Comprehensive Analysis on Topological Structure of Modular Multilevel Converters

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Abstract. This paper discusses the importance and application of modular multilevel converter (MMC) in the field of power conversion. Firstly, the article starts with the basic concept of MMC and introduces its key role in high-power electrical energy conversion. Subsequently, to address the complexity of MMC, the article describes in detail the common topologies of MMC, including diode-clamped multilevel topology, flyover capacitor topology, H-bridge cascade topology, and switched-capacitor multilevel topology, and also emphasizes the different scenarios in which they are applied to power systems. The last section describes the capacitor voltage balancing strategy in MMC. Several common capacitor voltage balancing strategies, including hardware clamping method, capacitor voltage closed-loop method, and capacitor voltage sequencing method, are comprehensively discussed in this paper, and the principles, advantages, disadvantages, and applicability of each strategy are thoroughly analyzed. Ultimately, this article offers academics and engineers a thorough review of MMC and offers valuable references for further study and real-world applications in the areas of power system conversion and energy management.

Keywords: Modular Multilevel Converter; Sub-Module; Topological Structure; Capacitor Voltage Balance.

1. Introduction

Energy is the support for the development of modern societies; however, with population growth, accelerated urbanization and increasing industrialization, the world's energy problems are becoming more and more pronounced, and we must take active measures to meet this challenge.

With the growing demand for electricity and the increasing importance of renewable energy, power conversion technology plays a crucial role in the energy sector. Modular Multilevel Converter (MMC), as a disruptive power conversion technology, has attracted much attention due to its high efficiency, flexibility and adaptability. MMC is becoming an important choice in the fields of power transmission, motor drive, and grid connection. This review aims to delve into the core concepts, common sub-modules, topologies, and strategies for capacitive voltage balancing of MMC, with a view to providing readers with a comprehensive understanding and reference to promote the development and application of power conversion technologies.

Renewable energy, as a keyway to address the energy crisis and environmental pollution, has received widespread attention and esteem worldwide. Among various renewable energy sources, wind power is one of the most important and widely used forms due to its environmentally friendly, sustainable and widely distributed characteristics. However, a series of complex power electronic conversion processes are required to convert wind power into electrical energy for use in the power grid. In this process, the efficiency and performance of the power electronic equipment will directly affect the overall performance of the wind power generation system. Literature [1] points out that offshore wind farms have the difficulties of large transmission costs and low efficiency.

In the offshore wind sector, conventional power conversion technologies include direct-current-to-direct-current (DC-DC) converters and conventional power converters (e.g., centralized inverters). However, the use of these conventional technologies may encounter some problems in the operation of offshore wind farms:

(1) Transmission losses: As offshore wind farms are usually far from land, electricity needs to be transmitted back to the onshore grid through long-distance submarine cables. During the transmission process, power losses may increase, affecting the efficiency of power transmission.

(2) Grid Stability: Conventional power converters may introduce grid harmonics, voltage fluctuations and other problems that affect the stability of the grid. Offshore wind farms, as electrical energy injection points, need to ensure stable electrical energy injection to prevent adverse effects on the grid.

(3) Failure tolerance: harsh offshore environmental conditions make maintenance and repair difficult. Traditional power conversion technology may need to be shut down for repair when facing partial module failure, which is difficult to maintain and also affects the operational efficiency of the wind farm.

(4) Volume and weight: While conventional technologies may require greater volume and weight, which may be limited on offshore platforms, the modular design of the MMC can reduce volume and weight to some extent.

(5) Energy losses: Conventional technologies may incur large energy losses during electrical energy conversion, especially at high power conversion. This can reduce energy transmission efficiency and increase operating costs.

Although conventional power conversion technologies have a wide range of applications on land, they may face many challenges in offshore wind power. Modular multilevel converters, as a novel and efficient power conversion technology, are better adapted in offshore wind farms to solve the problems that may be faced by conventional technologies and provide higher energy transfer efficiency and system stability.

