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Beyond the MMC: Extended Modular Multilevel Converter Topologies and Applications

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ABSTRACT The unique advantages of modular multilevel converters (MMCs) have led to wide adoption of the converter topology in high voltage dc (HVDC) transmission systems, with great potential for use in medium voltage motor drive and dc grid applications. Inspired by the structure of the MMC, many extended converter topologies have been developed in the literature. These include, in addition to conventional parallel multiphase connection, a variety of series-connected topologies. Extended MMCs integrate the modular nature of cascaded SMs of the MMC but with different topology structure leading to substantially different operating principles. Given the growing number of such topologies, this paper provides a critical review of MMC derived topologies and summarizes individual advantages and disadvantages. The control schemes and application fields of these different topologies are analysed. This review facilitates the classification and understanding of extended MMCs and provides the necessary scaffold for the development of a general framework for new topologies and applications based on the MMC.

INDEX TERMS DC-AC multilevel converter topologies, modular multilevel converter (MMC), parallel-connected converter (PCC), series-connected converter (SCC).

NOMENCLATURE

MMC	Modular multilevel converter.
FACTS	Flexible AC transmission systems.
BESS	Battery energy storage system.
PCC	Parallel-connected converter.
SCC	Series-connected converter.
HB	Half-bridge.
IGBT	Insulated-gate bipolar transistor.
FB	Full-bridge.
PWM	Pulse width modulation.
NLM	Nearest level modulation.
AAC	Alternate arm converter.
AC	Alternating current.
FRT	Fault ride through.
DS	Director switch.
SO-AAC	Short overlap AAC.
EO-AAC	Extended overlap AAC.
ZCS	Zero current switching.
SAAC	Shared AAC.
IAAC	Improved AAC.
FC	Flying capacitor.
AT-AAC	Augmented trapezoidal AAC.
MEMC	Modular embedded multilevel converter.
AC-MMC	Active cross-connected MMC.
PC-MMC	Passive cross-connected MMC.
PHMC	Parallel hybrid multilevel converter.
PCUB	Parallel-connected unfolding bridge.
ZVS	Zero voltage switching.
HBHMC	H-bridge hybrid modular converter.
CTFB-HMC	Controlled transition FB hybrid multilevel converter.
HC-MMC	Hybrid cascaded MMC.
RFB-MMC	MMC with reduced FBSMs.
HCMC	Hybrid cascaded multilevel converter.
MVHP-MMC	MV high power MMC.
MMSPC	Modular multilevel series/parallel converter.

SC-MMC	Series-connected MMC.
SCAH-MMC	Series-connected asymmetrical hybrid MMC.
SHMC	Series hybrid multilevel converter.
MDSMC	Modular directed series multilevel converter.
SBC	Series bridge converter.
TAMBC	Thyristor augmented modular bridge converter.
METDC	Modular embedded thyristor directed converter.
MPC	Model predictive control.
ML	Machine learning.
IGCT	Integrated gate-commutated thyristor.
HCI	Half-cycle isolation.
SSMV	Single SM voltage.
HSMV	Hybrid SM voltage.
DAB	Dual active bridge.
FTF	Front-to-front.

I. INTRODUCTION

Since its introduction in the early 2000s [1], [2], the modular multilevel converter (MMC) has defined the principles for multilevel power conversion and has shifted the way that high-power power electronics are approached in the research, and in industrial applications. The MMC can operate with very low switching frequencies without compromising the quality of output waveforms. Cascaded submodules (SMs) are arranged in arms that act as controllable ac sources, that regulate internal and external electrical variables. The variety of SMs that can be adopted offers diverse characteristics to the operation of the MMC [3]. Depending on the design of a SM, features such as redundancy, improved voltage balancing, and dc fault blocking capability can be achieved.

The MMC has attracted great interest from academia and industry due to its unique benefits, such as high modularity and scalability [4] with high-voltage direct current (HVDC) power transmission becoming a prominent area of application for the converter. Many point-to-point (PTP), multiterminal and hybrid projects that are currently under operation, have demonstrated the advantages the MMC offers in HVDC applications [5], [6]. Ongoing research further supports its advantages in applications such as flexible alternating current transmission systems (FACTSs), medium-voltage (MV) dc grids, low-voltage (LV) dc distribution networks, photovoltaic systems, wind turbine, motor drives, dc-dc conversion, static compensators (STATCOMs), battery energy storage systems (BESSs), solid-state transformers (SSTs) and HV pulse generators [7], just to mention a few.

Despite the significant benefits and wide application of the MMC, certain challenges are required to be addressed. Such issues include high semiconductor count, large energy storage requirements in the SMs [8], handling of internal faults [9] and circulating current optimisation [10], [11]. Approaches to address these issues consider modifications either of the control or converter structure.

