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SURVEY

Modular Multilevel Converter-Based Microgrid: A Critical Review

SAFIA BABIKIR BASHIR[1], ALI AHMED ADAM ISMAIL[1,2], (Member, IEEE), A. ELNADY[1,3], (Senior Member, IEEE), MENA MAURICE FARAG[1], ABDUL-KADIR HAMID[1], (Senior Member, IEEE), RAMESH C. BANSAL[1,4], (Senior Member, IEEE), AND AHMED G. ABO-KHALIL[1], (Member, IEEE)

[1]Smart Grid and Power Systems Research Group, Sustainable Energy and Power Systems Research Center, Research Institute of Sciences and Engineering, Department of Electrical Engineering, University of Sharjah, Sharjah, United Arab Emirates
[2]Department of Electrical and Electronic Engineering, Omdurman Islamic University, Omdurman, Sudan
[3]Department of Electrical and Computer Engineering, Royal Military College, Kingston, ON K7K 7B4, Canada
[4]Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0028, South Africa

Corresponding author: Safia Babikir Bashir (safia.mohamed@sharjah.ac.ae)

ABSTRACT Recently, the Modular Multilevel Converter (MMC) has drawn significant attention due to its diverse merits and its applicability to a wide range of medium to high-power applications. The growing interest in the MMC can be attributed to its attractive features such as modularity, reliability, and high voltage capability. Significant research has been conducted on the MMC over the last few years to develop its operation and control in various applications. However, the application of MMCs in microgrids remains a largely unexplored topic. Therefore, this paper aims to address this research gap by offering an in-depth review of the latest developments concerning circuit topologies, control schemes, and fault-tolerance strategies of MMC within microgrid applications. This comprehensive review not only provides a synthesized overview of the current state of the art but also paves the way for future investigations in this promising field. The outcomes from this study are expected to stimulate further advancements in MMC applications in microgrid systems, thus contributing to the continuous improvement and evolution of microgrids.

INDEX TERMS Control schemes, microgrid, modular multilevel converter, operational schemes.

I. INTRODUCTION

Over the last few years, renewable energy sources have become increasingly important for supplying the world's energy demand. They account for 25% of world energy consumption and 29% of its electricity consumption [1], [2], [3], [4]. With the development of technological platforms, renewable energy resources (wind turbines (WT) and photovoltaic (PV) arrays) have been promoted in different ways that facilitate their efficient operation, which brings economic, environmental, and technical benefits [5], [6], [7], [8], [9], [10], [11].

An example of such a platform is a microgrid (MG), which is a low-voltage distribution network with an integrated energy resource (distributed generators, storage devices, and flexible loads) and a control system that facilitates grid-connected or disconnected operation [1], [12], [13].

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MG can be divided into three types: DC MG, AC MG, and AC/DC MG (hybrid MG) [14]. In low-voltage systems such as smart buildings, military locations, and rural regions, AC microgrids are often used in which distributed generation units and loads are all connected to an AC bus [15], [16]. DC microgrids, on the other hand, have grown in popularity in recent years. It was found that the integration of renewable energy systems (RES) and energy storage systems (ESSs) into DC systems is more economically feasible than AC systems [17], [18]. In addition, DC power is also greatly needed to operate modern loads, such as variable-speed drives for elevators [19], [20]. The growing DC loads and DC sources have created an impetus to move from AC microgrids to DC microgrids. However, due to the widespread of AC power systems, hybrid microgrids would be a better choice, since both DC and AC microgrids properties are present in the hybrid microgrids [21].

In microgrids, power electronics converters are essential components because microgrids rely on them to integrate renewable energy sources [22], electrify transportation [23], store energy, and provide computing power [24]. The widely used power electronics converters in microgrids are based on two-level voltage-source pulse width modulation (PWM) converters [25], [26], [27]. The rise in energy consumption has resulted in the development of new topologies of power converters, such as multilevel converters [28].

The multilevel converter is an advantageous topology since it reduces harmonic distortion, eliminates semiconductor series connections, and reduces electromagnetic interference (EMI) The MMC is a modern multilevel converter topology, that merges the merit of multilevel converters with additional attractive characteristics. These include modularization, scalability, a shared DC bus, transformerless functionality, and fault ride-through capability [29], [30], [31].

Researchers have investigated the MMC extensively, and several review papers have been published on the MMC development over the last few years. Table 1 provides a summary of the available MMC review papers that outline the challenges that the MMC faces and the proposed solutions to overcome them. These challenges include modeling, control, reliability, power topologies, and emerging applications.

Modular multilevel converters (MMCs) are well-suited for microgrids for several reasons:

- MMCs have a modular structure, which means they can be easily scaled up or down to match the size and power requirements of the microgrid. This makes them highly flexible and adaptable to different applications and operating conditions.
- MMCs have a high power density, which means that they can handle large amounts of power in a small physical space. This is particularly important in microgrids, where space is often limited.
- MMCs have low harmonic distortion, which means that they can generate high-quality, sinusoidal AC power with minimal distortion. This is important in microgrids, where the quality of the power being generated and distributed is critical.

Despite the suitability of the MMC for microgrids application, the use of MMC in microgrids is still limited, and more research is needed in this area. In addition, there are no review papers addressing the MMC-based microgrid that can serve as a foundation for future research and can promote its use.

Therefore, this paper aims to fill this gap by providing a comprehensive review of the use of the MMC in microgrid applications, focusing on the following main contributions:

- Identifies the current state of knowledge and understanding of the use of MMCs in microgrids.
- Examines the benefits and challenges of using the MMC in microgrids.
- Identifies potential applications and feasibility of MMCs in microgrids.
- Determines the current trends and future directions of research on this topic.

This paper is organized as follows: Section II gives an overview of the MMC. The various MMC topologies used in microgrids are discussed in section III. Section IV provides a review of the control strategies for MMC in microgrids. A summary of fault detection and classification techniques is presented in section V. Section VI explores the use of MMC as frequency support for microgrids. A discussion of future trends and challenges is provided in section VII. Finally, the concluding remarks are given in section VIII.

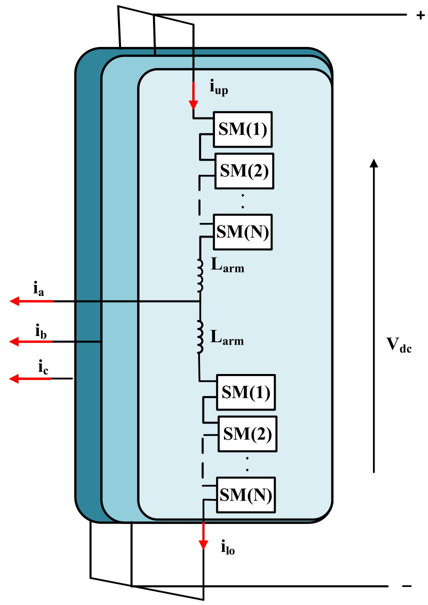

FIGURE 1. Three phase Modular Multilevel Converter (MMC).

II. AN OVERVIEW OF MMC

The MMC is an innovative converter topology, developed by Lesnicar and Marquardt [32]. This cutting-edge converter topology combines the advantage of the multilevel converters and other appealing features such as modularization, scalability, common DC bus, transformer-less operation, and fault ride-through capability [29], [30], [31]. As a result of these advantageous properties, MMCs have been extensively adopted in a variety of applications, including high-voltage direct current (HVDC) [33], motor drives [34], [35], flexible AC transmission systems (FACTS) [36], power electronic transformers (solid state transformers) [37], [38], uninterrupted power supply (UPS) [39], and integration of Energy storage systems (ESS) [40]. Generally, in the MMC topology, each phase is composed of two arms, which consist of N series-connected submodules (SMs) and a current-limiting inductor L_{arm} as illustrated in Fig. 1.

The MMC can utilize a variety of SM configurations to meet specific application requirements, such as blocking DC-side fault currents, minimizing capacitor voltage ripples and circulating currents, and optimizing efficiency [41]. Fig. 2 illustrates the most frequently used SM configurations in MMC.