Large offshore wind farms often utilize a DC transmission system to convert the AC power generated from the offshore wind turbines into DC power, which is then transferred to a converter station on land via high voltage DC cables. MMC are one of the most commonly used DC transmission technologies today, providing high voltage levels, lower harmonic content and better voltage control, making long-distance submarine cable transmission more efficient and reliable. It is also therefore possible to use high-voltage direct current transmission (HVDC) technology, at which time MMC also plays a key function, which can be applied to both high-power, ultra-high voltage AC/DC power conversion aspects, but also can complete the transition of power directly from low-voltage alternating current (AC) to high-voltage direct current (HVDC), which is a very suitable for offshore all-DC wind farms in the wind power generation converter topology. As a result, the modular multilevel converter has emerged as a key instrument for improving the wind power generating system, greatly enhancing its efficiency and dependability while fostering the growth and widespread use of renewable energy.

As a novel power conversion solution with modular structure, scalability and high efficiency, MMC is considered as an effective means that can address the challenges in high power power conversion. In the first part of this paper, we briefly introduce the fundamentals and importance of modular multilevel converters. Also in the first part, we will explore the common sub-modules of MMC in detail. These sub-modules, such as half-bridge sub-modules, full-bridge modules, bit-type three-level modules and fly-across capacitor-type three-level modules form the basic building blocks of MMC. By analyzing their strengths and challenges in depth, the author will provide the reader with a deeper understanding of the MMC system components.

Subsequently, in Part III, the author will introduce the common topologies of MMCs. These topologies, such as boost, buck, DC-AC, and AC-AC, are each suitable for different power conversion scenarios. We will emphasize the advantages and limitations of each topology for application in power systems.

Finally, this review will focus on the key issue of capacitive voltage balance. The challenge of capacitive voltage balancing has been the focus of research in the design and application of MMCs. We will comprehensively discuss several common capacitive voltage balancing strategies, which will help readers understand and solve the capacitive voltage balancing problem in MMC.

2. Introduction to Modular Multilevel Converters

MMC is a power electronic device used in the fields of high voltage direct current (HVDC) transmission, power system stability enhancement, and motor drive. It is a multilevel converter with a modular structure, which realizes efficient energy conversion and voltage transformation by combining several basic units (modules) together.

The MMC achieves high quality voltage and current waveform control by combining a large number of capacitors and switching tubes in a modular fashion to form a multi-level voltage waveform output. Each module is linked together using capacitors and switching devices to create several discrete voltage levels and a voltage waveform which resembles a sine wave. This makes the MMC suitable for applications requiring high quality voltage outputs, such as high voltage DC transmission and motor drives.

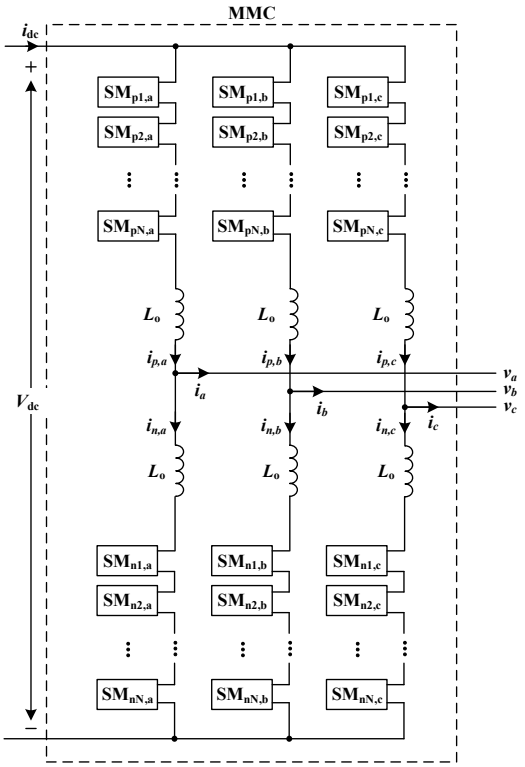


Fig. 1 Classic three-phase MMC topology [1]

Fig. 1 shows the classic three-phase MMC topology, which each phase consists of two bridge arm units, and the phase's switching output port is formed by the connection between the upper and lower bridge arms. Each bridge arm module can be composed of several basic functional units and an inductor. Each basic function unit (also called sub-module, Sub-module, SM).

Several modules make up MMC's fundamental structure, each of which has a corresponding purpose and topology. These modules can be the same or different, depending on the requirements of the specific application scenario, and MMCs realize the advantages of high quality voltage and current outputs, flexibility, maintainability, and scalability for a wide range of power electronics applications. This modular design is important in improving system performance, reducing maintenance costs, and adapting to diverse needs.

