Overview on Submodule Topologies, Modeling, Modulation, Control Schemes, Fault Diagnosis, and Tolerant Control Strategies of Modular Multilevel Converters*

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Abstract: In the present scenario, modular multilevel converters (MMCs) are considered to be one of the most promising and effective topologies in the family of high-power converters because of their modular design and good scalability; MMCs are extensively used in high-voltage and high-power applications. Based on their unique advantages, MMCs have attracted increasing attention from academic circles over the past years. Several studies have focused on different aspects of MMCs, including submodule topologies, modeling schemes, modulation strategies, control schemes for voltage balancing and circulating currents, fault diagnoses, and fault-tolerant control strategies. To summarize the current research status of MMCs, all the aforementioned research issues with representative research approaches, results and characteristics are systematically overviewed. In the final section, the current research status of MMCs and their future trends are emphasized.

Keywords: Capacitor voltage balancing control, circulating current control, fault diagnosis, fault tolerant control, modular multilevel converters, modulating strategy, modeling scheme, submodule topology

1 Introduction

The rapid development of large-scale distributed generation, along with its energy transmission and other industrial applications, has led to high demands such as high power ratings, efficiency, reliability, and output performance for high-power converters[1]. The indirect conversion approach is widely adopted for high-power converters where a DC link is used between the rectification and the inversion sides. In general, the approach can be divided into voltage source converters (VSCs) and current source converters (CSCs) according to the DC link characteristic[2]. Compared with the solution of CSCs, power converters based on VSCs have low dependence on AC grid strength and can provide reactive power compensation under AC faults[3-4]. Thus, VSCs have great marketing penetration and application prospect[5-7].

According to the number of output voltage levels, VSCs can be categorized into two-level and multilevel converters[6]. To share the huge amount of current or voltage stress, insulated gate bipolar transistors (IGBTs) devices have to be paralleled or series connected in low-voltage two-level VSC converters (690 V)[9] or high-voltage two-level VSC converters (>2.3 kV)[10], respectively. However, as semiconductor devices have to operate under high dv/dt stress[11], two-level VSC converters are not suitable in high-power applications. On the contrary, multilevel converters have significant merits over two-level converters with low dv/dt stress and low output total harmonic distortion (THD), which signify that the size of input and output filters can be reduced[12-13]. Currently, commercial multilevel converters can be classified into neutral point clamped (NPC), flying capacitor (FC), cascaded H-bridge (CHB), and modular multilevel converter (MMC)[14]. Alternatively, various multilevel converters based on the aforementioned multilevel topologies are also developed (e.g., NPC+ cascaded H-bridge)[15]. NPC and FC converters generate multiple voltage levels by applying clamped diodes to the DC link and FC between two devices, respectively[16-17]. However, the switching and conduction losses of power devices are often unevenly distributed, and the voltage balancing issue among different FCs is hard to resolve[18].

* Corresponding Author, Email: fdeng@seu.edu.cn
* Supported by the Science and Technology Program of State Grid Corporation of China (5100-2019992330A-0-0-00)
Digital Object Identifier: 10.23919/CJEE.2020.000001
Using series-connected H-bridge sub-modules, the output voltage and power rating of the CHB converter can be easily increased. The main drawback of the converter is the need for a phase-shifting transformer to generate multiple isolated DC sources\cite{18}. Compared with the CHB, the MMC comprises series-connected sub-modules with floating capacitors. It means that the equipment volume and investment can be significantly reduced\cite{19}. Thus, MMCs are effective in high-voltage direct current (HVDC) transmission\cite{20-21}, medium-voltage drives\cite{22-23}, and other industrial high-power applications. The classification of the family of high-power converters is shown in Fig. 1.

![Figure 1: Family of high-power converters](image)

Submodules (SMs) are basic components in the MMC that determine the internal and external performances of the converter. Over the past years, several studies have focused on different aspects of SMs and their influence on MMCs\cite{24-25}. Besides, as MMC is a multivariable coupling system, the modeling scheme has a big impact on the accurate description of characteristics in MMCs. Based on the structure and mathematical modeling of MMCs, researches on different modulation strategies, capacitor voltage balancing, circulating current control methods, fault diagnoses, and tolerant operations have been increasingly attractive as hot spots\cite{26-28}. This paper provides a comprehensive overview of all the aspects of MMCs (mentioned here) and their future research prospects.

The rest of the paper is organized as follows: Section 2 presents an overview of several classical and latest researched SMs in MMCs, along with their performance analysis. Section 3 overviews different modeling schemes of MMCs, along with the comparison analysis of their effects. Section 4 introduces a classification of modulation strategies of MMCs and analyzes their features. Sections 5 and 6 present various control methods with capacitor voltage balancing and circulating current in MMCs, respectively. Section 7 focuses on fault diagnosis methods under different conditions, including IGBT, diode, and capacitor faults. Section 8 summarizes the fault-tolerant operation methods with MMCs. Finally, Section 9 concludes with the research status and future research trends of MMCs.