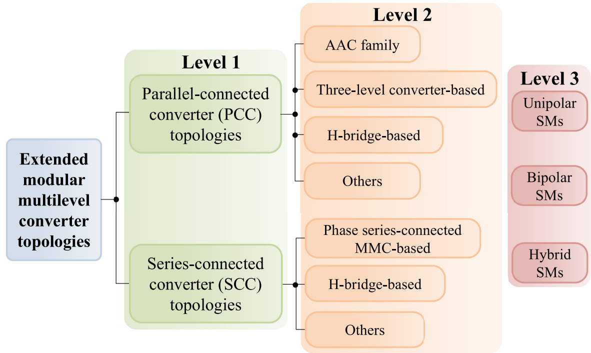

FIGURE 1. Classification of extended modular multilevel converter topologies.

Owing to the outstanding features of the MMC, the development of multilevel converters has become a trend in the literature, including novel SM topologies, converter configurations [12], control schemes, and modulation strategies [13]. Therefore, the review of MMCs is of great importance to the evaluation and improvement of multilevel converters. Detailed reviews of the development and achievements in MMCs referring to the challenges proposed previously are provided in [14]–[17], considering both the perspective of SM configurations and overall converter topologies. In addition to the modeling and control methods, new application areas and future development trends of MMCs are discussed in [18].

The current literature is rather MMC-centric, with focus on SM topologies, modeling, control schemes and applications. Inspired by the advantages of the MMC, a large number of converter topologies have been developed since, with the aim to further improve on the perceived operational and technical shortcomings of the conventional MMC structure. Usually such topologies are better suited to specific or niche applications compared to the broadly functioning voltage source converter uses of a conventional MMC. Therefore, a comprehensive overview and comparison of extended MMC topologies contributes to the selection and further modification of converters in dc-ac conversion. At this stage, only a limited number of the available converter topologies were previously summarized [19], with a limited scope focused on stationary applications. No detailed review is available to compare and provide insights for the many extended modular topologies that have been developed beyond the MMC.

A comprehensive overview of extended MMCs is the main aim of this paper, as shown in the classification on Fig. 1. The primary classification into phase parallel-connected converters (PCCs) and series-connected converters (SCCs) demonstrates the broad range of topologies and use cases found in the current literature. In PCCs, all phases are connected in parallel, following the conventional configuration of the MMC. In SCCs, all phases are connected in series and each phase withstands only one third of the total dc voltage, leading to fewer number of SMs in the converters. At the same time, the SCCs need to withstand full dc current, consequently requiring higher current ratings of components. The characteristics

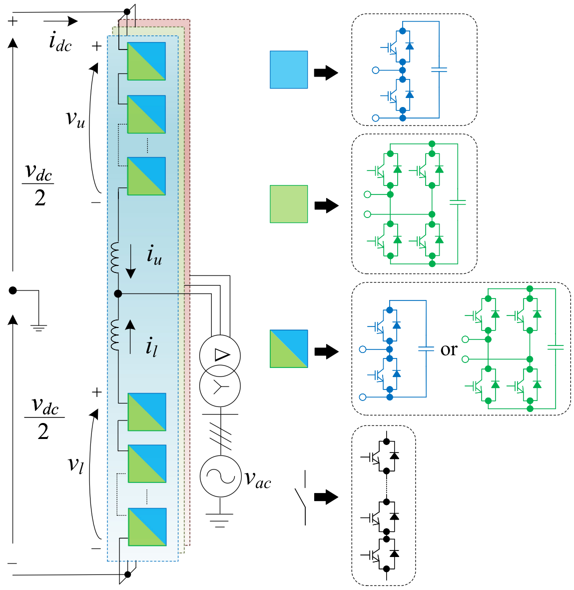

FIGURE 2. Circuit diagram of a three-phase MMC and drawing conventions used throughout this review article.

of SCCs contribute to the utilization in MVDC, HVDC systems and HVDC tapping applications. Further classification considers the internal structure of each extended topology, as well as the choice of SMs used in a converter.

This paper provides a detailed comparison of these converter topologies, including the structures, unique characteristics, advantages and disadvantages of each converter. According to the different topologies and functionalities, the key control schemes and application fields are analysed, offering a better understanding of extended modular multilevel converters and their potential for use in other applications. Through the up-to-date review, provided in this paper, readers can evaluate and compare these converters from operation principle, control complexity, power loss and investment cost. In addition, the summary of extended MMCs acts as a bibliographical reference allowing further modifications and inclusion of novel characteristics, appropriate to specific applications and scenarios.