In order to further reduce the MMC switching losses, literature [2] proposes an alternate arm multilevel converter (AAMC) with bridge arm switching, as shown in Fig. 2. During each half cycle of this arrangement, IGBT tubes are linked in series in the upper and lower bridge arms, respectively. This configuration allows the current to pass through the IGBT tubes more smoothly during the switching process, reducing the inrush and losses during the switching process.

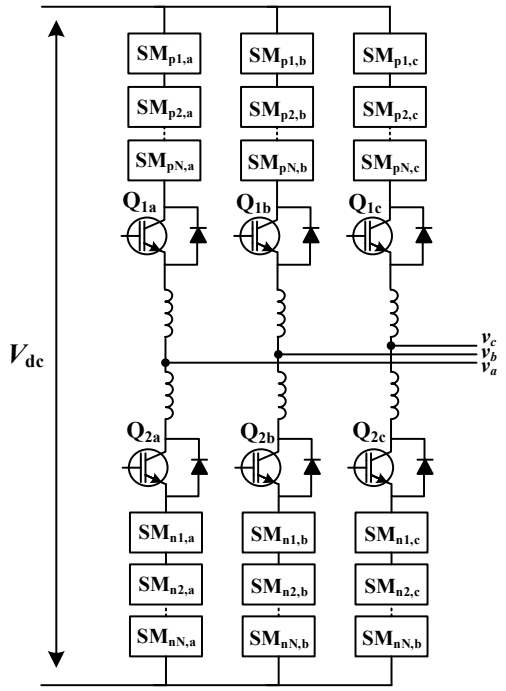


Fig. 2 Alternate arm multilevel converter [2]

In a conventional MMC, the switching state of each submodule can only control whether the current flows through the submodule or bypasses the submodule. In the structure with bridge arm switching, on the other hand, each bridge arm (upper or lower half bridge) can be switched, i.e., it can be switched to a different current path. This allows the converter to respond more flexibly to current variations. By switching different bridge arms, the output current can be adjusted over a wider current range to meet the demands of different operating conditions. At the same time, the bridge arm switching technique allows the current to flow through fewer sub-modules, which reduces switching losses and voltage drops and improves the conversion efficiency of the system. When coping with faults in certain fault conditions, such as a problem with one bridge arm, the system can be maintained by switching to other available bridge arms to improve system reliability.

Multilevel converters with bridge arm switching achieve a larger current regulation range, higher efficiency and better fault response by introducing bridge arm switching technology into the structure of multilevel modular converters. This makes this converter an important application prospect in fields such as high-voltage DC transmission.

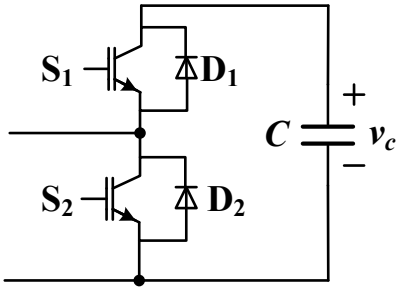


Fig. 3 Basic half-bridge structure

3. Common MMC topologies

3.1. Basic half-bridge structure

As seen in Fig. 3, the fundamental half-bridge construction is primarily composed of a half-bridge inverter and a capacitor. Two switching tubes make up this half-bridge inverter, usually a power switch (e.g., IGBT) and a diode in anti-parallel. The half-bridge inverter converts a DC voltage to an

AC output and its operation is controlled by a control signal. Each module also includes a capacitor for energy storage. The capacitor charges and discharges during voltage intervals (multilevel intervals) to smooth the output voltage waveform and reduce harmonic content.

By precisely managing the switching states of the upper and lower half bridges, AC current may be controlled. Changes in the switching state of each sub-module can charge and discharge the capacitor, leading to an output voltage waveform with many levels. An almost sinusoidal output voltage waveform will be created by superimposing the voltage differences created at each sub-module.

The control system of the MMC is responsible for monitoring the inputs and outputs of the system and switching each sub-module on and off at the right time according to the demand. The output voltage's amplitude and frequency may be managed, and uninterrupted voltage shifts can be achieved, by suitably controlling the switching state. In order to realize higher voltage levels, the MMC can build larger converters by connecting several half-bridge structures in parallel.