The Half-Bridge Submodule (HB-SM), commonly referred to as a chopper cell, is depicted in Fig. 2 (a). This

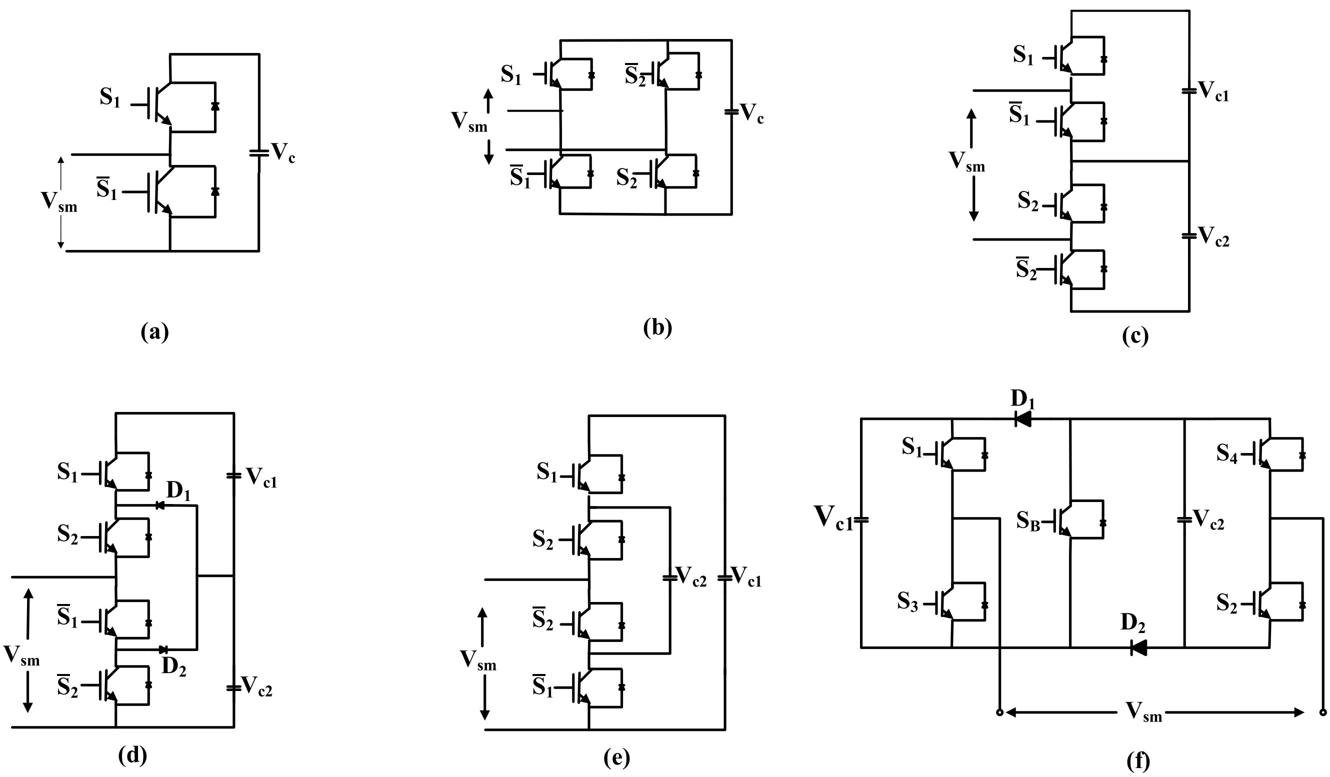

FIGURE 2. SMs circuit topologies (a) Half-Bridge (b) Full-Bridge (c) Cascaded H-Bridge (d) Neutral-Point clamped (e) Flying capacitor (f) Clamp double.

type of SM is widely employed in MMC-HVDC transmission systems. Owing to its simple construction, the HB-SM enables easy control and design execution. During standard operation, a single switching device remains in the "ON" state, resulting in decreased power losses and improved efficiency.

Nevertheless, the output voltage produced by the HB-SM is restricted to positive voltage levels (0 and V_c) and lacks the capability to accommodate bipolar functionality or DC fault blocking. To tackle the issue of DC-side fault currents, a technique that involves an antiparallel connection of thyristors across the AC output terminals of the HB-SM is proposed in [42]. The Full-Bridge Submodule (FB-SM), also referred to as an H-bridge circuit, presents its structure in Fig. 2(b). In comparison to the HB-SM for an equivalent voltage rating, the FB-SM demands twice the number of semiconductor devices. Nevertheless, the intricacy of control and design is comparable to that of the HB-SM. During standard operation, a pair of switching devices in the FB-SM conduct the current, leading to increased power losses and reduced efficiency. The FB-SM produces three voltage levels: 0, V_c, and $-V_c$. By employing the negative voltage level, the DC-side fault current can be eradicated from the system [65]. Given the same power rating and number of SMs, the FB-SM-based MMC necessitates only 50% of the total DC-bus voltage to generate a similar AC output voltage as the HB-SM-based MMC. As a result, each FB-SM capacitor can be designed with a voltage rating corresponding to 75% of the HB-SM rated voltage [66]. Moreover, the FB-SM-based MMC exhibits a reduced capacitor voltage ripple when compared to the HB-SM-based MMC.

Enhancing the efficiency and performance of SMs can be achieved by replacing the traditional SMs with multilevel SMs. While multilevel SMs effectively reduce the footprint of MMCs, they introduce greater design complexity. Within the MMC context, multilevel SMs provide a significant number of redundant switching states, which notably improve the controllability of the SM capacitor voltage. In recent years, as depicted in Fig. 2, a diverse range of multilevel SMs has been developed and investigated for their potential applications in MMCs.

By linking two HB-SMs in a series arrangement, a Cascaded H-Bridge Submodule (CHB-SM or CH-SM) can be established, as illustrated in Fig. 2(c). This configuration yields three distinct voltage levels at the SM AC output terminals. The primary attributes of the CH-SM include simple control and minimized design complexity. In addition, the CH-SM exhibits low device power loss and high efficiency attributes similar to the HB-SM.

The three-level Neutral Point Clamped SM (3L-NPC-SM) comprises four semiconductor devices, a pair of clamping diodes, and two capacitors as depicted in Fig. 2 (d). The main challenges faced in the NPC-SM include loss distribution between devices and maintaining a balanced neutral-point voltage [67]. As a result of the neutral-point balancing challenges, the operational range of the NPC-SM becomes

TABLE 1. Comparison of recent state-of-the-art review articles on MMC with this article.

Article	Contributions
[43]	Discussed the implementation of MMC configurations, and its operation, and control in stationary applications. A detailed discussion is given to compare the control methods under different grid conditions and the challenges that are expected.
[44]	Reviewed the various MMC circuit topologies available in the scientific literature, providing a generalized discussion on their applications in HVDC transmission systems.
[45]	Explored recent research in MMC power-based converter aspects such as modelling, control strategies, power balancing topologies, and emerging applications.
[46]	The article reviewed various MMC circuit topologies used for PV application integration. Focusing on the latest submodule topologies employed in PV application. Besides, different control methods are discussed under balanced and unbalanced grid conditions.
[47]	Focused on different topologies and technical challenges for MMC and their associated submodule circuit design for PV applications. Multiple power balancing strategies are discussed to provide an appropriate solution for large-scale grid-connected PV systems.
[48]	Reviewed the active power balancing strategies that are actively used in the operation of the MMC under unbalanced operating conditions in large-scale PV applications and the unequal power sharing in battery energy storage systems (BESS).
[49]	Discussed the various MMC circuit structures including traditional and novel proposed structures, highlighting their control strategy, modulation techniques, and the applications where such structures are used.
[50]	Reviewed the contributions made in MMC circuit design, technical challenges, fault-tolerant techniques, and control methods in MMC-based electric transportation application.
[51]	Comprehensively reviewed and classified the recent submodule circuit topologies. A comparative assessment is provided to discuss the loss comparison of submodule configurations.
[52]	Reviewed the current MMC circuit topologies and their respective mathematical models. Besides, control strategies such as classical and model predictive control (MPC) are discussed along with modulation techniques. The various applications of MMC and their possible challenges are further explored in this study.
[53]	Investigated the MMC in detail including various components such as the topological variants, modulation techniques, modeling and capacitor voltage balancing techniques, fault-tolerant techniques, control strategies, and providing future trends and prospective challenges.
[54]	Provided an overview of multiple research issues present with the deployment of MMC for high-voltage and high-power applications such as fault diagnoses and fault tolerant control techniques, submodule topologies, and control strategies for effective voltage balancing. The article systematically reviewed the present approaches based on the reported results and characteristics from the literature.
[55]	Extensively reviewed the reported state-of-the-art dc fault protection techniques for MMC based HVDC grids. In particular, the dc fault characteristics were analyzed in terms of frequency, time, and modal domains which facilitate the protection design.
[56]	Comprehensively reviewed the control and protection strategies for MMC-based multi-terminal direct current (MTDC) systems. An overview of the present issues and challenges related to their deployment was reviewed. In addition, DC fault detection and localization algorithms are explored to provide AC system support for robustness of such systems. Finally, prospects are provided in detail in the development of MTDC based systems.
[57]	Explored the electromagnetic interference (EMI) issues present due to nonlinear switching behavior in MMC submodules. Different EMI sources are reviewed by analyzing various topologies and modulation methods. Furthermore, EMI reduction methods are summarized to provide minimal propagation of EMI.
[58]	Reviewed various types of faults associated with MMCs and discussed various protection schemes under failure conditions. An extensive discussion on fault diagnosis and control techniques to overcome various MMC faults.
[59]	Comprehensively reviewed various submodule and MMC topologies that are capable of overcoming DC faults and ride-through and are assessed in terms of component requirements, semiconductor losses, and DC fault handling ability.
[60]	Offered a detailed overview of current DC-DC modular multilevel converter topologies for HVDC, and DC-DC MMC control techniques.
[61]	Provided a comparative analysis of various concepts of MMC to maximize its potential in integration with medium-voltage (MV) and high-voltage (HV) applications. Different topologies are discussed presenting their merits and demerits, providing computational simulation and comparison of existing cascaded full-bridge topologies.
[62]	Contributed comprehensively to reviewing the recent progress in MMC in terms of the SM configurations deployed. A systematic assessment of various models of MMC, to provide appropriate selection based on application and desired accuracy.
[63]	Presented and reviewed leading laboratory scale prototypes for MMC implementation, summarizing the development of MMC testbench to indicate critical design considerations when constructing laboratory-scale cascaded multilevel converters (CMCs) and MMC.
[64]	Presented an overview of the various MMC applications and the deployed circuit configurations. The article discussed various topologies, modelling techniques, modulation strategies, fault-tolerant strategies, and voltage balancing techniques.
This work	This work reviews the MMC in microgrids as an unexplored topic within MMC applications. A detailed discussion is presented for the evolution of circuit design schemes, control strategies, and fault-tolerant strategies to facilitate the use of MMCs in microgrids' applications. As a result, this study provides a pathway for future research in MMC deployment in microgrid applications.

constrained at higher modulation indices [68]. In comparison to the HB-SM, the NPC-SM exhibits higher power losses in devices and diminished efficiency.