II. BRIEF MMC OVERVIEW

The circuit diagram of a three-phase MMC is shown in Fig. 2. Each phase-leg of the MMC includes multiple SMs per arm (typically more than 100 for HV applications), and one arm inductor. The SMs in each arm are controlled to generate ac voltages, while the arm inductor limits fault currents and helps to control the circulating current [20].

The half-bridge SM (HBSM) is a widely used topology constituted by two fully-controller devices, which typically are insulated-gate bipolar transistors (IGBTs), with a capacitor in parallel. However, MMCs with HBSMs cannot interrupt fault current via converter blocking during dc faults. Hence, bipolar SMs such as full-bridge SMs (FBSMs) can be used to provide fault interruption path. The MMC uses cascaded SMs with low switching frequency in each arm to synthesize ac waveforms [21]. The number of SMs to be inserted/bypassed in each arm are determined by the control and modulation stage based on duty cycles.

Different modulation techniques can be applied in the modulation stage. The typical modulation techniques are pulse width modulation (PWM) and nearest level modulation (NLM). PWM-based methods deliver good tracking performance of modulation waveform with relatively simple implementation [22]. As the number of SMs increases, NLM provides a simpler approach to the operation of the MMC. Nevertheless, conventional NLM leads to severe current distortion when it is applied in MVDC systems due to significantly reduced number of SMs. Compared to NLM technique, PWM or hybrid modulation scheme combining NLM and PWM shows better voltage and current harmonic characteristics in the application of MMCs with fewer SMs [23]. There are many reviews dedicated to the MMC in the current literature. Interested readers can refer to [2], [8]–[11], [21], [24] for detailed analysis of the MMC.

III. PARALLEL-CONNECTED CONVERTER TOPOLOGIES

The most common configuration of extended MMCs, as with most dc-ac voltage source converters (VSCs), is that of parallel-connected phases to the dc link; each phase has to support the full dc voltage. The unique characteristics and benefits/drawbacks of such extended topologies including the alternate arm converter (AAC) family, three-level converter-based converters, H-bridge-based and other other converter topologies are also summarised in Tables I to IV, respectively.

A. AAC FAMILY

The family of AACs includes different converter topologies that combine the characteristics of the MMC and the two-level converter (through the use of the director switches) in a modular topology (Fig. 3). The converters are better suited to HVDC applications [25]–[27]. The alternate arm operation of the AAC leads to fewer SMs in each arm since the maximum voltage that each arm has to generate is equal to half of the dc bus voltage. AACs can also provide fault ride through (FRT) capability due to the use of bipolar SMs. The peak-to-peak energy deviations for AACs are smaller than those in the MMC, hence reduced SM energy storage is required in AACs considering the same capacitor voltage ripple [28], [29].

However, the alternate operation results in an inherent energy balancing point that is determined by the zero net energy from the energy exchange between the ac and the dc sides [30]. To balance the arm energy in AACs, an overlap period is introduced around the zero-crossing points of the modulation waveform, mimicking the MMC operation. The length of overlap period defines further operation of AACs and can also be used to separate AACs with short and extended overlap periods. Moreover, the 6th harmonics in the dc current have to be filtered by installing dc filters. The dc filters can be removed by extending the overlap period to achieve active filtering [31], [32].

TABLE I **PCC - Alternate Arm Converter Family**

Converters	Characteristics	Advantages	Disadvantages
SO-AAC [30]	1*. Alternate arm operation 2*. Natural over-modulation operation 3. DC-link filters	1*. DC fault handling capability 2*. Reduced number of SMs 3*. Reduced energy in SMs (kJ/MVA) 4. ZCS of DSs	1*. 6th harmonics in the dc current 2. Fixed energy balancing point
EO-AAC [33]	1. Overlap period of 60°	1. Elimination of dc-link filters 2. Decoupling of ac and dc sides 3. Restriction lifting on operating points	1. Increased number of devices 2. ZCS and active filtering trade-off
SAAC [34]	1. Dynamic middle arm insertion into upper/lower arm 2. DC-link filters	1. ZCS of DSs	1. Additional two sets of DSs 2. Fixed energy balancing point
IAAC [35]	1. Arm current transfer path via FCs	1. Elimination of dc-link filters 2. Continuous arm currents	1. Hard-switching of DSs 2. Fixed energy balancing point 3. Energy balancing of FCs and SM capacitors
AT-AAC [36]	1. Arm current conduction path via antiparallel thyristors	1. Lower conduction losses of SMs 2. Possible elimination of DSs	1. Additional control of thyristors 2. Inclusion of commutating inductors

*: Common characteristics and advantages/disadvantages of the whole category.