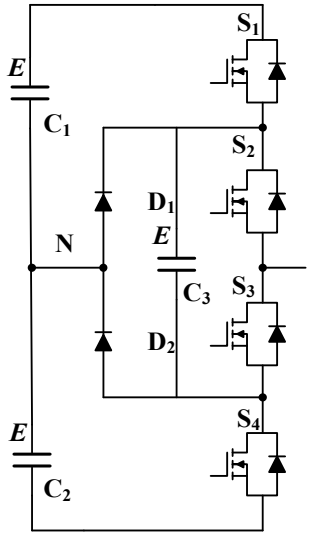


Fig. 4 Diode-clamped multilevel topology

3.2. Diode-clamped multilevel topology

Diode-clamped multilevel topology (DCMT) is a multilevel converter topology used to convert a DC power supply into multiple discrete AC output voltage levels. In this topology, to obtain various voltage level outputs, clamping diodes are utilized to restrict the voltage of the capacitors. This topology is typically used in applications that require high quality output voltages with low harmonic content, such as AC transmission and motor drives. The three-level DCMT consists of two capacitors C1 and C2, four switching tubes S1, S2, S3, and S4, and two clamping diodes D1 and D2, respectively, as shown in Fig. 4, and as shown in Fig. 4, the basic unit of this topology is made up of a half-bridge basic unit and a clamping basic unit. These two basic units are combined with each other in the diode-clamped topology to realize the multilevel output.

This topology operates with a half-bridge basic unit for generating intermediate voltage levels and a clamping basic unit for limiting the voltage of the capacitor. This combination allows the system to operate at different voltage levels, thus realizing a multilevel output. Throughout the process, the voltage of the capacitor is switched at different voltage levels, thereby realizing a multi-level output. The clamping diode serves to limit the voltage of the capacitor to prevent it from being overloaded or overvoltage. By reasonably controlling the operating timing of the switching tube and the clamping diode, output voltage regulation and waveform control can be realized. In this topology, each switching tube may be subjected to a different voltage stress. The conduction of the clamping diode leads to some voltage drop, so the switching tubes connected to the clamping diode may be subjected to higher voltage stresses, which may affect their life and reliability. At the same time, the combination of switching tube and clamping diode may cause some back-voltage problems. In some

cases, after the clamping diode conducts, the switching tube may be subjected to a backvoltage from the clamping diode, which may affect the operating performance of the switching tube and make it difficult to be applied to applications where reliability is required.

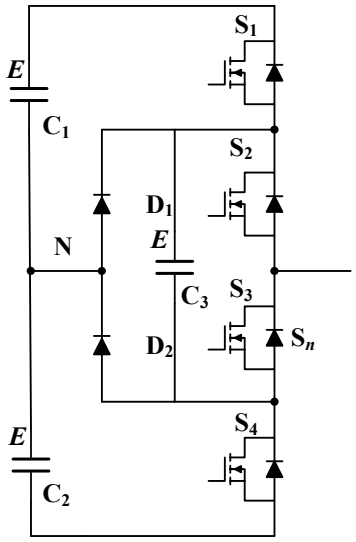


Fig. 5 Capacitor voltage self-balancing topology [4]

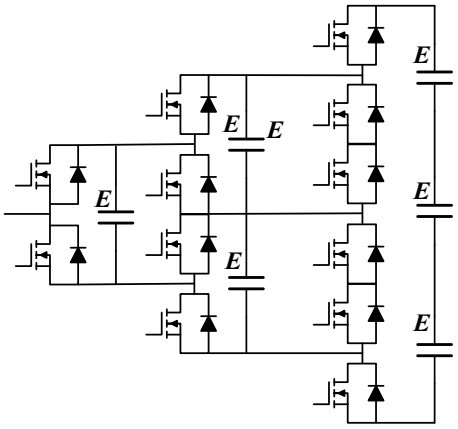


Fig. 6 Self-Balancing Generalized Topology Architecture for Capacitor Voltage [5]