The three-level flying capacitor SM (3L-FC-SM) consists of four semiconductor devices and incorporates a nested cell design, as shown in Fig. 2 (e). By providing identical gating signals to switching devices S1 and S2, the FC-SM can operate similarly to an HB-SM. This distinctive characteristic allows researchers to examine the performance of not only HB-SM and FC-SM but also hybrid MMC systems (consisting of both HB and FC-SM) using solely the FC-SM [69]. In comparison to HB-SM-based MMCs, the FC-SM-based MMC demonstrates lower capacitor voltage ripple and circulating currents; leading to enhanced efficiency. Nonetheless, the FC-SM produces exclusively positive voltage levels and is unable to block the DC-side fault current.

Another type of the hybrid SM is the three-level clamp-double SM (CD-SM) [70]. As shown in Fig. 2 (f), a CD-SM configuration is achieved by connecting two HB-SMs in series and adding two extra diodes and an IGBT. During regular operation, the switching device SB in Fig. 2 (f), consistently maintains an "ON" state, thus facilitating a cascaded connection between two HB-SMs. In the event of a DC fault, all devices in the CD-SM switch to the "OFF" state, yielding positive or negative voltage levels at the output, depending on the current flow direction. Thus, the CD-SM proves valuable in HVDC applications for mitigating DC-side fault currents [71]. However, the inclusion of extra devices leads to considerable increases in power losses, diminished efficiency, and greater design complexity. A summary of MMC's different SM configurations is provided in Table 2.

III. MMC-BASED MICROGRID TOPOLOGIES

An overview of MMC-based microgrid topologies is given in this section. The first subsection discusses the different topologies when the MMC is used as an interlinking converter for hybrid microgrids. The second subsection addresses the different topologies when MMC is used as an interface converter for Distributed Energy Resources (DERs).

A. MMC AS A GRID-INTERLINKING CONVERTER

Multi-terminal hybrid AC/DC microgrids have gained tremendous attention from researchers all over the world due to the large-scale integration of distributed generators (DGs) and the growing demand for medium- and low-voltage DC power [72]. There are usually three stages of power conversion in conventional multi-terminal hybrid AC/DC microgrids. Therefore, to reduce the number of conversion stages and to meet transmission demands, several research papers have proposed the use of MMC as an interlinking converter.

The utilization of an MMC-based power electronic transformer (PET) is provided in [73]. This topology integrates the half-bridge (HB) Submodule (SM) of the MMC with a Dual Active Bridge (DAB) converter and connects the output terminals of the DAB converters to a common Low voltage AC (LVAC) grid via DC/AC converter. As illustrated in Fig. 3, this multi-terminal hybrid microgrid contains one Medium-Voltage AC (MVAC) microgrid, one Medium-Voltage DC (MVDC) microgrid, and one LVAC microgrid, which makes power transmission less flexible.

In [74], [75], [76], [77], and [78], an improved MMC-based hybrid AC/DC microgrid is proposed. It differs from the above-mentioned topology in that the low-voltage DC (LVDC) microgrid is connected to each SM-DAB or LVAC

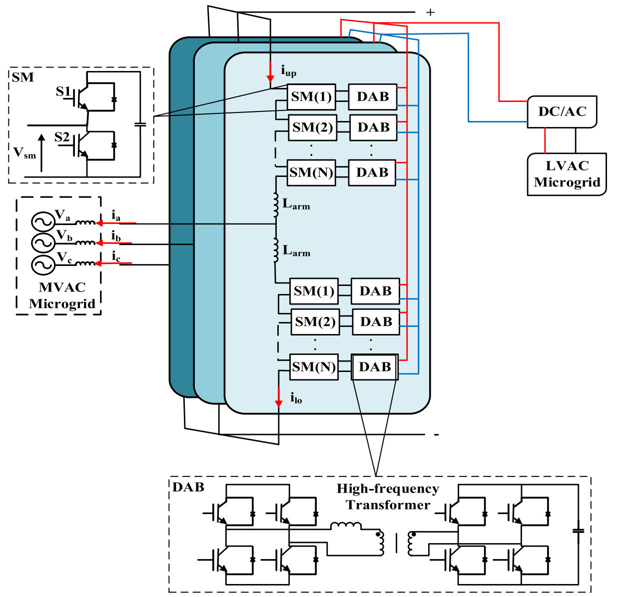

FIGURE 3. MMC-based hybrid AC/DC microgrid in [73].

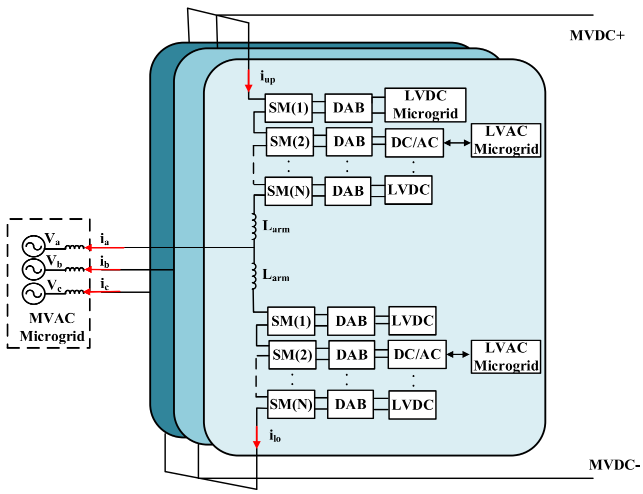

FIGURE 4. MMC-based multi-terminal hybrid AC/DC microgrid in [74], [75], [76], [77], and [78].

microgrid is connected to each SM-DAB via a DC/AC converter, as shown in Fig. 4.

The use of this topology increases the number of microgrids that can be linked together, which increases power feasibility. However, when the distribution of the power between different LVDC and LVAC microgrids is unequal, this topology is prone to various control challenges.

To improve the system's ability to operate during unbalanced power distributions, each DAB converter is interconnected to an SM, and the output terminals of the DAB in each arm are connected to an LVDC microgrid, as reported in [72]. This topology increases the power transmission flexibility since it connects two LVDCs, one MVDC, and a MVAC as shown in Fig. 5. Nevertheless, it still faces a limited operating capability during unbalanced power distribution between the

TABLE 2. Comparison of different MMC submodule topologies.

Type of MMC Submodule	Configuration	DC Fault Blocking	Voltage Levels	Complexity	Power Losses	Applications
Half-Bridge (HB-SM)	Fig 2 (a)	NO	2 levels	Low	low	HVDC, FACTS devices, Microgrid
Full-Bridge (FB-SM)	Fig 2 (b)	Yes	3 levels	Low	Moderate	Medium-voltage drives, grid integration of renewables
Cascaded H-Bridge (CH-SM)	Fig 2 (c)	NO	3 levels	Low	Low	Medium-voltage drives, renewable energy systems, active filters
Neutral Point Clamped (3L-NPC-SM)	Fig 2 (d)	NO	3 levels	High	Moderate	Medium-voltage drives, grid integration of renewables, FACTS devices
Flying Capacitor (3L-FC-SM)	Fig 2 (e)	NO	3 levels	High	High	Medium-voltage drives, grid integration of renewables, active filters
Clamp-Double (CD-SM)	Fig 2 (f)	Yes	3 levels	High	High	HVDC applications for mitigating DC-side fault currents

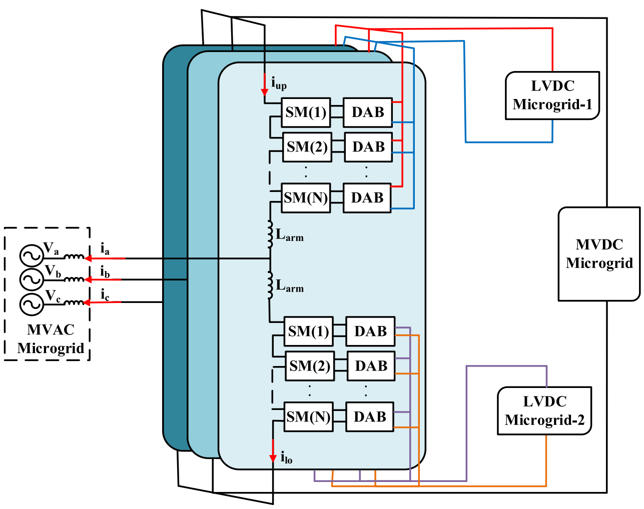

FIGURE 5. MMC-based multi-terminal hybrid AC/DC microgrid in [72].