### 2 Analysis of SM topologies in MMCs

The generalized three-phase MMC topology is shown in Fig. 2. The MMC comprises six arms, marked as Arm 1 to Arm 6. A common DC link is connected across the positive bars of upper arms (Arms 1, 3, and 5) and negative bars of lower arms (Arms 2, 4, and 6), which are used to stabilize the DC link voltage and achieve bilateral energy transmission. All the arms are symmetrically connected among three phases (Phases A, B, and C), and the three-phase AC output bars are connected to the middle points of the upper and lower arms per phase, respectively. A group of SMs is series-connected, along with an inductor ($L_s$) in each arm. The arm inductor is used to limit the increasing rate of current under DC or AC short-circuit fault and compensates the imbalance between the phase voltage and the DC link voltage caused by fluctuations in capacitor voltage or other factors. Besides, a virtual resistor ($R$) is series-connected in each arm to describe the loss effect in the MMC.

Various SM topologies have been reported because of different application requirements\cite{29-30}. The most common is the half-bridge SM (HB-SM; Fig. 3a)\cite{31}. With two switches operating in a complementary state, HB-SM has two voltage-level output capabilities and offers high efficiency and reliability at a low cost. To further improve the output performance and reduce the footprint size of the MMC, SMs with multioutput voltage levels are presented. This multilevel SM category is represented by neutral-point-clamped SM (NPC-SM; Fig. 3b)\cite{32} and flying capacitor SM (FC-SM; Fig. 3c)\cite{33-34}. Although the available switching modes for MMCs are widely expanded, additional control methods are required to regulate the neutral point voltage within NPC-SM\cite{32} and balance...
different capacitor voltages within FC-SM. To reduce the control complexity, a cross-connected SM (CC-SM) combined with HB-SM and full-bridge SM (FB-SM) is applied \[36\], as shown in Fig. 3d. In normal operation, the CC-SM can be controlled in units with two HB-SMs and provide additional operation modes, e.g., HB-FB series-connected SMs, according to the control requirements.

Compared with the FB-SM, the clamped-double SM (CD-SM) can reduce the total number of switching devices used per arm in the MMC (Fig. 3f) \[^{37-39}\]. Another advantage of the CD-SM is that it contains multiple redundant operating states, which are quite suitable for fault-tolerant control. Similar to the CD-SM, the series-connected double SM (SC-SM; Fig. 3g) also has redundant operating states and can further reduce the number of diodes and enhance the DC fault current-blocking capability \[^{40}\].

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**Fig. 2** Generalized three-phase MMC topology

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(a) HB-SM topology

(b) NPC-SM topology
Moreover, the SM terminal voltage characteristics are influenced by its structure and operating principle. For the CD-SM, when the diodes, $D_{B1}$ and $D_{B2}$, are all conducted, the two capacitors are connected parallelly. Thus, the equivalent capacitance value is increased, which is beneficial for the capacitor voltage fluctuation suppression and the improvement of the SM terminal voltage characteristics. Besides, the double-submodule (D-SM) allows the parallel operation of the capacitors within SM and thus reduces the capacitor voltage fluctuation and the SM size (Fig. 3h)\textsuperscript{[41]}.

3  Review of modeling schemes of MMCs

The MMC is a multivariable coupling system that relies on multiple differential equations to accurately analyze its characteristics under transient and steady states. However, in actual MMC applications, multiple control objectives are required. To guarantee the response speed of the controller, the appropriate modeling schemes of MMCs are used to balance the
simulation accuracy and rapidity. Currently, various equivalent circuit models of MMCs are presented in literatures. As the number of SMs per arm in MMCs is more and the fluctuation is less than 10% of the average capacitor voltage\(^{[42]}\), the SM capacitors can be modeled as identical constant DC voltage sources, and the performance of the MMC is completely controlled by the switching SM number (Fig. 4)\(^{[43-46]}\). This simplified model allows a faster and relatively accurate model for the MMC in the steady state. However, as various harmonic components caused by the capacitor voltage fluctuation are neglected, this model is not suitable for situations where fluctuations in the capacitor voltage in MMCs are big or big disturbance in MMCs occurs.

![Fig. 4 Equivalent circuit of MMC based on ideal constant DC voltage source SM model](image)

To address this problem, the average-value modeling of MMCs is proposed on the basis of the simplification of the HB-SM as a two-port network model with controlled sources (Fig. 5)\(^{[47]}\).

