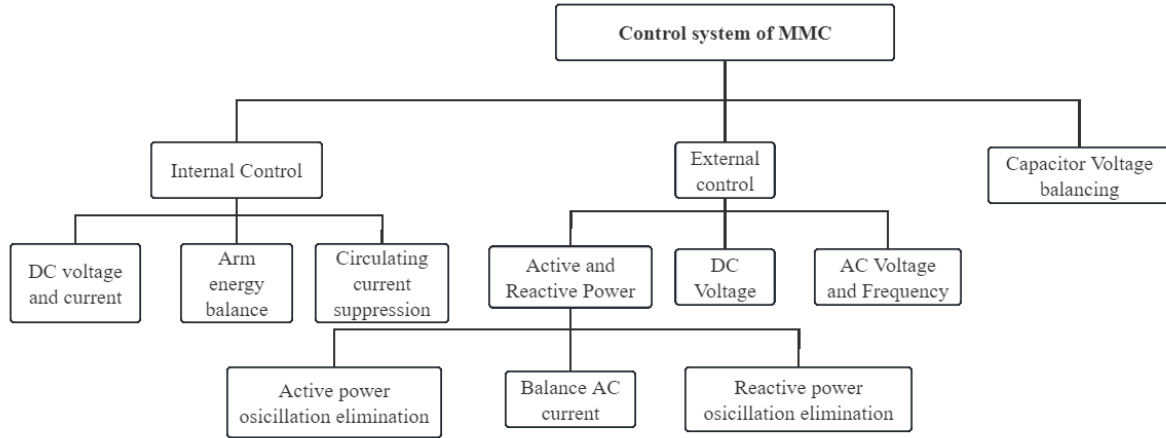


Figure 6: Control for MMC [5]

#### 4.1. Capacitor Voltage Balance

The control approaches of balancing capacitor voltage depends on the modulation it used. As shown in Figure 7, additional balancing control method is used for phase-shifted carrier modulation, since it is used for MMC which has fewer SMs. The greater the capacitor voltage error, the greater the additional active power generated and the stronger the regulation effect. And it is a feedback control. Sorting pressure equalization algorithm is for staircase modulation. As among the total number of sub-modules, it is free to select a certain number of sub-modules. This control method uses this degree of freedom to adjust the charge and discharge time of the sub-module capacitor. It is a feedback control as well.

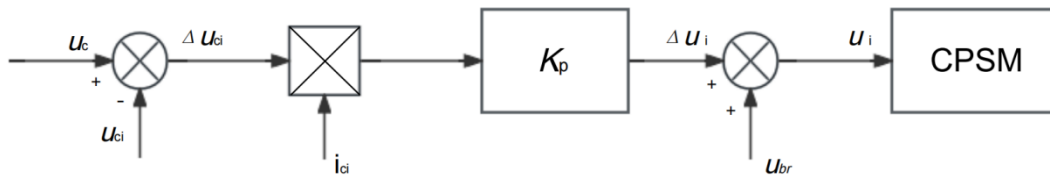


Figure 7: Additional balancing control for MMC [6]

#### 4.2. Internal and External Control

PI Control and Model Predictive Control are the two control approaches mostly used. Therefore this section will focus on the two strategies [7].

Proportional-Integral (PI) control is a fundamental control strategy used in MMC to control several system parameters, for example output current, voltage, and capacitor voltage balance. PI control is widely favored for the simplicity, effectiveness, and ease of implementation. PI control combines two components: the proportional (P) and the integral (I) actions. The primary role of this proportional action is to reduce the error quickly. While the integral action eliminates steady-state error by adjusting the control output until the accumulated error is zero [8].

Model predictive control (MPC) is an advanced control algorithm that uses a mathematical model of the system to predict future behavior and optimize the control input at the current moment to meet

future output requirements. MPC uses rolling optimization to calculate a series of control inputs based on the prediction model each time, and selects the optimal input for application. MMC control sensors measure these parameters: inner current and voltage, output current and voltage, and internal circulating current. Then, the model estimate all the possible output variable values in next set interval for all the possible switching signals. Next, it calculates the MPC cost function regarding the output/circulating current. A cost function is designed to quantify the error between the predicted future behavior of the system and the desired reference values [9]. This cost function can include multiple terms, such as: current tracking error (difference between actual and reference current), voltage balancing (ensuring that the voltages across the submodule capacitors remain balanced) and reduction of harmonic distortion in the output voltage and current. Finally, the MPC algorithms will choose the most ideal switching signal. And the optimized switching signals are used to control the MMC.

The comparison between PI and MPC control are summarized in Table 1. Generally, the PI control algorithm is simple, requires little computing, and is easy to implement on low-cost hardware. It is relatively simple to implement, but parameter adjustment becomes complicated in high-order systems.

Since MPC needs to solve optimization problems in real time, it requires a large amount of calculation, especially in multi-variable systems. High-performance processors and fast numerical solvers are required. Implementing MPC is relatively complex, especially the model construction and optimization solution parts, and the system modeling accuracy requirements are relatively high.

Nowadays, many researchers aim to improve MPC to make it faster and cost less. Including simplifying the mathematical model by grouping and clustering the data points. Additionally, using a machine-learning toolbox in the control system. Put each input and output variables into this toolbox and trained the machine. After enough training, the machine learning is able to find the output directly without any calculations, thus eliminate the delay [10].

Table 1: Companion between PI and MPC controls for MMC

Aspect	PI Control	Model Predictive Control
Control Principle	Based on error correction using proportional and integral terms	Predicts future behavior based on a model of process
Handling of Constraints	Cannot directly handle input and output constraints	Can handle constraints on inputs, outputs and states
System Dynamics	Works well for simple, linear systems	Can handle complex, multi-variable, and non-linear systems
Response Time	Faster but may overshoot or oscillate	Slower but optimized for the entire prediction horizon
Computation Requirement	Low computational demand, real-time execution	High computational demand, requires solving optimization problems

## 5. Conclusion

To conclude, this review includes the topology, operating principles, modulation schemes and control strategies of the MMC. Analyzing and discussing the challenges faced and how to solve it in the future. However, the Fault-tolerant operation and reliability of the control system of MMC are not contained in it, it should be analyzed in the future. In the future, the intelligent and digital control of MMC will be further improved. Future MMC will integrate more intelligent algorithms and real-time monitoring functions to achieve adaptive adjustment to dynamic changes in the power grid. This intelligent control system can significantly improve the system's operating efficiency and fault handling capabilities, while reducing maintenance costs. Additionally, with the advancement of

power electronic device material technology, such as the application of new semiconductor materials such as silicon carbide and gallium nitride, the switching frequency and efficiency of MMC will be significantly improved. This will reduce the loss of the system, further reduce the size of the equipment and reduce the cost, making it have higher application value in more industrial and commercial fields.

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