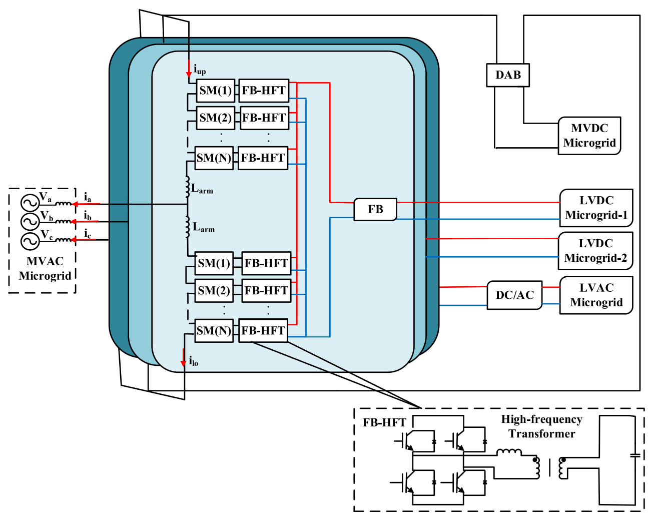

FIGURE 6. MMC-based multi-terminal hybrid AC/DC microgrid in [79].

LVDC microgrids that are connected to the upper and lower arm of the MMC.

A five-terminal hybrid AC/DC microgrid system based on MMCs is proposed in [79] to enhance the interconnection flexibility and the system operation capability when the power distribution is unbalanced. In this topology, each half-bridge SM is connected to a Full-Bridge High-Frequency Transformer (FB-HFT). The output terminals of FB-HFT of each phase (Phase A and B) are connected to a LVDC microgrid through a Full-Bridge (FB). The output terminals of FB-HFT in phase C are connected to a FB and then to a LVAC microgrid through a DC/AC converter. As illustrated in Fig. 6, this five terminal hybrid AC/DC microgrid connects one MVAC microgrid, one MVDC microgrid, one LVAC microgrid, and two LVDC microgrids, which will increase the consumption of clean energy and strengthen the mutual support between the different microgrids. A comparison of the above-mentioned topologies is given in Table 3.

MGs are directly connected to the MMC in the aforementioned topologies. It is also possible to connect multiple microgrids that are geographically close to each other via a distribution feeder. An advanced microgrid interface called the Hybrid Unit of Common Coupling (HUCC) that replaces the conventional Point of Common Coupling (PCC) is proposed in [80] and [81]. The MMC serves as the core component in the HUCC and provides both AC and DC

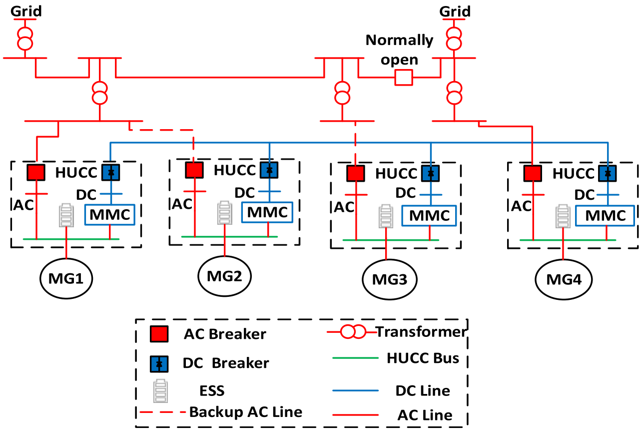

FIGURE 7. HUCC-based microgrid in [80] and [81].

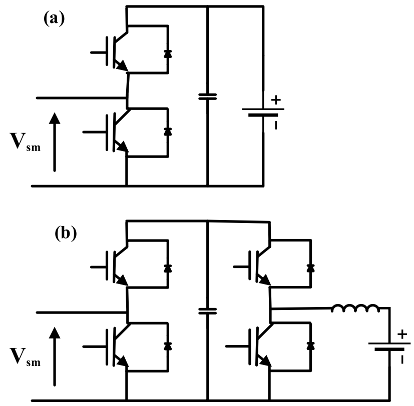

FIGURE 8. SMs configurations used in the MMC based BESS (a) Direct connection (b) connection through DC-DC converter.

interfaces. As shown in Fig. 7, the HUCC is composed of an energy storage system (ESS), and three buses, including the HUCC bus, the AC bus, and the DC bus. The ESS facilitates the transfer of power between microgrids. HUCC buses connect the microgrid to the two other buses (DC and AC). The AC bus connects the MG to the host utility grid while the DC Bus is used to connect the MGs together. The MMC is used as a rectifier Between the DC bus and the HUCC bus. The replacement of the PCC with the proposed HUCC has led to improved coordination between the microgrids and provided more flexibility in the configuration.

B. MMC AS INTERFACE CONVERTER FOR DISTRIBUTED ENERGY RESOURCES (DERs)

The use of the MMC for solar PV applications is still under investigation. MMC-based PV topologies can be categorized into those that integrate PV into the MMC's common DC link and those that integrate PV arrays into the MMC SMs.

In [82], a large number of PV modules have been connected to the common DC link of a single-phase MMC. Despite the simplicity and cost reduction provided by this topology, its energy yield is reduced during partial shading or module mismatch. This reduction in energy is due to the use of only one maximum power point tracking (MPPT) for several PV strings.

A new MMC topology for PV module integration has been presented in [83], where its proposed topology replaces MMC arm inductors with open-ended transformers. The advantage of this topology is that it reduces the electrical stresses in MMC, the voltage rating of power devices, and the size of SMs capacitors. The PV modules in this topology are also connected directly to the DC link, so only one MPPT is used for several PV strings, which will result in reduced energy yield when partial shading occurs.

A Multi-string PV topology that utilizes DC/DC converters connected in parallel to form a DC link as an input to MMC was depicted in [84]. This topology provides distributed MPPT among PV strings. However, since these PV strings represent the DC link of the MMC, they are forced to work near their maximum power during shading to ensure that the MMC DC link voltage is constant. Further, DC/DC converters do not provide galvanic isolation for PV systems, making the use of a low-frequency transformer necessary, which will increase the system's cost and losses.

The integration of solar PV into the MMC SMs has been proposed recently [85], [86], [87], [88]. This integration of PV arrays into the SMs has emphasized the modularity and scalability features of the MMC, and it can improve efficiency and reduce the costs of the whole system [89], [90]. Moreover, it facilitates the independent MPPT of the PV arrays. This integration of PV arrays into the SMs introduced a new challenge which is unbalanced power during inhomogeneous irradiation. The proposed solutions in the literature to this problem are given in detail in section IV.

Despite the MMC's apparent suitability for PV applications, so far, no studies have been done to compare the performance of the MMC-based PV systems with the currently available PV plants.

The MMC has recently attracted researchers' attention when it comes to the integration of battery energy storage systems (BESSs) [91], [92], [93], [94], [95], [96], [97]. BESSs are generally integrated into SMs of the MMC, and there are two methods for connecting the batteries to the SMs of the MMC. In the first method, the batteries are directly connected to the SM capacitors, as shown in Fig. 8 (a) [98]. Fig. 8 (b) shows the second method where the batteries are connected to SMs through DC-DC converters [90], [91], [97]. The drawback of directly connecting the batteries to the capacitors of the SM is that the batteries will be exposed to the second harmonic current/voltage. Thus, batteries must be protected from these harmonics by increasing the size of the SM capacitors. On the other hand, with the DC-DC converter in the second method, the batteries are decoupled from the SM capacitors which reduces the DC-filter requirement for the batteries, increases its lifespan, and reduces the SM capacitor requirement.

Wind Energy Conversion Systems (WECSs) are used in a wide range of applications nowadays, including microgrids.

TABLE 3. Comparisons between the proposed MMC based multi-terminal hybrid microgrid.

	Fig. 3 [73]	**Fig. 4** [74]–[78]	**Fig. 5** [73]	**Fig. 6** [79]
Number of LV MG (AC or DC)	1	6×N (N is the number of SM in each arm)	2	3
Functionality during power unbalance	High	Low	Medium	High
IGBT count for N=4 SM (N is the number of SM in each arm)	244	240+4×x (x is the number of LVAC)	240	170
Advantages	- Unbalanced power distribution does not pose a control challenge.	- Multiple LV microgrids can be integrated.	- Enhanced functionality during unbalanced power distribution.	- Fewer IGBTs are needed Compared to existing MMC-based hybrid microgrids. - MGs can operate in the grid feeding mode and grid forming mode.
Disadvantages	- Only one LVAC MG is connected.	- Operation is limited under unbalanced power.	- Increased loss due to the injection of the circulating current to balance the power. - The MGs operate only in the grid feeding mode.	- Increased loss due to the injection of the circulating current to balance the power.

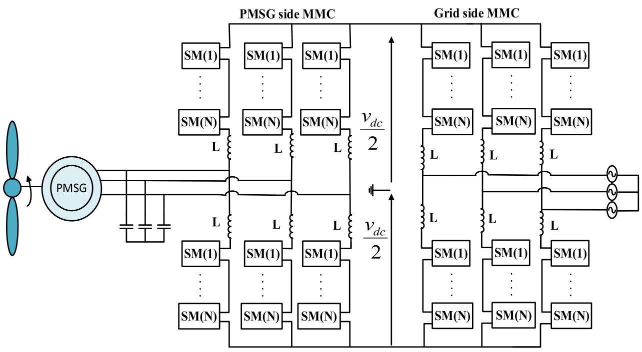

FIGURE 9. BTB-MMC based PMSG wind power system.

These systems consist of a permanent magnet synchronous generator (PMSG) together with a wind turbine and a power electronic interface [99]. Reference [100] proposes the use of Back to Back MMC (BTB-MMC) as an interface converter for WECS as illustrated in Fig. 9. The main drawback of this topology is the severe SM capacitor voltage fluctuation that results from the low frequency of the stator current of the wind power generator. Hence, this topology is not widely used in WECS applications.