![Fig. 5 Two-port network model with controlled sources](image)

Based on the control of equivalent switching function \(S\), the external characteristic of the two-port network model can be expressed as\(^{[47]}\)

\[
\begin{bmatrix}
V_{\text{vcs}} \\
i_{\text{vcs}}
\end{bmatrix} =
\begin{bmatrix}
S & 0 \\
0 & S
\end{bmatrix}
\begin{bmatrix}
V_c \\
i_c
\end{bmatrix}
\]  

(1)

where \(V_{\text{vcs}}\) and \(i_{\text{vcs}}\) represent the SM terminal voltage and current, respectively. \(V_c\) and \(i_c\) refer to the capacitor voltage and current, respectively. In fine switching function analysis, \(S\) is nonlinear and is determined by modulation strategy and capacitor voltage balancing control. Ignoring the high-frequency components that have low influence on \(S\), it can be linearized and the upper arm voltage of phase \(j\) \((j=a, b, c)\) can be expressed as\(^{[48]}\)

\[
v_{u,j} = \frac{N}{4C_{SM}} (1-m_j^*) \int i_{u,j}(1-m_j^*) dt
\]

(2)

where \(N\) and \(C_{SM}\) represent the number of SMs per arm and SM capacitance, respectively. \(m_j^*\) and \(i_{u,j}\) refer to the reference modulation index in the AC side and upper arm current of phase \(j\), respectively. A significant advantage of the equivalent-value circuit model is that the internal harmonic components of MMCs can be easily calculated by analyzing the THD of \(m_j^*\) based on formula (2). The equivalent average-value circuit model of MMCs is shown in Fig. 6\(^{[48]}\). The cyclic coupling relationship among the arm current, capacitor voltage fluctuation, and the circulating current is further explored and the relationship between the possible resonant frequency and MMC parameters has been provided\(^{[49]}\).

Several studies have focused on the modeling schemes of MMCs under special conditions. In terms of detailed dynamics and analysis of harmonic components in MMCs, the simulation accuracy based on the average-value model is unsatisfactory. To address this problem, a small-signal modeling based on the harmonic state-space (HSS) method is applied\(^{[50]}\) by transferring the periodically changing state variables in time domain to a series of constant values under complex frequency domain. Besides its high accuracy, another significant advantage of this method is that it can simultaneously represent multiple high-frequency responses of different state variables of MMCs (e.g. capacitor voltage, arm current, circulating current, and others). For the transient process modeling in MMCs, an MMC model based on the Thevenin equivalent algorithm is being analyzed\(^{[51-52]}\), which enables the valve-blocking capability during start-up and protective actions. This model can provide accurate internal and external behaviors compared with the detailed model\(^{[53]}\). Thus, it is suitable for simulating the transient characteristics of a large-scale DC grid with multiple MMCs. To further improve the simulation
efficiency, an optimal design method of MMC levels is proposed\cite{53}, and compromise between accuracy and computational efficiency is achieved. Moreover, a discrete time-domain SM model is also presented\cite{54}. In this SM model, each switching device in SM is replaced as a changeable voltage source in series with a resistor, and each device shows satisfactory simulation speed and stability.

4 Review of modulation strategies of MMCs

The essence of modulation in MMCs is to acquire the desired controllable voltage in arms or the AC side by controlling the gating signals of switching devices. However, owing to limited switching frequency, some internal characteristics (e.g. capacitor voltage fluctuation, distribution of energy and losses among SMs) and external characteristics (e.g. AC voltage harmonics) are all affected by different modulation strategies with the same reference waveform. Several studies have focused on the analysis of modulation strategies, along with their characteristics. Currently, the most widely used modulation strategies of MMCs can be categorized as multiple-carrier-based modulation, staircase waveform modulation, and space vector modulation.

4.1 Multiple-carrier-based modulation strategy of MMCs

The multiple-carrier-based modulation is a high-frequency modulation strategy that relies on the application of multiple triangular or saw-tooth carriers stacked symmetrically in vertical direction or displaced with fixed phase-shift in horizontal direction, respectively, named as carrier-disposition (CD) PWM or phase-carrier-shift (PSC) PWM. As the SMs per arm work in the PWM mode under this condition and the equivalent switching frequency is high, the multiple-carrier-based modulation strategy is suitable for MMC applications with a small number of SMs, e.g., flexible DC power distribution system. The CD-PWM strategy is further developed into phase-disposition (PD) PWM (Fig. 7a), phase-opposition disposition PWM (POD-PWM), and alternate-POD PWM (APOD-PWM) methods (Fig. 7b)\cite{55}. Through dual Fourier transform analysis, it is verified that the APOD-PWM method has the lowest low-harmonic components and is quite beneficial for single-phase multilevel converters\cite{56}. Moreover, it has the lowest THD, which is relatively high in the POD-PWM method. The disadvantage of the CD-PWM method is the unbalanced distribution of capacitor voltage fluctuation and energy among SMs and thus will cause large circulating currents and THD on the AC side. Several researches have been done through appropriately modifying CD-PWM methods to solve this problem\cite{57-59}. Based on the carrier rotation, an improved CD-PWM method is proposed where all triangular carriers are rotated among all SMs with a period of one carrier\cite{57}. This method has been verified to be efficient in balancing all capacitor voltages with no increased total switching losses or THD. Besides, a modified CD-PWM method based on the detection of the direction of arm currents and SM capacitor voltage status is analyzed to minimize capacitor voltage differences\cite{58}. A significant characteristic of this technique is that the comparison result of the reference modulation signal with the triangular carrier is not assigned to a particular SM. Focusing on the photovoltaic grid connection application, another improved CD-PWM method based on the selective virtual loop mapping (VSM) can further simplify the capacitor voltage difference minimization algorithm and is verified to be more easily realized\cite{59}. Another study reveals that high-frequency currents would be caused in the DC link with the circulating current suppression control by the CD-PWM strategy\cite{60}. Thus, a modified CD-PWM modulation strategy based on the variable carrier phase-shift angle is being analyzed to effectively solve the aforementioned problem\cite{60}.