TABLE II **PCC - Three-Level Converter-Based**

Converters	Characteristics	Advantages	Disadvantages
HMMC [37]	1. Alternate switch operation 2. Three different working states 3. DC-link filters	1. Reduced number of SMs 2. Smaller SM capacitance (HMMC 1, HMMC 3) 3. Reduced power losses (HMMC 1, HMMC 3) 4. DC fault handling capability (HMMC 2) 5. Decoupling of ac and dc sides (HMMC 2) 6. Improved switch commutation process	1. Middle point voltage control 2. No dc fault handling capability (HMMC 1 and HMMC 3) 3. Larger SM capacitance (HMMC 2) 4. Higher power losses (HMMC 2)
MEMC [38]	1. Alternate switch operation 2. Three different working states 3. Low conduction loss path via thyristors	1. Reduced number of SMs 2. Smaller SM capacitance (MEMC 1) 3. Reduced power losses (MEMC 1) 4. DC fault handling capability 5. Lower conduction losses	1. Middle point voltage control 2. Control complexity of thyristors 3. Larger SM capacitance (MEMC 2) 4. Higher power losses (MEMC 2)
AC-MMC [39]	1. Energy exchange by cross-connected SM arms 2. Energy balancing in full speed range 3. Suitable for motor drive applications	1. Operation over a wide frequency range 2. Avoidance of common-mode voltage injection	1. Additional introduction of cross-connected arms 2. Increased number of SMs
PC-MMC [40]	1. Energy exchange by cross-connected flying capacitor 2. Energy balancing in full speed range 3. Suitable for motor drive applications	1. Operation over a wide frequency range 2. Avoidance of common-mode voltage injection	1. Additional introduction of flying capacitor 2. Half-arm capacitor voltage control

TABLE III **PCC - H-Bridge-Based**

Converters	Characteristics	Advantages	Disadvantages
PHMC [42]	1*. Fundamental frequency switching of H-bridge 2*. 120° displacement operation of SM arms between phases	1*. Reduced number of SMs 2*. Higher dc voltage utilization 3*. Lower power losses 4. DC fault handling capability	1*. Fixed energy balancing point 2*. Power losses of H-bridge 3. Hard-switching of switches in H-bridge
PCUB [43]	1. DC-link harmonic cancellation	1. DC fault handling capability 2. ZVS of H-bridge	1. Introduction of more SMs 2. Arm energy balancing of HBSM- and FBSM-based branches
Parallel-HBHMC [44]	1. Natural over-modulation operation	1. DC fault handling capability	1. Hard-switching of switches in H-bridge
CTFB-HMC [45]	1. No fundamental frequency in SM capacitor voltage	1. No dc current in SM arms	1. No dc fault handling capability 2. Hard-switching of switches in H-bridge

*: Common characteristics and advantages/disadvantages of the whole category.

TABLE IV PCC - Others

Converters	Characteristics	Advantages	Disadvantages
HC-MMC [46]	1. No active power transfer function in FBSM arms	1. DC fault handling capability 2. Reduced energy in FBSMs (kJ/MVA) 3. Reduced number of devices	1. Increased number of SMs
RFB-MMC [47]	1. DC voltage synthesis by HB- and FB-MMC 2. DC-link capacitor in FB-MMC 3. DC-link connector and breaker	1. DC fault handling capability 2. Small proportion of FBSMs 3. Relatively lower power losses	1. Additional introduction of a 3-phase MMC 2. Additional components on dc-link
HCMC [48]	1. Alternate arm operation 2. Natural overmodulation operation	1. DC fault handling capability 2. Reduced number of SMs	1. 6th harmonics in the dc current 2. Fixed energy balancing point 3. Relatively complex fault handling 4. Hard switching of arm switches
MVHP-MMC [49]	1. Alternate switch operation 2. Three series-connected arms per phase	1. Reduced number of SMs 2. High dc voltage utilization	1. No dc fault handling capability 2. Addtional switches
MMSPC [50]	1. Series or parallel connectivity of SMs 2. Simplified SM capacitor voltage balancing	1. Sensorless voltage balancing 2. Capacitance reduction 3. Arm current sharing 4. Reduction of conduction losses 5. Modulation stage simplification 6. DC Fault handling capability	1. Increased number of semiconductor devices 2. Increased control complexity due to additional SM operating states

TABLE V SCC - Phase Series-Connected MMC-Based

Converters	Characteristics	Advantages	Disadvantages
SC-MMC [59]	1*. HVDC tapping application	1*. Reduced number of SMs 2*. Reduced power losses	1*. Reduced power rating 2*. 3rd harmonic currents 3*. Unbalanced dc voltage under asymmetrical faults 4. No dc fault handling capability
SCAH-MMC [60]	1. Employment of FBSMs	1. DC fault handling capability	1. Increased number of semiconductor devices 2. Additional power losses of FBSMs

*: Common characteristics and advantages/disadvantages of the whole category.