In [21] and [101], an MMC with full-bridge SMs was used in WECS with a three-phase open-winding PMSG. The problem with this simple topology is that the generator suffers from current distortion and power losses due to the zero-sequence current of the open windings. A modular multilevel matrix converter for the WECS was used in [102], as shown in Fig. 10. This topology increases the efficiency since it is a one stage conversion. However, this topology has many internal channels for loop currents, which requires a complex control system [103]. Another one-stage conversion topology was proposed in [104], which is based on a hexagonal modular multilevel converter. The advantages of this topology include low power losses, low capacitor voltage ripple, and transformer-less grid connections. A summary of the above mentioned MMC-based topologies for different DERs is presented in Table 4.

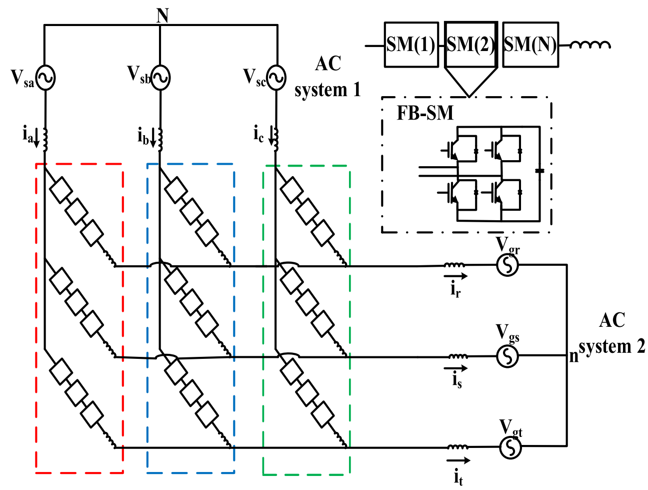

FIGURE 10. Topology of the modular multilevel matrix converter.

IV. CONTROL STRATEGY

Multiple objectives must be met simultaneously as part of the control objectives/outcomes of the MMC. The control must maintain the target voltage for all SM capacitors for the proper operation of the MMC. The control objectives can also include reducing switching losses, mitigating ripple voltages in SM capacitors, and minimizing the harmonic content in circulating currents [105], [106], [107]. Some of these objectives conflict with each other; therefore, when developing

TABLE 4. Summary of MMC-based topologies for different DERs.

DERs	Topology	Reference(s)	Advantages	Disadvantages
Solar PV	MMC with PV modules connected to the common DC link.	[82]	- Simplicity and cost reduction.	- Reduced energy yield during partial shading or module mismatch.
	MMC with open-ended transformers replacing MMC arm inductors.	[83]	- Reduced electrical stresses, voltage rating of power devices, and SM capacitor size.	- Reduced energy yield during partial shading.
	Multi-string PV topology with DC/DC converters connected in parallel forming a DC link to MMC.	[84]	- Distributed MPPT among PV strings.	- PV strings are forced to work near maximum power during shading. - No galvanic isolation. - Increased costs and losses due to the use of low frequency transformer.
	Integration of solar PV into the MMC SMs.	[85]–[88]	- Facilitates the independent MPPT of the PV array. - Reduced costs. Improved efficiency.	- Unbalanced power during inhomogeneous irradiation.
BESS	Direct connection of batteries to SM capacitors.	[98]	- Simplicity.	- Exposure to second harmonic current/voltage. - Increased SM capacitor size.
	Connection of batteries to SMs through DC/DC converters.	[90], [91], [97]	- Reduced DC-filter requirement. - Increased battery lifespan. - Reduced SM capacitor requirement.	- Increased cost.
WECS	Back-to-back MMC as an interface converter.	[100]	- Simplicity.	- Severe SM capacitor voltage fluctuation.
	MMC with full-bridge SMs used in WECS with a three-phase open-winding PMSG.	[101] ,[21]	- Simplicity.	- Generator suffers from current distortion and power losses due to zero-sequence current open windings.
	Modular multilevel matrix converter.	[102]	- Increased efficiency since it is one stage conversion.	- Complex control system due to many internal channels for loop currents.
	Hexagonal modular multilevel converter-based topology.	[104]	- Low power losses. - Low capacitor voltage ripple. - Transformer-less grid connections.	- Complex control system

the control strategies, a trade-off between these objectives must be considered. There is a wide range of literature on MMC control strategies. In general, the control structure of the MMC can be divided into two levels: the high-level control and the low-level control as illustrated in Fig. 11. The high-level control utilizes the two degrees of freedom of MMC, which are output current control and circulating current control to achieve DC/AC power balance (grid synchronization) and energy balance between the arms. On the other hand, the low-level control determines the gate signals of submodule switches according to the references and the measured values, in addition to balancing the submodule capacitor voltages within each arm.

A. MMC AS INTERLINKING CONVERTER

1) CONTROL METHOD

The multiterminal microgrid that is shown in Figs. 5 and 6 can be controlled in various ways. In general, the grid-feeding approach is used if the voltage in the MGs is determined

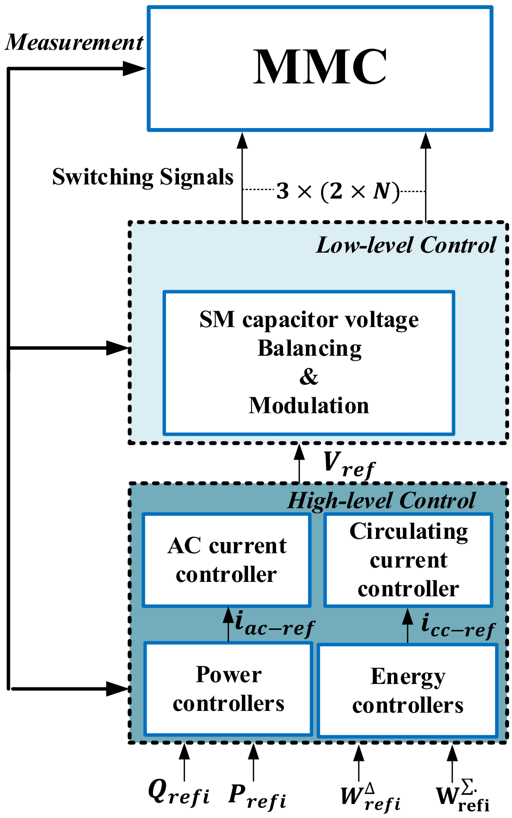

FIGURE 11. The hierarchical control structure of the MMC.

externally (by the grid). The power transfer among the MGs is regulated in the grid-feeding approach. In contrast, a grid-forming approach is used when MGs voltages need to be internally established. It is not possible to achieve power balance by configuring all MGs in grid-forming mode since the power is not controlled in this case. Thus, the operation mode of at least one MG must be set to grid-feeding mode. Despite the approach (grid-feeding or grid-forming) being implemented, the capacitor voltages of the MMC SMs must always be maintained at their target voltage [108]. Generally, the control system includes the control of the MMC and the MGs interlinking converters (DAB or FB-HFT). Fig.12 illustrates the control structure of the MMC, which includes AC output current control and DC circulating current control. Regardless of the approach used (grid-feeding or grid-forming), the MMC is controlled in the same way (vector control strategy). Thus, the MGs interlinking converters (DAB or FB-HFT) are responsible for controlling the MG power if the grid-feeding approach is used or MG voltage if the grid-forming approach is used.

The vector control strategy is used to control the MMC output AC current in the multiterminal microgrid. This strategy controls the converter voltage to follow a current reference injected into the AC system. It requires the transformation of the three-phase system to the DQ synchronous reference frame. One of the most useful features of using vector control is that the vectors of the AC voltages and currents after the DQ transformation appear as constant vectors in steady state, and hence simple PI controllers can be used to remove the static errors that appear in the control system. This control strategy is realized in the form of a cascade structure, with two control loops in cascade. The outer control loop provides the set points to the inner current control loop [88].

In Fig. 12, the active current reference i_d^* is obtained from a PI controller that is based on the voltage error between the sum of all SM capacitor voltages and its reference. If the sum of the capacitor voltages is lower than the reference, the MMC absorbs the active current. On the other hand, if the sum of all SM capacitor voltages is higher than the reference, the MMC injects active current. The reactive current reference i_q^* is calculated by the MVAC reactive power requirements for reactive power compensation, which is $i_q^* = 2 \times Q\mathrm{MVAC}/3Vg$ (QMVAC is the reactive power of the MVAC grid and Vg is the amplitude of the MVAC grid voltage). A Phase Locked Loop (PLL) is utilized to determine the phase angle which is necessary to transfer the voltages and currents between the ABC reference frame to the DQ reference frame. The inner control loop generates the necessary d-axis (v_d) and q-axis (v_q) voltage components. Once these voltages have been generated, they are converted to the ABC reference frame (v_a, v_b, v_c) and sent to the balancing system along with voltage generated from the circulating current control to generate MMC gate pulses. Typically, the circulating currents control method is used to reduce the MMC losses by suppressing the second harmonic component of the circulating current [109], [110], [111]. However, in multiterminal MGs, the circulating current is also used to regulate the arm and leg voltages of the MMC. In order to control the leg voltages, DC circulating current components are injected into each phase leg. On the other hand, the arm voltage is controlled by injecting a fundamental component into the circulating current. Controlling the voltage between the MMC arms and legs will result in a balanced power between them.