Compared with the CD-PWM method, the characteristic of PSC-PWM modulation strategy, as shown in Fig. 7c, is mainly influenced by the phase-shift angle. Usually, the phase-shift angle is fixed and...
set as $2\pi/N$, where $N$ is the number of SMs per arm with the spinning reserve SMs included. This is beneficial for the natural balancing of SM capacitor voltages as the switching states are similar among all SMs and good output waveform quality is achieved. Moreover, the other modified PSC-PWM methods, along with corresponding influences, are analyzed\[61-63\]. The best capacitor voltage natural balancing phase-shift angle among different carriers can be found using the PSC-PWM method\[61\]. It has been proved that the PSC-PWM method with the interleaving angle between the upper and lower arm in one phase can achieve twice effective switching frequency than that without the interleaving angle\[62\]. In this way, the output THD of the MMC is improved but at the cost of the larger arm circulating currents. Another disadvantage of the PSC-PWM method is its relatively high switching losses because of its relatively high switching frequency. With additional capacitor voltage balancing algorithm, a low-carrier-frequency-based PSC-PWM technique is introduced\[63\]. As the switching frequency is not high enough, the introduced technique should be applied to MMCs equipped with a large number of SMs per arm to improve the output performance.

4.2 Staircase waveform modulation strategy of MMCs

The staircase waveform modulation of MMCs is a kind of low-frequency modulation strategy represented by the nearest level control (NLC) modulation and the selective harmonic elimination (SHE) modulation. The NLC modulation is realized by selecting the voltage level nearest to the desired reference waveform\[64\], as shown in Fig. 7d. Compared with the multiple-carrier-based modulation strategy, the equivalent switching frequency of the NLC modulation strategy is relatively low, and thus, it is widely used in MMC-based HVDC applications, where hundreds of SMs are equipped per arm; therefore, the output THD is quite low. To further improve the output performance, the NLC modulation is modified with the interleaving angle and can be equivalent to the carrier-based modulation\[65\]. Moreover, a new NLC scheme is applied considering the operation of redundancy SMs with reduced voltage harmonics and switching losses\[66\]. Compared with the NLC, the SHE modulation strategy is operated by calculating the switching angles to eliminate the specific low-order harmonic components in the output voltage of the MMC\[67\]. However, as the calculation complexity increases drastically with the increase in the voltage levels, the SHE method is often applied by referring to tables that contain precalculated switching angles\[68\].
4.3 Space vector modulation strategy of MMCs

Different from the modulations that control the MMC arm voltage, the space vector modulation (SVM) strategy directly controls the AC line-to-line voltages and generates phase voltages implicitly\(^{69-70}\). By flexibly selecting the switching states of MMCs, the SVM strategy is used to optimize the performance of MMCs, including optimized capacitor voltage fluctuations, circulating currents, and output voltage harmonics. However, the algorithm of the SVM strategy would be much complex with the increasing number of SMs and would be difficult to use in MMCs. Thus, several studies have researched on the optimization and improvement control of the SVM strategy. A sampling-time-staggered SVM strategy based on the SM regroup has been proposed, where three SMs from three phases, respectively, are grouped and controlled as one unit\(^{71}\). Compared with the traditional SVM strategy, this modified SVM algorithm can easily expand with the increasing number of SMs. Focusing on fully utilizing the redundant switching sequences and adjustable duty cycles of the SVM strategy, another optimized SVM strategy has been analyzed\(^{72}\). The advantage of this optimized SVM strategy is that the optimal capacitor voltage and circulating current control of MMCs can be easily achieved.