3.3. Fly-Through Capacitive Topology

The capacitor clamped topology configuration [3] was first pointed out by T.A. Myenadr and H. Foch at the PESC conference in 1992. In contrast to the three-level diode-clamped topology configuration, the fly-span capacitor-type topology generates multiple voltage levels by realizing the exchange of electrical energy between different capacitors. The energy exchange between the capacitors allows the transfer of energy from one capacitor to another, which causes the output voltage to be regulated. The basic unit analysis method allows us to analyze the function and interrelationship of each basic unit step by step. In the fly across capacitor type topology, the capacitor module stores energy, the switching tubes control the energy exchange, the control system ensures system stability, and the power supply provides energy support. These basic units work together to realize the multi-level output function of the topology. The fly across capacitor type topology has the added advantage that its level count is relatively easy to scale. Extending the amount of capacitor modules, capacitors, or changing settings could result in more level outputs. This allows higher level counts to be realized to meet specific application requirements. However, level count scaling for clamped topologies might be more complex since doing so necessitates adding additional capacitors and switching states, which can make controlling the system more difficult. In spite of this, in the fly-span capacitor-type structure, the energy exchange between capacitors determines the output voltage, and the energy exchange process may be affected by several factors such as system parameters,

control strategy, capacitor parameters, etc., which can lead to unstable energy exchange and thus make the capacitor voltage difficult to control. Literature [4] provides a capacitor voltage self-balancing topology for the challenging fly-through capacitive architecture capacitor voltage control with respect to the common characteristics of capacitor-clamped topology and high-voltage diode-clamped topology. Fig. 5 shows that the dc bus capacitor is charged to the suspended capacitor until both voltages are balanced with the minimum change in the neutral voltage. In literature [5] a generalized topology architecture for self-balancing of capacitor voltages is proposed by using a cascade of half-bridge units, as shown in Fig. 6, which indicates that in each level adjacent switching tubes are interlocked, and when only one switching state is confirmed, the rest of the switching states of this level are also confirmed, and capacitors of the neighboring levels can be connected in parallel for the purpose of self-balancing of the voltages; however, if an increase in the amount of the output level is required, the However, if the amount of output level required increases, the number of switching tubes as well as capacitors will increase exponentially.

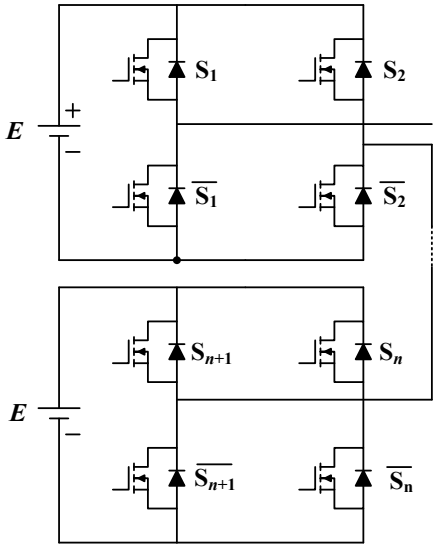


Fig. 7 H-bridge cascade topology [6]

3.4. H-bridge cascade type topolog

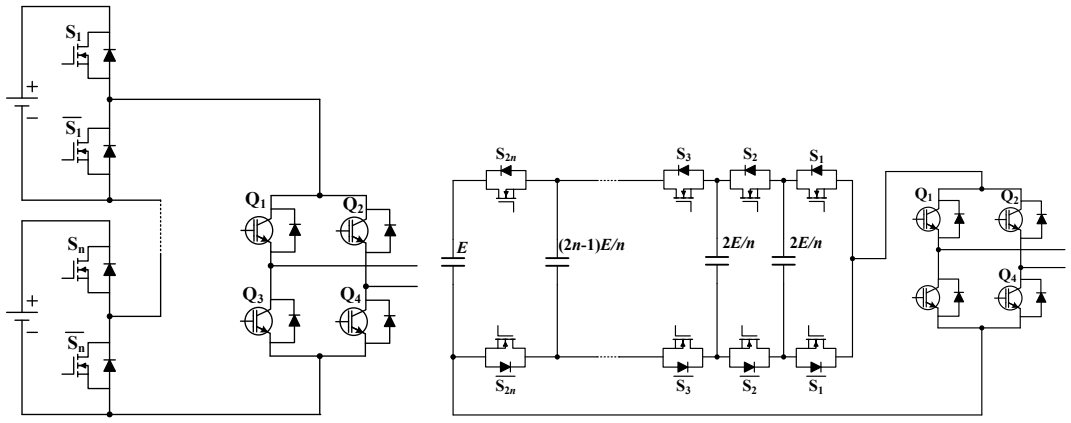
Fly-span capacitive topology In practice, there may be some differences in the parameters between different capacitors, such as capacitance and internal resistance. This leads to inconsistent capacitor charging and discharging rates, which makes it difficult to maintain uniform capacitor voltage. The H-bridge cascade type topology is more suited for medium and high voltage operations than the first two types of topology architecture.The parallel topology of H-bridge stage was put forward by P. Hammond et al. in 1998 [6]. The fundamental component of this architecture is the H-bridge circuit. Four switching tubes—typically MOSFETs or IGBTs—make up the device. Both positive and negative voltage outputs can be achieved by carefully regulating the conduction and disconnection of these switching tubes. Each H-bridge circuit can provide two level outputs, i.e., positive and negative. each H-bridge circuit in the H-bridge cascade type topology is supplied with a separate DC power supply, so that under normal operation, there is no equalization of currents between the individual H-bridge circuits. As seen in Fig. 7, the H-bridge cascade-type topology is able to share the current load properly with other multilevel converters, decreasing the stress on individual units. This increases the longevity of the device and lowers switching loss and heat stress on the switching tubes; the redundant switching states can be adjusted for each H-bridge unit; the H-bridge cascade topology can provide flexible voltage outputs to adapt to different voltage requirements, and the adjustment methods are flexible and various; and the number of input and output levels can be easily expanded, among other advantages. However, due to the multiple switching tubes and connection circuits involved, the H-bridge cascade topology may face certain challenges in package design, and heat dissipation, pin layout, electromagnetic interference and other issues need to be considered. Additionally, the H-