2) PULSE WIDTH MODULATION (PWM)

There are several pulse width modulation (PWM) techniques available for generating gating signals for the MMCs. Based on switching frequency, these pulse width modulation (PWM) techniques can be organized into three categories: high switching frequency PWM (HSF-PWM), medium switching frequency PWM (MSF-PWM), and fundamental switching frequency PWM (FSF-PWM) [52], [112]. An increase in the switching frequency leads to an increase in the semiconductor switching losses. Thus, when a small number of submodules is employed, the high switching frequency method is generally used, whereas when substantial submodules are involved, the low switching frequency and fundamental switching frequency schemes are used [113].

The carrier-based PWM method falls under the HSF-PWM category, and it creates gating signals for multilevel converters by comparing the modulation reference of each

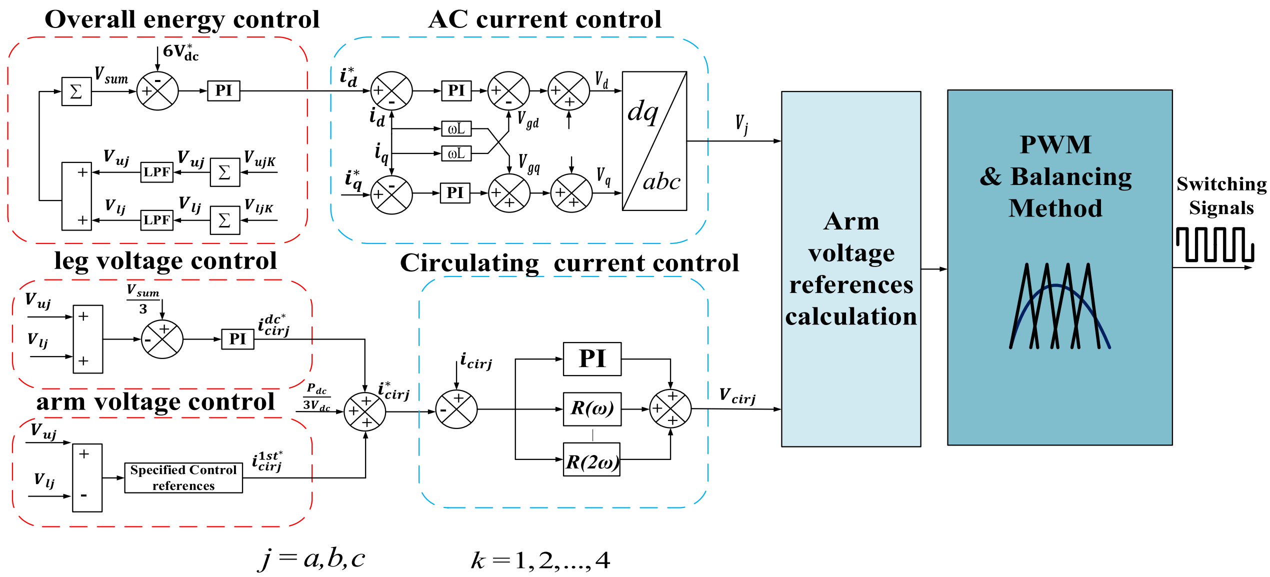

FIGURE 12. Overall control structure of the MMC.

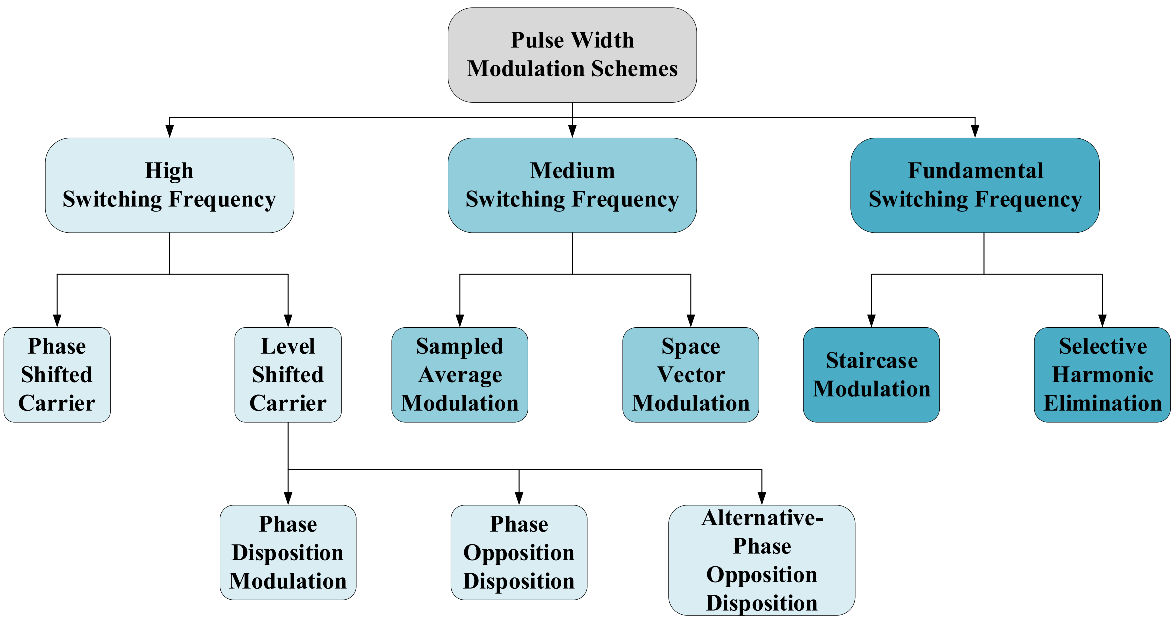

FIGURE 13. Pulse width modulation schemes.

phase with multiple carrier waveforms [114]. The sawtooth or triangular waveforms are often used as carrier signals. The modulation reference signal, on the other hand, is the output of the control system. As shown in Fig. 13 the carrier-based PWM schemes are classified into phase-shifted carrier PWM (PSC-PWM) and level-shifted carrier PWM (LSC-PWM) techniques [115]. The PSC-PWM technology uses N identical triangular carrier waveforms shifted horizontally by $2\pi/N$ (where N represents the number of SMs in each arm). These N carrier signals are then compared with the reference modulation signals which results in an output voltage with N + 1 levels. An output voltage with 2N + 1 can be generated by the MMC when the upper and lower arms' carrier waveforms have a $\pi/2$ interval angle [68], [116]. Due to the increased voltage level in the 2N + 1 method, the output voltage will have less harmonic distortion compared to the output voltage from the N + 1 method. Microgrids based on MMCs widely use the PSC-PWM modulation approach. A review of the other modulation schemes for the MMCs can be found in [89].

3) BALANCING METHODS

To ensure the proper operation of the MMC, the SMs' capacitor voltages must be balanced. Depending on whether the voltage balancing occurs at the control or modulation stages, the capacitor voltage balancing methods can be classified as distributed or centralized. In the distributed balancing method, each SM capacitor voltage is regulated at its reference voltage using closed-loop controllers, which requires PI controllers for each SM [117], [118]. Thus, the distributed method becomes ineffective as the number of SM increases. On the other hand, the centralized method is applied after the modulation stage. In this method, the SM selection is achieved by the sorting algorithms and relative comparison logic [118], [119]. The centralized method involves sorting the SM capacitor voltages either in ascending or descending order. Then during the positive direction of the arm current, the SM with the lowest voltage is inserted to charge the SM capacitor, and during the negative direction of the arm current, the SM with the highest voltage is inserted to discharge the SM capacitor.

B. MMC AS INTERFACE CONVERTER FOR DISTRIBUTED ENERGY RESOURCES (DERs)

1) POWER UNBALANCE IN PHOTOVOLTAICS

One of the main control challenges faced when solar PV arrays are integrated into the MMC SMs is the power unbalanced during different irradiation conditions. There are two types of power imbalances in the MMC topology which are the inter-phase power imbalance and the inter-arm power imbalance. Thus, various power-balancing control strategies were proposed. A summary of these control strategies can be found in Table 5. The authors of [85] have proposed the injection of Zero Sequence Voltage (ZSV) into the MMC phase voltage to balance the inter-phase power. However, when the generated power is heavily unbalanced, injecting ZSV will result in overmodulation and will degrade the voltage quality.

Additionally, this approach is not capable of resolving inter-arm power imbalances.

A power mismatch elimination strategy is proposed in [87]. This proposed method balances both the phase power and arm power by injecting a DC and a fundamental AC component of the circulating current. Power mismatch between the MMC phases is regulated through the DC component of the circulating current by keeping each leg's energy equal so that one-third of the power flows in each arm. On the other hand, the AC fundamental frequency component of the circulating current minimizes the energy difference between the arms of the same phase which will eliminate the power mismatches between them.

2) STATE OF CHARGE BALANCING IN BESS

Due to the inconsistency of batteries and the difference in power of SMs in the MMC-based BESS, the State of Charge (SOC) between battery packs will vary [27]. Therefore, the MMC-based BESS requires SOC balancing control to improve both the efficiency and the reliability of the capacity utilization. In [120] a ZSV is injected to balance the SOC between the phases of the MMC. However, determining the proper ZSV requires complex mathematical calculation which increases the calculation burdens of the Hardware. SOC balancing can also be realized by sorting the SOC of all SMs using the carrier-based disposition PWM method [117]. However, this method becomes increasingly complex as the number of submodules increases. A closed-loop method for achieving SOC balance between SMs within an arm and phase legs was proposed in [121]. However, no consideration was given to the problem of balancing the SOC between the upper and lower arms. Table 5 provides a summary of control strategies for SOC balancing in BESS.