TABLE VI SCC - H-Bridge-Based

Converters	Characteristics	Advantages	Disadvantages
SHMC [61]	1*. Fundamental frequency switching of H-bridge 2*. 120° displacement operation of SM arms between phases	1*. Reduced number of SMs 2*. Reduced losses of SMs 3*. Reduced energy in SMs (kJ/MVA) 4. ZVS of H-bridge	1*. Fixed energy balancing point 2*. Power losses of H-bridge 3. No dc fault handling capability
MDSMC [62]	1. Two arm current flowing paths	1. ZVS of H-bridge	1. No dc fault handling capability 2. Additional arm introduction
SBC [63]	1. DC-link harmonic cancellation	1. DC fault handling capability 2. ZVS of switches in H-bridge	1. Introduction of more SMs 2. Arm energy balancing of HBSM- and FBSM-based branches
Series-HBHMC [44]	1. Natural overmodulation operation	1. DC fault handling capability	1. Hard-switching of switches in H-bridge

*: Common characteristics and advantages/disadvantages of the whole category.

1) SO-AAC

The short overlap AAC (SO-AAC) adopts a short overlap angle (typically below 20°, Fig. 3(a)). It requires partial dc filtering due to the 6th harmonic in the dc-link. In addition, zero current switching (ZCS) of the director switches (DSs) can also be ensured by forcing the arm currents to zero before the DS is opened. A typical approach is to introduce a fixed overlap period and generate a negative voltage across arm inductors [30].

2) EO-AAC

The extended overlap period AAC (EO-AAC) increases the overlap angle to 60°, providing a full-time conduction path for the dc current [see Fig. 3(b)]. Due to the longer overlap period, the ac currents have a continuous circulating path in each phase resulting in possible independent control of ac and dc currents. DC filters can be removed and the energy balancing is not limited to a single point at the cost of more SMs in the arms. Another challenge for the EO-AAC is the ZCS and active filtering trade-off. Both ZCS and active filtering have to be achieved relying on the circulating current, but they cannot be realized simultaneously due to only one degree of freedom in the circulating current [33].

3) SAAC

The shared AAC (SAAC) introduces a middle arm and extra

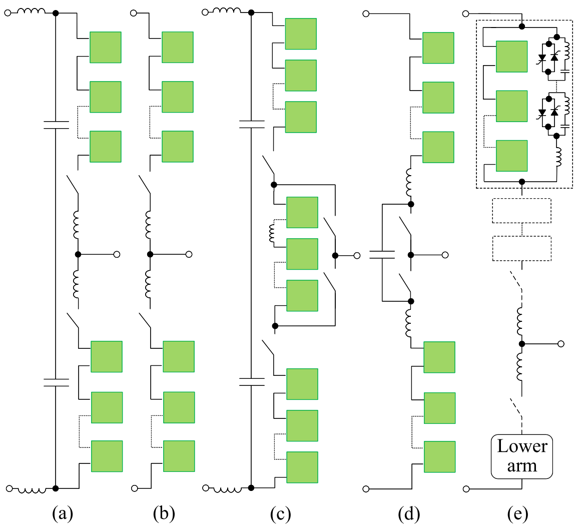

FIGURE 3. PCC - AAC family topologies: (a) SO-AAC, (b) EO-AAC, (c) SAAC, (d) IAAC, and (e) AT-AAC.

two sets of DSs in each phase to further reduce the total number of SMs [see Fig. 3(c)]. The middle arm is a common arm that works with the upper arm or lower arm together via switching of additional two sets of DSs. Although the SAAC requires fewer number of SMs, more DSs in the converter lead to additional power losses [34].

4) IAAC

For providing continuous current between the upper and lower arms, a flying capacitor (FC) is introduced in the improved AAC (IAAC) across the DSs to avoid arm current interruption [see Figure. 3(d)]. However, the switching losses of the IAAC are higher than in the conventional AAC due to the hard-switching of DSs. Moreover, the energy balance between the FCs and SM capacitors has to be determined by the arm current direction and switch operation leading to a more complicated energy balancing scheme in the IAAC [35].

5) AT-AAC

The augmented trapezoidal AAC (AT-AAC) uses antiparallel thyristor valves to transfer the current through SMs achieving alternate arm action. The DSs can be removed with little impact of the overall converter efficiency [see Fig. 3(e)]. The introduction of antiparallel thyristor valves also leads to lower conduction losses of SMs. However, the thyristor valves have to be commutated on/off in coordination with the arm SMs across the additional commutating inductor. The commutation of the thyristor valves also results in high complexity of controller design [36].