bridge cascade architecture requires a separate power supply for each H-bridge unit, which might complicate and raise the cost of the system's power supply design, particularly in high-voltage applications. Finally, the cost of the H-bridge cascaded topology may be high due to the involvement of multiple switching tubes, circuit components, and control systems, including component costs, control system costs, and manufacturing costs.

3.5. Hybrid Cascaded Multilevel Converter

The literature [7] suggests hybrid cascaded multilevel converter (HCMC), a unique topology created to increase the converter's efficiency, reduce the cost, and reduce the use of switching devices and batteries. This architecture is comprised of a cascade of an H-bridge basic unit and a half-bridge basic unit, as seen in Fig. 8(a). The half-bridge basic unit usually consists of two switching devices for generating a sinusoidal half-wave, while the H-bridge basic unit is used to invert the fundamental waveform, thus realizing a multilevel output. The advantage of this topology is to combine the characteristics of the half-bridge and the H-bridge in order to realize an AC multilevel output. With appropriate control strategies, the use of switching devices can be reduced and efficiency can be improved. In addition, since only the inversion of the fundamental waveform needs to be realized, fewer switching devices are required compared to the conventional multilevel converter, which is expected to reduce the cost. Moreover, the H-bridge operates at the fundamental frequency and soft-switching state with low switching losses.

Literature [8] adopts the same approach and proposes hybrid multicell converter (HMC) by realizing a multicell cascade by paralleling a fly across capacitor (FC)-type topology with an H-bridge as the basic unit, thus achieving a similar effect to the hybrid cascaded multilevel converter (HCMC) topology. It is shown in Fig. 8(b).



(a) (b)

Fig. 8 Hybrid MMC. (a) Hybrid Cascaded MMC [7] (b) Hybrid Multicell MMC [8]

3.6. Switched-capacitor multilevel topology

The literature [9] initially suggested switched-capacitor topologies, which combine capacitors with switching elements to provide the necessary multilayer output voltage. By managing the switching states and capacitor voltages, this structure aims to provide output voltage waveforms of greater quality with less harmonic components, making it appropriate for a number of applications like inverter drives, power transmission, etc. according to Fig. 9. On the basis of additional research, literature [10] suggests the boosted multilevel architecture with switched capacitors seen in Fig. 10. This topology is comparable to the design stated above and can achieve a nine-level output. his topology also has a capacitor voltage self-equalization effect, which reduces the number of required components and makes the converter more efficient and less costly. To solve the problem of uneven voltage applied to the switching tubes, literature [11] adjusts the position of the switching devices to achieve an even distribution of voltage stress, reducing the exposure of specific switching tubes to

excessively high voltages, thus reducing the risk of failure and increasing the reliability of the system, as shown in Fig. 11.