5 Review of capacitor voltage balancing control of MMCs

As the SM capacitors are floating in MMCs, different capacitor voltages among SMs must be balanced for the normal operation. Considering \(n\) SMs equipped per arm and the upper arm of phase A (as an example), the mathematical relationship of arm energy and capacitor voltage can be expressed as\(^{73}\)

\[
p_{up} = C \sum_{i=1}^{n} \left( u_{emi} \frac{du_{emi}}{dt} \right) = CV_{dc} \frac{dV_{dc}}{dt}
\]

where \(p_{up}\) and \(u_{emi}\) are the upper arm power of phase A and the \(i^{th}\) (i=1, 2, ..., n) capacitor voltage, respectively. \(C\) is the SM capacitance capacity and \(V_{dc}\) is the DC side voltage. Formula (3) reveals that the DC voltage balance, along with the balanced power distribution among the arms, are the preconditions of capacitor voltage balancing. Thus, a double closed loop is used for the capacitor voltage balancing in which the outer voltage loop maintains the balance of the DC side voltage, while the inner current loop regulates the DC current to achieve the active power balance\(^{74}\).

In fact, the capacitor voltage balancing is achieved by properly assigning trigger signals among the SMs. Various capacitor voltage balancing schemes have been proposed and can be classified into distributed and centralized approaches. A widely used distributed voltage balancing approach is shown in Fig. 8a, where a compensation modulation signal is generated according to the direction of the arm current and the voltage difference between the reference and the actual value\(^{75-76}\). Moreover, another novel distributed control scheme is analyzed in which good capacitor voltage balancing control effect is achieved through regulating the DC component in the capacitor current of the SM\(^{77}\). A significant advantage of this scheme is that it is irrespective of the value of current, which saves the cost of sensors and improves the control reliability. However, these approaches can be only applied with PSC-PWM modulation. Compared with the distributed control approach, the centralized control approach is implemented by selecting a certain number of SMs under the modulation schemes. As the voltage balancing is not achieved independently among SMs, this method can be applied with all the modulation strategies mentioned in Section 4\(^{78-80}\). An effective and widely applied scheme for centralized capacitor voltage balancing control is based on the capacitor voltage sorting method\(^{81-82}\) and is shown in Fig. 8b. In this approach, the voltages of all SM capacitors within an arm are measured and sorted in the descending or ascending order in every control cycle. Besides, the direction of the arm current is also detected. Suppose that \(N_{on}\) SMs are ready to be inserted in a certain arm according to the modulation result, the switching function of each SM in the arm is determined through such procedure: if the direction of the arm current is positive (negative), then the \(N_{on}\) SMs with lowest (highest) capacitor voltages are inserted while other are bypassed. Although good voltage balancing effect is achieved, the sorting-based method produces additional unnecessary switching states, and thus, additional switching power losses are caused. A reduced switching-frequency (RSF) capacitor
voltage balancing approach is used to solve this problem\[^83\]. In this approach, SMs are sorted to be switched on from the removed SMs when extra SMs need to be inserted into the arm. Similarly, SMs are sorted to be switched off from the on-state SMs when the number of expected inserted SMs decreases. When the number of expected inserted SMs is balanced, then the current gating signals among SMs do not change. In addition, a modified RSF method is analyzed, which further improves the voltage balancing effect by introducing a balancing adjusting number\[^84\].

Some other novel researches on capacitor voltage balancing have also been done. By assigning the low-frequency modulation pulses with different pulse widths, the capacitor voltage balancing process can be controlled at grid frequency\[^85\]. This method reduces power loss effectively and does not rely on the measurement of arm current. Based on the PSC-PWM modulation, another capacitor voltage balancing method is applied\[^86\] which also needs no arm current measurement process. In this method, the capacitor voltage balancing is achieved by controlling the high-frequency current components. Based on the linearization method for pulse sorting, another capacitor voltage balancing method is proposed\[^87\] and has several advantages\[^85-86\]. Moreover, the proposed method can reduce computational intensity and improve the arm current waveform quality. Other methods based on open-loop\[^88\], closed-loop\[^89\], and predictive control algorithms\[^90\] are analyzed to further improve the capacitor voltage balancing effect and are verified to be effective.

6 Review of the circulating current control of MMCs

Based on the actuate modeling for MMCs (Section 2), it can be further calculated from formula (2) that common voltages are generated in the upper and lower arms, which result in circulating currents flowing inside the MMCs\[^91\]. The characteristics of circulating currents can be summarized as follows\[^91\]:

1. The main component of circulating currents is second-order harmonic current of negative sequence.
2. The second-order harmonic current flows through three-phase arms with no impact on the AC side. The existence of circulating currents has additional dynamic influence on the performance of MMCs and, thus, should be controlled to an expected value according to different control targets. In general, the control targets can be classified as circulating current elimination and circulating current injection.