3) VOLTAGE RIPPLE REDUCTION METHODS IN WECS

In wind energy conversion systems WECS employing PMSG, phase currents can lead to considerable voltage fluctuations in SM capacitors [122]. The fluctuation magnitude is directly related to the PMSG current magnitude and inversely related to the current frequency. These voltage fluctuations would require increased capacitance and power device rating, which are not appropriate for wind tower applications due to space constraints.

Similar challenges have been identified during the start-up procedure of variable speed drives (VSD). The proposed methods for mitigating SM capacitor voltage ripple in VSD mainly focus on high-frequency circulating current and common-mode voltage (CMV) injections [123], [124], [125], [126]. These methods effectively transform low-frequency energy fluctuations into higher-frequency variations [123]. However, introducing high-frequency components in the MMC for WECS is less desirable due to several shortcomings:

- CMV superposition may result in leakage current through the bearing of WECS leading to premature failure [127].
- The incorporation of circulating current results in heightened stress on power devices, necessitating an increase in current ratings [125], [128] and potentially compromising system reliability. As the SM capacitor voltage ripple reaches its maximum at rated wind speed [129], it is essential to maintain a minimal CMV magnitude to avoid overmodulation [126]. Given the constrained CMV margin under rated operating conditions, the magnitude of the injected circulating current amplifies, as it exhibits an inverse relationship with CMV [123].
- Controlling high frequency circulating current and CMV is difficult, requiring additional control loops and potentially decreasing stability, especially during transient processes [128].

Alternative techniques for suppressing voltage ripple include control strategies proposed in [130] and [131]. However, most of these methods involve variable DC bus voltage control, which is impractical for offshore DC wind turbines that need a constant DC bus voltage for parallel or series connections.

An alternative approach for mitigating voltage ripple involves the injection of the second-order harmonic circulating current (SHCC) [100], [132], [133], [134], [135]. Since SHCC is predominant in circulating current harmonics, adequate control is necessary for suppression [110]. Compared to high-frequency component injection and topology improvement, SHCC injection neither demands additional control loops nor variable DC bus voltage, making it easier to implement, particularly in MMCs for WECS [100]. Interestingly, proper SHCC amplitude and phase angle can also lower MMC power loss due to reduced average arm current [136], which is advantageous for WECS in achieving low-cost and lightweight cooling systems. Although SHCC injection for MMCs in WECS is studied in [100], this method ignores harmonic components and only eliminates the fundamental component of capacitor voltage. In [133], SHCC injection cancels the second-order component of capacitor voltage ripple, while [137] suppresses both fundamental and second-order components. However, no evidence suggests that the fundamental component dominates capacitor voltage in WECS applications, and the ripple characteristics across the entire wind speed range remain unknown. Therefore, a comprehensive analysis of ripple characteristics is necessary to develop an appropriate SHCC injection method.

It is worth noting that no discussion on SHCC injection methods for limiting MMC capacitor voltage ripple throughout the entire wind speed range has been conducted.

V. FAULT DETECTION AND FAULT TOLERANCE CONTROL

Due to the growing use of MMC, there has been a recent focus on developing methods for detecting and addressing faults in the MMC. This section provides an overview of the latest fault detection and fault tolerance control strategies for MMCs.

A. FAULT DETECTION

MMCs are known for their high component counts, which make them prone to failure. MMCs have a large number of SMs, and the most common cause of SM failure is the IGBT damage caused by short-circuit or open-circuit faults [138]. It has been found that open-circuit faults are more likely to persist without being detected for longer periods, which may adversely affect the output of the MMCs and overcharge the capacitors in the faulty SMs.

Recently, several methods have been developed for detecting faults in MMCs. These methods can be divided into software-based and hardware-based methods [139]. The large number of submodules (SMs) in an MMC makes the hardware approach impractical; thus, the software-based approach is preferred. Software-based fault detection methods are generally classified into three categories: model-based methods, signal processing methods, and data-driven methods [140]. Table 6 includes a comparison of the advantages and disadvantages of these methods.

In the model-based method, internal characteristics and external characteristics are compared to detect faults. The Luenberger observer [141], sliding mode observer [142], [143], and Kalman filters [144], [145] are classified as model-based approaches and used for fault detection in the MMC.

Signal processing-based fault detection methods process output characteristics, such as voltage and current signals, to detect faults in real time. Recently, researchers have regarded signal processing-based approaches as reliable and effective [146], [147]. However, the model and signal processing-based approaches are not robust since they rely on obtaining suitable and appropriate inner features or thresholds of specific derived indices, such as zero-crossing current slope or harmonic content.

Fault detection approaches that are data-driven employ artificial intelligence techniques (e.g., machine learning) to analyze data, recognize patterns, and uncover relationships that facilitate the detection process. Generally, these methods train a machine learning model using a dataset containing labeled examples, with the labels signifying the existence or nonexistence of different MMC faults. The dataset might also comprise various measurements and sensor data like voltages, currents, and MMC operating condition details. Once the model is trained, it can be used to make predictions on new data, allowing it to identify potential faults in the MMC.

One of the widely used data-driven methods for detecting faults is Neural Networks (NNs) [148]. Despite their wide usage, NNs require a lot of training data and time. Another data-driven method that is utilized to diagnose the faults of MMC is the support vector machine (SVM) [149] and its optimization algorithms [150], [151]. The above-mentioned methods involve feature extraction techniques that can affect the precision and efficiency of fault detection. Feature extraction can be avoided by using deep learning. However, the related literature on MMC is very limited.

It is worth noting that most of the mentioned fault detection methods are for MMC-based HVDC. Thus, more research is required to examine their effectiveness in MMC based microgrids which could be a potential research area.

B. FAULT TOLERANT STRATEGIES

To improve MMC's fault tolerance, several strategies have been proposed in the literature [152], [153], [154], [155], [156], [157], [158], [159], [160], [161], [162], [163], which can be classified as hardware-based or software-based strategies. Hardware-based fault tolerance strategies involve the use of redundant SMs. These redundant SMs can be designed to be either cold-reserved or hot-reserved. Cold-reserved methods involve bypassing the redundant SMs during normal operation and only inserting them when a failure occurs. This causes transient problems when bypassing or inserting the redundant SMs. In the hot-reserved method, the redundant SMs are not bypassed and work as the other SMs during normal operation [164]. The faulty SM is bypassed when a fault occurs while the MMC continues to operate normally. In addition to exposing the converter to asymmetrical operation, the hot-reserved method may also result in large power losses. Furthermore, both the hot and cold reserved methods

TABLE 5. Summary of control strategies for power unbalance, SOC balancing, and voltage ripple reduction.

Control Challenge	Control Strategy	Reference(s)	Limitations
Power Unbalance in Photovoltaics	Injection of Zero Sequence Voltage (ZSV) into the MMC phase voltage.	[85]	- Overmodulation. - Degraded voltage quality. - Unable to resolve inter-arm power imbalances.
	Power mismatch elimination strategy.	[87]	- Severe arm power unbalance· - Energy loss.
State of Charge Balancing in BESS	Injection of Zero Sequence Voltage (ZSV).	[120]	- Increased hardware calculation burden.
	Carrier-based disposition PWM method.	[117]	- Complexity increases with the number of submodules.
	Closed-loop method for achieving SOC balance.	[121]	- Does not address balancing the SOC between the upper and lower arms.
Voltage Ripple Reduction Methods in WECS	High-frequency Circulating Current & Common-mode Voltage (CMV) Injections.	[123]–[126]	- Leakage current through bearing. - Increased stress on power devices. - Control difficulty.
	Second-order Harmonic Circulating Current (SHCC) Injection.	[100], [132]–[135]	-Ignores other harmonic components. -limited analysis of ripple characteristics in WECS across wind speed range.

increase the cost of the system due to the use of redundant SMs.

To overcome the challenges associated with hardware-based tolerance strategies, reference [165] introduces a fault-tolerant SM with integrated operating and backup half-bridge SMs (HBSMs), simplifying the fault-tolerant method (FTM). The proposed SM efficiently charges capacitors, ensures post-fault output voltage levels, and mitigates drawbacks of existing FTMs. Therefore, hardware-based fault tolerance strategies are not practical.

Software-based fault tolerance strategies have recently been developed as an alternative to hardware-based strategies. These strategies rely on techniques to recover from failures without requiring redundant hardware, which can provide a more cost-effective and flexible approach to fault tolerance. After bypassing the faulty SMs, reference [166] proposes a method for restoring the voltage of the faulty phase by changing the modulation reference and increasing the voltage level of the capacitor. However, this approach ignores the line voltage requirement, such as Total Harmonic Distortion (THD) and the amplitude. Another interesting software-based fault tolerance strategy that has gained interest among researchers in recent years is the neutral-point-shift (NPS) method [162], [163]. This method involves shifting the neutral point to balance the three-phase line voltage. In [162], the NPS is realized by altering the references of three-phase voltages. In reference [163], a carefully calculated voltage is added to the output voltage to achieve the NPS. The NPS method offers a flexible and cost-effective way to ensure the proper postfault operation of MMC.