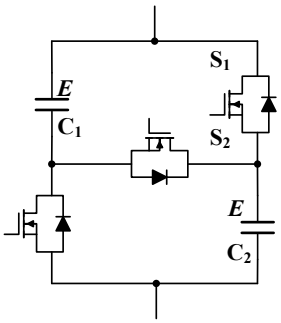


Fig. 9 Switched-capacitor multilevel topology [9]

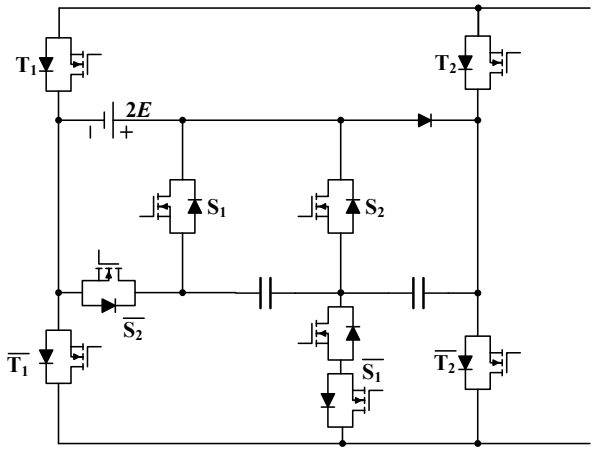


Fig. 10 Boosted Multilevel Topology with Switched Capacitor [10]

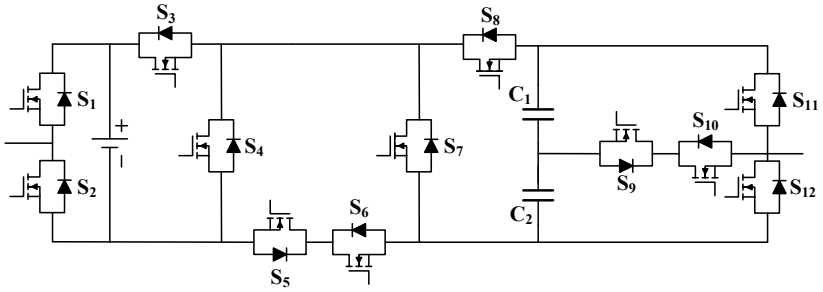


Fig. 11 Boosted Multilevel Topology with Switched Capacitors [11]

3.7. Summary and Comparison

Various topologies of MMC have their own advantages and disadvantages, and when choosing a converter topology, it is necessary to make trade-offs and choices according to the actual application requirements and performance indexes. As one of the most basic topologies of MMC, the basic half-bridge structure has the advantages of simple structure, low cost, low switching loss, and wide range of applications, but it also has the disadvantages of unstable output voltage and low efficiency, and the output frequency is limited by the charging and discharging rate of the capacitor, so the potential performance may be affected in the higher frequency range. Diode-clamped multilevel topologies continue the advantages with higher reliability, but they can create energy feedback problems and require additional control strategies to manage and balance the energy flow in the system. The fly-across capacitor topology can be used in high-voltage scenarios and requires fewer switching devices, but it also has energy consumption issues that need to be controlled.The H-bridge cascade topology is more reliable and has fast fault detection and troubleshooting, but it also has the disadvantage of current equalization issues and complex thermal management. Hybrid cascaded multilevel converters

can combine the advantages of multiple topologies, but are more complex to design and control, and have lower efficiency. The switched capacitor type multilevel topology has a wide output voltage range and low switching losses, but capacitor matching and equalization is difficult and the control strategy is complex.

Regardless of which topology is chosen, MMC has the advantages of increasing energy conversion efficiency and improving voltage quality and is expected to continue to be widely used and developed in the future.

Table 1. Comparison of various topologies

Topology type	Advantage	Drawbacks
Basic half-bridge structure	Simple structure, low cost, lower losses, versatile use	Unstable output voltage, harmonic problems, lower efficiency
Diode-clamped multilevel topology	Lower switching losses, lower voltage stress, universal applicability	Higher number of devices, control complexity, energy return, higher costs
Fly-Through Capacitive Topology	Applicable to high-voltage scenarios, capacitor devices share voltage, a small number of switching devices	Energy consumption issues, risk of failure of capacitor devices, complex control strategies, higher costs
H-bridge cascade type topolog	High reliability, flexibility, high voltage capability, good scalability, fast maintenance and troubleshooting	Current equalization issues, thermal management, switching losses, higher cost
Hybrid Cascaded Multilevel Converter	High voltage capability, high stability, adapts to multiple frequencies, takes advantage of multiple topologies	Design and control complexity, reduced efficiency and higher costs
Switched-capacitor multilevel topology	Low switching losses for high-frequency applications, wide output voltage adjustment range	More capacitor parts, difficult matching and equalization of capacitors, complex control strategies, and Higher cost