6.1 Circulating current elimination control

As the circulating current does not contribute to the AC current but distorts arm current and increases power losses in the arm, the circulating current is often expected to be eliminated. Therefore, various circulating current elimination schemes have been proposed. A simplest and straightforward method is increasing the inductance of arm inductors\[^92-93\]. However, this method can only suppress and not eliminate circulating currents. Furthermore, it increases the size and the total costs in MMCs. Based
on the estimation of the AC components of the arm current, a design method for arm inductor and SM capacitors can be used to suppress the circulating current\[94\], which improves the inductor design to some extent. The second-order harmonic circulating current can be suppressed by connecting LC double-fundamental frequency resonant filter between the bridge inductors\[95\]. However, the control effect is greatly affected by the parameters of LC resonant filters. To eliminate the circulating current completely, methods based on voltage compensation in MMC arms are widely used. The voltage compensation can be generated through an open-loop method based on the estimation of the arm energy\[96\]. However, the control effect relies on the precise measurement of AC output current and DC voltage, which puts high demand on the reliability and sensitivity of sensors. Compared with the open-loop method, a closed-loop control approach based on the three-phase decoupling control in synchronous-\(dq\) frame is widely used\[83,97\], as shown in Fig. 9a. In this decoupling control approach, the second-order circulating current is transformed into \(d\)-axis and \(q\)-axis components and controlled independently through PI controller. Thus, it can achieve perfect dynamic and steady-state control performance. Based on the similar control principle, the circulating current of each phase is suppressed independently based on the single-phase vector control\[98\]. Compared with the aforementioned approaches\[83,97\], this method can be applied to the multiphase system. The repetitive controller is used to further increase the bandwidth of the controller\[99-100\]. In addition, the proportional resonant (PR) controller, as shown in Fig. 9b, is also applied\[101\] considering the advantages of effective elimination effect on specific harmonic circulating current, fast response, and simple controller structure\[101-102\]. It is also suitable for circulating current control under unbalanced conditions, while additional sequence component control is required in decoupling control approaches\[20\]. To further improve the robustness of the PR controller, quasi-proportional-resonant (Quasi-PR) controller is applied\[102\], as shown in Fig. 9c. By appropriately reducing the gain of PR controller and increasing its bandwidth, the control effect, as well as anti-interference performance, is achieved.

Fig. 9  Circulating current elimination controllers

6.2 Circulating current injection control

Although circulating current elimination strategies mentioned in Section 6.1 can improve the arm current waveform quality and reduce power losses, it is not optimal for capacitor voltage fluctuation minimization, which has high impact on the AC output voltage quality. Injecting certain second-order circulating current based on the lookup table method is a feasible way to achieve this goal\[103-104\]. To further avoid the complicated lookup table procedures, the unified online calculation of the circulating current injection method based on instantaneous information of MMCs is analyzed\[105\]. In this scheme, the reference circulating current of phase A can be expressed as\[105\]

\[
\dot{\text{i}}_{\text{diff},\text{ref}} = \frac{m_a I_{\text{so}} \cos \phi}{4} + k I_{\text{so}} \cos (2 \omega t + \phi) \tag{4}
\]

where \(k\) can be selected according to the required capacitor voltage fluctuation and arm current value. Moreover, other related control variables in formula (4) can be determined through system level control. This formula is also applied in other optimal circulating current injection application conditions, such as variable-speed drives\[106\], loss optimization\[107\], energy storage requirement optimization\[108\], capacitor voltage balancing under PTG faults\[109\], and others.

7 Review of the fault diagnosis methods of MMCs

As mentioned in Section 2, a large number of SMs and power devices are integrated in MMCs. Thus,
the status of SMs and power devices directly affect the reliability of MMCs. Different SM fault causes are listed and classified, including interconnects, packaging, components, and operation conditions\cite{110}. However, the MMC faults caused by interconnects and packaging are random and hard to analyze and handle. Moreover, the main reason for MMCs faults caused by abnormal operation conditions, such as overload and high temperature, is the fault in components within SMs. A pie chart of different fragile components responsible for converter failure in power electronic systems is shown in Fig. 10\cite{111}. It can be seen from Fig. 10 that power devices and capacitors contribute nearly half of the component failure possibility. Thus, many researches have been conducted on fault diagnosis or monitoring methods on power devices (including IGBTs and diodes) and capacitors within SMs.

Different from the normal operation condition, a series of parameters of MMCs will change with the occurrence of faults. Thus, in general, two discriminant methods can be used to indicate a fault: on the one hand, the difference between the measured and reference values will exceed a certain threshold; on the other hand, certain patterns indicating faults are detected\cite{112}. The framework of the fault diagnosis of MMCs is shown in Fig. 11\cite{112}. First, some essential electrical quantities are monitored and sampled in each sampling period, and relevant sampled values are sent and collected in the interface. Then, the fault detection methods are activated to detect if any fault occurs in MMCs using the data information from the interface. Through filtration, normalization, and extraction, the fault features are extracted, which indicate certain fault type if some faults occur. Finally, the type and location of the occurred fault can be analyzed with specific fault diagnosis methods, including sliding mode observer, neural network, etc. This framework can be applied to all fault diagnosis methods mentioned below.