VI. MMC FREQUENCY SUPPORT FOR MICROGRID

Recently, power systems have experienced a significant reduction in system inertia provided by the rotating masses, mainly due to the replacement of conventional synchronous generators (SGs) with renewable energy. This makes the power systems more susceptible to frequency events. Frequency events such as low-frequency nadir and high Rate of Change of Frequency (RoCoF) may cause a cascading failure, load shedding, or even large-scale blackouts, which may lead to economic losses [167], [168]. Therefore, it is imperative to address the frequency nadir and the RoCoF to avoid undesirable disturbances in the power system. In [167], battery and ultracapacitor energy storage devices are installed to compensate for frequency deviations. References [169], [170] proposed controlling grid-connected voltage source converters (VSC) to act as SGs that could provide virtual inertia and frequency support. According to [171], during frequency events a fixed amount of MMC capacitor energy can be injected into the grid. However, MMC capacitors are found to have a smaller energy capacity than conventional power systems, resulting in insufficient frequency support.

This can be different for microgrids since the SMs energy capacity is sufficient to support the line frequency of the microgrid. Reference [172] has explored the possibility of MMC synthetic inertia in supporting microgrid line frequency. The total inertia analysis that has been conducted in [172] shows that the system inertia can be improved and maintained regardless of the renewable penetration ratio through the synthetic inertia provided by the SM capacitors of the MMC. There are several aspects of microgrid frequency support through MMC that need to be investigated, which can be explored in future research.

VII. FUTURE TRENDS

Despite the large body of literature on MMC, there are still areas that require further research and development as follows:

TABLE 6. Comparisons between different fault detection strategies.

Fault Detection strategies	Advantage	Disadvantage
Model method [110]-[114]	- Ability to detect and diagnose multiple types of faults. - Can provide more accurate and detailed information about the fault.	- Need for accurate system models. - Dependence on obtaining suitable inner features or thresholds of specific derived indices
Signal processing method [115]-[116]	- Highly sensitive, allowing for the detection of even small faults that might otherwise go unnoticed. - High accuracy	- Dependence on obtaining suitable inner features or thresholds of specific derived indices. - Need for computational resources to run signal processing algorithms.
Data driven method [117]-[120]	- Less sensitive to changes in the system. - Do not require prior knowledge of system.	- Requirement for large amounts of high-quality and representative data - Need for computational resources to train and run the machine learning models

- IGBTs are currently the dominant semiconductor technology for MMC. This can be attributed to their low switching frequencies. However, they are known to have thermal limits which pave the way for thermal management control methodologies. Such methodologies would optimally maintain submodule operating conditions, even under temperature uncertainties among submodules caused by variation in loads and ageing. Thereby, these methodologies provide longevity of semiconductor submodules.
- Another solution to manage abrupt thermal limits present in semiconductors is the development of mature wide bandgap devices, like silicon carbide (SiC) and gallium nitride (GaN), which would be beneficial for the MMC by decreasing the switching losses and minimizing cooling system requirements [173]. Therefore, further investigation is required to properly model wide bandgap devices and to determine their effectiveness in MMC for Microgrid applications.
- Additionally, interesting research areas involve developing control methods using parameter estimation approaches and sensorless techniques to replace the current and voltage sensors. The exclusion of physical sensors contributes to several merits in optimizing the operation of the MMC. Costs of initial installation and maintenance are significantly reduced, which is critically considered for large-scale MMCs [174]. Moreover, employing sensorless techniques enhances both the reliability and fault tolerance of MMCs by eliminating potential sensor failures [175]. Furthermore, sensorless techniques would avoid inherent latency associated with physical sensors, providing instantaneous response rates for unpredictable variations in control systems, hence enhancing MMC's control precision and overall efficiency.
- Furthermore, cybersecurity is an emerging critical topic that requires attention, particularly in microgrid applications. The possible threats emerge as the digitization of microgrids takes place and their interconnection such as manipulation of control signals, false data injection, and denial of service attacks become more prevalent. Particularly, critical cybersecurity threats such as false data injection in the sensors of the MMC can affect the stability of its control system. In this regard, research needs to explore advanced cybersecurity measures and develop reliable cybersecurity protocols and intrusion detection schemes in MMC based microgrids.

VIII. CONCLUSION

There is considerable interest from academia and industry in the salient features of MMC. Thus, during the past decade, there has been significant research on MMC that has resulted in new topologies, modulation schemes, and control methods. However, the use of MMC in microgrids is still immature and comprehensive research is required in this field.

This paper aims to deliver an in-depth insight and a critical review into the current state of knowledge while concurrently highlighting promising directions for future research. In this paper, the latest research contributions were reviewed focusing on the circuit topologies, control schemes, and fault-tolerance strategies of MMC within microgrid applications, highlighting their merits and demerits. In conclusion, with the progression of MMC, it becomes clear that its maturity in microgrid applications relies on continual research, innovation, and refinement. It is projected that MMC will play an increasingly vital role in future microgrid applications, leading to profound potential in its deployment.

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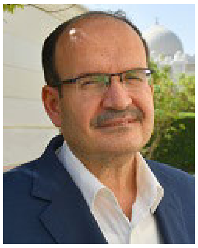
SAFIA BABIKIR BASHIR received the B.Sc. degree in electrical engineering from Ajman University, United Arab Emirates, in 2013, and the M.Sc. degree in electrical engineering from the Petroleum Institute, United Arab Emirates, in 2016. She is currently a Research Assistant with the Smart Grid and Power Systems Research Group, University of Sharjah. Her research interests include multilevel converters, electric drive, renewable energy systems, and HVdc transmission systems.

ALI AHMED ADAM ISMAIL (Member, IEEE) received the B.Sc. degree from the University of Khartoum, Sudan, in 1991, the M.Sc. degree from the University of Baghdad, Iraq, in 1997, and the Ph.D. degree in electrical engineering from Yildiz Technical University, Istanbul, Turkey, in 2007. His research interests include the control of electrical machines, power electronics applications, low frequency electromagnetic waves, filters, and smart grids.

A. ELNADY (Senior Member, IEEE) received the bachelor's and master's degrees from Cairo University, Cairo, Egypt, in 1990 and 1998, respectively, and the Ph.D. degree from the University of Waterloo, Waterloo, ON, Canada, in 2004. His research interests include power-electronics applications in power systems, power quality in distribution systems, smart grids, and the integration of renewable sources within power grids.

MENA MAURICE FARAG received the B.Sc. degree in electrical and electronics engineering from Al Ghurair University, Dubai, United Arab Emirates, in 2020. He is currently pursuing the M.Sc. degree in electrical and electronics engineering with the University of Sharjah, Sharjah, United Arab Emirates. He is a Graduate Research Assistant with the Smart Grid and Power Systems Research Group, University of Sharjah. His research interests include power systems, renewable energy systems, grid-connected PV systems, MPPT control algorithms, smart grids, microgrids, modular multilevel converters (MMC), photovoltaic-thermal (PV/T) systems, optimization models, the Internet of Things (IoT), sensors, and artificial intelligence.



ABDUL-KADIR HAMID (Senior Member, IEEE) received the B.Sc. degree from the West Virginia Institute of Technology and University, Montgomery, WV, USA, in 1985, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Manitoba, Winnipeg, MB, Canada, in 1988 and 1991, respectively. From 1991 to 1993, he was with Quantic Laboratories Inc., Winnipeg, MB, Canada. From 1994 to 2000, he was with the Faculty of Electrical Engineering, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. Since September 2000, he has been with the Department of Electrical Engineering, University of Sharjah, Sharjah, United Arab Emirates. He has published more than 200 conference and journals papers. His research interest include applied EM, grid connected PV systems, PV thermal, PV modeling, MPPTs, optimization, optical filters for PV systems, imaging, and the IoTs.

RAMESH C. BANSAL (Senior Member, IEEE) has more than 25 years of diversified experience in research, teaching and learning, accreditation, industrial, and academic leadership in several countries. He is currently a Professor with the Department of Electrical Engineering, University of Sharjah, and an extraordinary Professor with the University of Pretoria (UP). Previously, he was a Professor and the Group Head (Power) with the Department of Electrical, Electronic and Computer Engineering, UP. Prior to his appointment with UP, he was employed with The University of Queensland, Australia; the University of the South Pacific, Fiji; BITS Pilani, India; and Civil Construction Wing, All India Radio. He has significant experience of collaborating with industry and government organizations and design and delivery of CPD programmes for professional engineers. He has published more than 400 journal articles, presented papers at conferences, books, and chapters in books. He has Google citations of more than 17000 and H-index of 61. He has supervised 25 Ph.D. scholars, 20 master's scholars, and five postdoctoral scholars. His research interests include renewable energy, power systems, and smart grids. He is a fellow and a Chartered Engineer of IET, U.K., and a fellow of the Institution of Engineers, India, and SAIEE, South Africa. He is an Editor of *IET Renewable Power Generation* and *IEEE Systems Journal*.

AHMED G. ABO-KHALIL (Member, IEEE) was born in Egypt, in 1969. He received the B.S. and M.S. degrees in electrical engineering from Assiut University, Assiut, Egypt, in 1992 and 1996, respectively, and the Ph.D. degree in electrical engineering from Yeungnam University, Gyeongbuk, South Korea, in 2007. Since 2021, he has been with the Department of Sustainable and Renewable Energy Engineering, University of Sharjah, United Arab Emirates. His research interests include power electronics, energy conversion, and power quality and control.