4. MMC Capacitor Voltage Balancing Strategy

The quality of the output voltage waveform and the safe and reliable functioning of the system depend greatly on the capacitor voltage balance inside each sub-module of the MMC system, which consists of many sub-modules linked in series to provide a multi-level output. Capacitor voltage balancing has a direct impact on the system's efficiency, dependability, and stability. Below is a description of several capacitor voltage balancing techniques.

4.1. Hardware clamping method

Literature [12] presents a method using diode clamping, which is a common strategy used to achieve capacitor voltage balancing in diode-clamped multilevel topologies, often referred to as the "bottom and top balancing method". This method is indeed effective in achieving capacitive voltage balance, especially in diode-clamped multilevel topologies. The clamping method limits the capacitance voltages of all sub-modules to the two most extreme voltages by clamping the capacitance voltages between the bottom and top sub-modules. Additional hardware circuitry can be used to balance the capacitive voltages of the bottom and top submodules by means such as adjusting the current or voltage depending on the actual capacitive voltages. This helps to eliminate capacitance voltage differences and ensures that the capacitance voltages of all sub-modules are within reasonable limits. This method is indeed effective in real-world applications to achieve balanced capacitance voltages, thereby improving system performance and stability. However, designing and implementing these additional hardware circuits requires some technical and cost investment.

4.2. Capacitor voltage closed loop method

A capacitor voltage closed-loop control method is proposed in the literature [13] primarily for the carrier phase-shift modulation method. In this method, components for preserving the overall voltage balance of the upper and lower bridge arms, the overall voltage equalization of individual bridge arms, and the capacitor voltage equalization of individual sub-modules are superimposed on top of the original modulation signals. These additional components can be adjusted by closed-loop control to equalize the capacitor voltages. An advantage of this approach is that the execution of the modulation algorithms can be distributed among each submodule controller, thus reducing the burden on the upper-level total controller. However, the interaction between multiple closed-loop controllers may introduce instability and needs to be carefully considered.

4.3. Capacitor-voltage sequencing method

Literature [14] proposes a method to realize capacitor voltage balancing by sequencing. First, the number of submodules that need to be put into operation is obtained according to the need at the current moment n. The suitable order of operation is chosen based on the direction of the bridge arm current. When the bridge arm current can charge the capacitor, the submodules with capacitance voltage from low to high are selected; when the bridge arm current can discharge the capacitor, the submodules with capacitance voltage from high to low are selected. This sequence helps to achieve capacitor voltage balance. Despite the relative simplicity of this approach, there are some problems. Frequent sequencing and selection of capacitor voltages can increase the computational burden of the system. Additionally, random selection and casting introduce extra switching operations, and the extra switching operations may raise the device's switching frequency, which has an impact on the system's effectiveness and stability. Literature [15] proposes some improved methods to address these problems, but none of these methods can simultaneously solve the problems of high device switching frequency and high computational burden. How to solve these two problems simultaneously will be the main research direction in the future.

5. Conclusion

The article focuses on the basic structure and common sub-modules of MMC and analyzes the basic principles of multilevel circuits, level extraction methods, and characteristics of multilevel circuits. The paper introduces and summarizes four different topologies, i.e., monopole clamp multilevel topology, flyover capacitor topology, H-bridge cascade topology, and switched-capacitor multilevel topology, and explains their respective advantages, as well as the drawbacks and shortcomings that must be overcome in the future. Meanwhile, three MMC capacitor voltage balancing strategies are introduced in this paper, but these three strategies have the disadvantages of high cost, low stability, high device switching frequency, and high computational effort, respectively, which will be the key breakthrough direction for future research. With the help of MMC, the seamless connection between renewable energy and power system will be realized in the future, which will also stabilize the performance of the power system. Intelligent control and management is also a key development direction of MMC to realize more advanced control strategies, adapt to different operating conditions and load requirements, and improve the reliability and efficiency of power conversion. In the future, the development of new materials and semiconductor devices will bring higher performance and efficiency to MMCs, facilitating their wide application in various fields.

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