![Pie chart of different fragile components responsible for converter failure in power electronic systems](image1)

7.1 IGBT fault diagnosis method

In general, the IGBT faults can be categorized into short-circuit and open-circuit faults. As the IGBT short-circuit faults may cause overcurrent in MMCs, integrated short-circuit protections are commonly equipped with industrial gate drivers to shut down IGBT immediately as long as short-circuit is detected\cite{113-114}, which incurs additional cost. In contrast, the IGBT open-circuit fault may not seriously affect the normal operation of MMCs and may remain undetected for a long time. However, it may cause overvoltage (secondary damage) in power devices in the course of time. Recently, many researches have been conducted on the fault diagnosis methods for IGBT open-circuit faults in MMCs based on sliding-mode observer, Kalman filter, state observer, and others\cite{115-116}. The fault diagnosis criteria are based on different voltages and current characteristics under different fault conditions, as listed in Tabs. 1 and 2\cite{117}. Here, $S_1$ and $S_2$ are the IGBTs in the HB SM, as shown in Fig. 3a. $i_o$ and $i_a$ refer to the actual and ideal output currents, respectively. $i_c$ and $i_c^\sim$ refer to the actual and ideal circulating current, respectively.
Although the aforementioned methods\(^{[115-117]}\) can effectively diagnose the faulty IGBT, only the inverter mode of MMCs is considered here. In fact, the capacitor voltage of fault SM will maintain balance under the rectifier mode, and thus, no change occurs in the output or circulating current\(^{[118]}\). The lower IGBT open-circuit fault in SM can be diagnosed by detecting the capacitor voltage difference when the arm current is positive\(^{[118]}\). A significant advantage of this method is its feasibility for both inverter and rectifier modes of MMCs.

Although these state-observer-based IGBT fault diagnosis methods are more accurate, the fault diagnosis and fault location time taken is quite long and usually greater than one fundamental period. Moreover, a large computational burden is introduced, which may not be tolerated in engineering applications.

### 7.2 Diode fault diagnosis method

According to some related studies, the arm current will flow through diodes and the SM is in uncontrolled rectification mode when IGBT open-circuit fault occurs\(^{[115-117]}\). However, the arm current may be blocked when the diode open-circuit fault occurs. Thus, the arm inductor will generate a high self-inductive overvoltage, which is imposed on the SM terminal and generates overvoltage in power devices within an SM. Considering the turn-off time of IGBT, the generated high self-inductive overvoltage can be calculated and expressed as\(^{[119]}\)

\[
u_{\text{adi}(t_0)} = -L_s i_{\text{ua}}(t_0) / \Delta t
\]

where \(i_{\text{ua}}(t_0)\) represents the upper arm current of phase A at time \(t_0\) and \(\Delta t\) represents the normal turn-off time of IGBT. SM voltages under different diode fault conditions are listed in Tab. 3\(^{[119]}\) according to Fig. 3a. Here, \(D_1\) and \(D_2\) are diodes in the HB SM, as shown in Fig. 3a.

### 7.3 Capacitor monitoring method

Electrolytic capacitors are widely used in motor drives and micro-grids as their capacitance per unit volume is high\(^{[120-122]}\). However, owing to the chemical process or aging effect, the capacitor in MMCs would gradually deteriorate and the capacitance will drop\(^{[123-124]}\), which would affect the performance of the MMCs\(^{[125]}\). Thus, capacitor monitoring in MMCs is essential. Recently, many studies have focused on effective monitoring methods for SM capacitors. Thus, capacitor monitoring methods based on the recursive least square algorithm\(^{[123]}\) or the Kalman filter algorithm\(^{[124]}\) have been presented. However, the actual algorithm complexity is high and additional control strategies are required for it to be applicable to real MMCs. This reduces the reliability of the MMC system. A simple capacitance estimation monitoring method based on the relationship between the arm average capacitance and the capacitance in each SM is used to solve the aforementioned problem, in which the SMs’ switching states and capacitances are required\(^{[126]}\). As a modification for this method, a reference submodule (RSM)-based capacitor monitoring strategy is applied, which does not rely on the state information in each SM\(^{[127]}\). Another significant advantage of the RSM-based method is its simplicity, along with its feasibility.