B. THREE-LEVEL CONVERTER-BASED TOPOLOGIES

The substitution of series connected devices with SM-based arms can be expanded beyond the two-level converter to well-known three-level converter configurations. Six converter topologies are summarised in this section with applications ranging from HVDC to MVDC and MV motor drive applications. The alternate operation of switches in the arms for the first five topologies [see Fig. 4(a)–(e)] leads to three working states that generate positive, negative and zero ac voltages, respectively. By considering a pseudo-three-level operation of the converters, the number of SMs can be reduced (by roughly half) compared to the MMC. However, connection to the mid-point of the dc-link requires both dc link capacitors and additional control of the neutral point voltage.

The modified converter of the MMC can be used in MV motor drives to solve the issue of energy balancing between the upper and lower arms at a low speed [see Fig. 4(f)]. It can be achieved by cross-connecting additional SM arm in each phase.

1) HMMC

Three variations of the three-level derived hybrid MMC (HMMC) use two HBSM arms and four switches (two sets) in each phase [see Fig. 4(a)–(c)]. Also, a dc-link capacitor is adopted to facilitate the switch commutation process during the working state change of the output voltage. Two of the proposed structures (i.e., HMMC 1 and HMMC 3) have smaller capacitance and lower overall power losses compared to the MMC. Although HMMC 2 requires larger SM capacitance and has higher power losses, it possesses dc fault clearance capability by replacing a set of switches with reverse blocking devices. Unlike HMMC 1 and HMMC 3, the interactions of ac and dc sides for the HMMC 2 are fully decoupled. Hence, the modulation index of HMMC 2 is no longer limited [37].

2) MEMC

All previous topologies have used fully controlled devices, such as IGBTs and IGCTs. The substitution of the series connected devices of the HMMC1 and HMMC2 with thyristors leads to two different configurations of the modular embedded multilevel converter (MEMC) [see Fig. 4(d) and (e)]. Furthermore, the use of FBSMs provides both topologies with dc-fault ride through capabilities. However, the thyristors have to be forced to switch off [38].

3) AC-MMC

The active cross-connected MMC (AC-MMC), shown in Fig. 4(f), is specifically developed for MV motor drive applications to avoid common-mode voltage injection throughout the full speed range. The energy between the uppper and lower arms can also be balanced by additional an energy distribution path in the cross-connected arm in each phase at the cost of increased number of SMs [39].

4) PC-MMC

The passive cross-connected MMC (PC-MMC) [40], shown in Fig. 4(g), is also called flying-capacitor MMC (FC-MMC) in [41]. It can be used in medium-voltage motor drive systems and inherits the structure of the AC-MMC, while the cross-connected SM-based arm is replaced by a FC in each

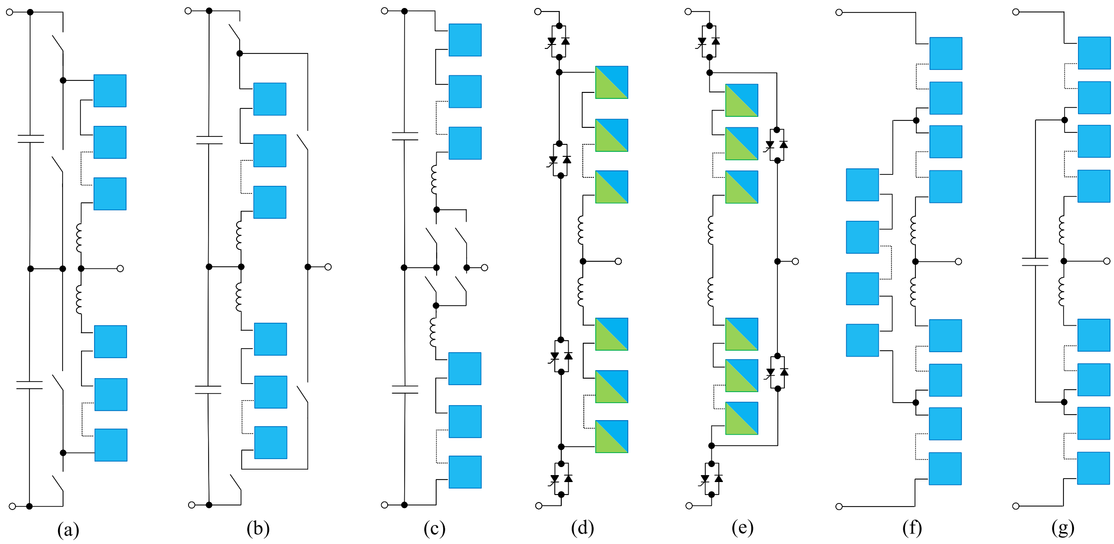

FIGURE 4. PCC - three-level converter-based multilevel converter topologies: (a) HMMC 1, (b) HMMC 2, (c) HMMC 3, (d) MEMC 1, (e) MEMC 2, (f) AC-MMC, and (g) PC-MMC.