Although the SM capacitance can be accurately
estimated using the aforementioned methods, another important parameter, equivalent series resistance (ESR), is often not considered, which also indicates the deterioration of capacitors. Usually, a capacitor is needed to be replaced when its capacitance drops below 80% of the rated value or its ESR is over 2 times of rated value\(^{[120]}\), as shown in Fig. 12\(^{[128]}\). Thus the increase of ESR can better reflect the deteriorated capacitor in comparison with the reduction of capacitance\(^{[129-131]}\). Recently, several studies focusing on the ESR monitoring methods have been reported, which are based on the recursive least square algorithm\(^{[132]}\), discrete Fourier transform algorithm\(^{[133]}\), Newton–Raphson algorithm\(^{[134]}\), short time least square Prony’s algorithm\(^{[135]}\), and artificial neural network algorithm\(^{[136]}\), respectively. However, the algorithm complexity of the ESR monitoring methods mentioned above limits their applications in MMCs. Besides, the ESR monitoring error is \(~5\%\) on an average\(^{[133]}\), which is still not high enough. Thus, a sorting-based monitoring method is reported; it monitors the capacitance together with the ESR of capacitors\(^{[137]}\). In this method, only capacitors with the biggest ESR or smallest capacitance are monitored. Thus, the monitoring algorithm can be quite simplified with the required accuracy.

When SM-level fault occurs, as mentioned in Section 7, the faulty SMs are separated and bypassed and the redundant SMs are inserted into the arm. In general, the redundant SMs are classified into cold reserve SMs and spinning reserve SMs. The cold reserve SMs are inserted into MMCs only under fault conditions. This operation mode has been named as Scheme 1 and shown in Fig. 13a\(^{[140]}\). As the cold reserve SMs do not participate in the normal operation of MMCs, the control system is easy to apply. Moreover, as the cold reserve SMs are usually bypassed by mechanical switches parallelly connected at the SM port, the caused losses or heat is minimal, which is advantageous for MMC applications with a large number of SMs, e.g., MMC-HVDC. However, the use of cold reserve SMs is relatively low, which incurs a high cost. The long charging time is often needed to initiate cold reserve SMs.

Fig. 12  Capacitor deterioration curve

8  Review of the fault-tolerant control of MMCs

As component faults are hard to be predicted and may affect the performance of MMCs, it is highly demanded that the normal operation of MMCs continues even under fault conditions\(^{[112]}\). In general, the fault types in MMCs include SM level faults (caused by component failure) and converter or system level faults (caused by asymmetric short circuit faults)\(^{[138]}\). For SM-level fault-tolerant control, redundant or spare SMs are integrated into arms\(^{[139]}\). On the contrary, the spinning reserve SMs operate as normal SMs; therefore, the arm transient current caused by SM failure is small, and the dynamic
performance of MMCs is excellent. However, the caused losses or heat is relatively high in this case\cite{141}. Thus, the spinning reserve SMs are advantageous for MMC applications where the number of SMs is relatively small and good dynamic performance of MMCs is required. The corresponding fault tolerant control strategies for spinning reserve SMs mainly include three schemes: Schemes 2, 3, and 4 (Figs. 13b\cite{140}, 13c\cite{142}, and 13d\cite{140}).

Except for bypassing the faulted SM, Scheme 2 also bypasses the same number of healthy SMs in the other five arms. Thus, a good energy-balancing effect is achieved for MMCs. However, the extra bypassed SMs lead to the low utilization of SMs. As an improved version of Scheme 2, Scheme 3 only bypasses the same number of healthy SMs in the other arm of the same phase, along with the faulted SMs. In this way, the phase unit with the faulty SMs can effectively balance energy, and the bypassed number of SMs is reduced\cite{142}. On the contrary, no additional healthy SMs are bypassed in Scheme 4. Thus, this scheme can achieve maximum utilization of SMs but at the cost of unbalanced energy distribution among the three phases. In this case, a fault-tolerant control method is analyzed; it effectively improves the energy balance in the MMC\cite{143}.

The main aim of a converter in system-level fault-tolerant control is to achieve power balance among different arms or phases of MMCs. Thus, fault-tolerant control methods based on arm-energy regulations are applied to suppress the power or capacitor voltage oscillations\cite{144-145}. Besides, according to different sequence component characteristics under different asymmetric faults, independent sequence control strategies are widely applied for the protection of MMCs and DC voltage harmonic suppression\cite{146-147}. In all, the effectiveness of fault-tolerant control is based on the accurate description of the transient MMC model under converter or system level faults.

9 Conclusions

Based on the development status of high-power converters, in this paper, an overview of the recent development of MMCs in terms of SM topologies, modeling schemes, modulation strategies, capacitor voltage balancing and circulating current control strategies, fault diagnosis, and tolerant control strategies has been summarized. As per the recent analyses, the capacity of MMCs is increasing, and the control or potential fault problems are becoming more complicated. As a result, the future research trends of MMCs are listed below.

(1) The SM topologies can provide multilevel output voltages.

(2) The SM topologies are equipped with redundant switching states and flexible to adapt to different fault-tolerant control strategies.

(3) Control strategies for MMCs should have faster response and better robustness characteristics.

(4) Artificial intelligence methods play a vital role in the state monitoring and process control of MMCs.

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