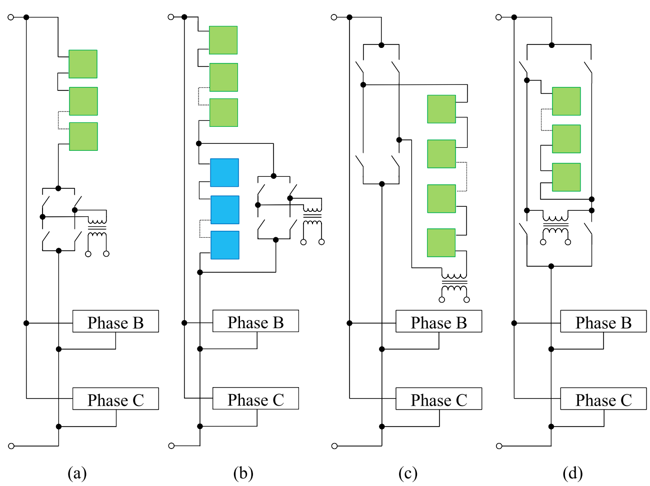

FIGURE 5. PCC - H-bridge-based converter topologies: (a) PHMC, (b) PCUB, (c) parallel-HBHMC, and (d) CTFB-HMC.

phase. Although it does not require additional SMs in cross-connected arms, half-arm capacitor voltage control has to be adopted since the FC splits one arm to two half arms.

C. H-BRIDGE-BASED TOPOLOGIES

Different hybrid multilevel converters can be constituted by combining an H-bridge and different arrangement of SM branches in each phase (Fig. 5). This type of converter topologies aims to reduce the total number of SMs, therefore reducing power losses and compact footprint. These converters can achieve higher dc voltage utilization compared to the MMC.

However, the coupling between the ac and dc side typically leads to a fixed energy balancing point, which means a fixed modulation index for these converters under normal operation. Three separate transformers are required in the converter topologies SM branches, and series-connected SMs are used to synthesize the three single-phase ac voltages.

1) PHMC

In the parallel hybrid multilevel converter (PHMC), the H-bridge is connected as an unfolding bridge after a series-connection of SMs [see Fig. 5(a)]. The series connected FBSMs are arranged in the dc-link to coordinate with the H-bridge to generate multilevel ac output voltage. In addition, the PHMC has dc fault handling capability which inherits the major benefit of the MMC with bipolar SMs, although soft switching of switches in the H-bridge cannot be achieved.

2) PCUB

Unlike the PHMC, HBSMs are connected in parallel with the H-bridge to synthsize the multilevel ac voltage directly in parallel-connected unfolding bridge (PCUB) [see Figure. 5(b)]. Zero voltage switching (ZVS) of switches in the H-bridge can be guaranteed by the parallel-connected HBSMs. Series-connected FBSMs in the dc-link cancel out ac components generated by HBSMs. The PCUB has the potential to handle dc faults due to the introduction of FBSMs. During the operation of the PCUB, the energy of both, the HBSM and FBSM arms, need to be balanced leading to a complicated controller design [43].

3) PARALLEL-HBHMC

The parallel H-bridge hybrid modular converter (parallel-HBHMC) operates in the overmodulation range, hence bipolar SMs have to be used. The topology offers inherent dc fault handling capability [see Fig. 5(c)]. Nevertheless, the HBSMs are arranged at the ac terminal in each phase, thus soft switching in the H-bridge cannot be realized in such a converter topology [44].

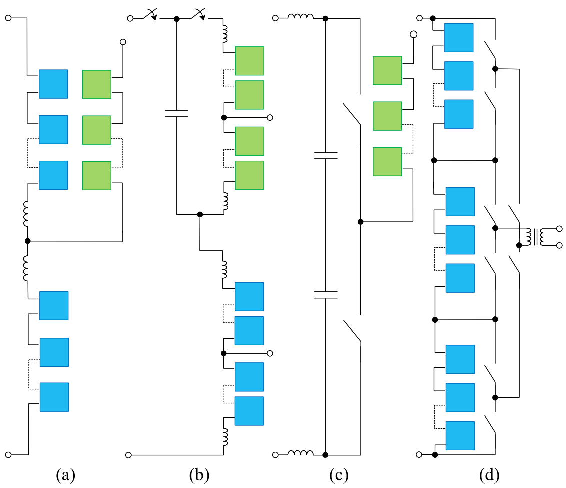

FIGURE 6. PCC - other PCC topologies: (a) HC-MMC, (b) RFB-MMC, (c) HCMC, (d) MVHP-MMC.

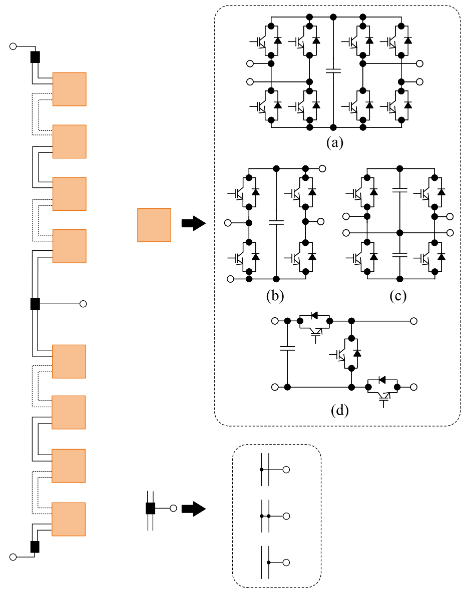

FIGURE 7. PCC - other PCC topologies: MMSPC. Typical SM configurations: (a) Double-H-bridge SM, (b) asymmetrical double-half-bridge SM, (c) symmetrical double-half-bridge SM, and (d) three-switch SM.

4) CTFB-HMC

FBSMs in the controlled transition full-bridge hybrid multilevel converter (CTFB-HMC) are employed between the two legs of the H-bridge in each phase, hence no dc current is present in the FBSMs [see Figure. 5(d)]. Similar to the parallel HBHMC, soft switching in the H-bridge cannot be achieved as well. It is noted that the FBSM arm can be considered as a parallel connection with each ac terminal, thus CTFB-HMC cannot interrupt fault current under dc faults [45].

D. OTHER PCC TOPOLOGIES

Certain PCC topologies cannot be classified in the previous categories, due to their unique structure and operation principles. The MVHP-MMC is proposed to be used in MVDC applications, while the HC-MMC, RFB-MMC, and HCMC are designed with HVDC transmission systems as a focus (Fig. 6). The MMSPC can be considered as a MMC with series and parallel SM connectivity (Fig. 7). Unique parallel operating states offer opportunities to the MMSPC to be applied in more scenarios, such as low-frequency applications and STATCOMs. The detailed topology descriptions are provided below.

1) HC-MMC

The hybrid cascaded MMC (HC-MMC) with hybrid HBSMs and FBSMs has been proposed for improving the dc fault tolerance and reducing the power losses of the FB-MMC [see Fig. 6(a)]. Although additional FBSMs are used at the ac terminal, they do not contribute to the active power transfer leading to significant capacitor energy storage reduction in the FBSMs [46].

2) RFB-MMC

The topology of MMC with reduced FBSMs (RFB-MMC) adopts series connection of a 3-phase high voltage HB-MMC and a low voltage FB-MMC [see Figure. 6(b)]. Only a small proportion of FBSMs are used as the function of the FBSMs is commutating the fault current from the FB-MMC to the fault breaking circuit, which includes the dc capacitor, connector and breaker. Compared with the FB-MMC, the RFB-MMC has lower total power losses and maintains the dc FRT capability, although additional components are introduced in the dc-link for clearing dc faults [47].

3) HCMC

FBSMs are also arranged at the ac terminal in the hybrid cascaded multilevel converter (HCMC) [see Fig. 6(c)]. The HCMC has a fixed energy balancing point, and the arm switches operate under fundamental frequency as the AACs. However, the HCMC cannot achieve soft-switching as the conventional AAC due to the different arrangement of SM arms [48].

4) MVHP-MMC

The medium voltage high power MMC (MVHP-MMC) is designed for reducing the SMs and improving the dc voltage utilization [see Figure. 6(d)]. Nevertheless, it is complex for the MVHP-MMC to expand to a true three-phase converter due to the coordination of three arms and four sets of switches in each phase. Moreover, the operation of switches leads to additional losses, and this converter has no dc fault handling capability [49].

5) MMSPC

The series and parallel connectivity of the modular multilevel series/parallel converter (MMSPC) is achieved at a SM rather than a phase level. SM parallelization allows pairwise module interconnection (Fig. 7) [50], [51]. SMs with four

TABLE VII SCC - Others

Converters	Characteristics	Advantages	Disadvantages
TAMBC [64]	1. Arm current conduction path via anti-parallel thyristors	1. DC fault handling capability 2. Reduced number of SMs 3. Reduced power losses of SMs 4. Reduced energy in SMs (kJ/MVA)	1. Additional control of thyristors 2. Inclusion of commutating inductors 3. Additional power losses of FBSMs
METDC [65]	1. Low conduction loss path via thyristors	1. DC fault handling capability 2. Reduced number of SMs 3. Reduced power losses of SMs and thyristors	1. Fixed energy balancing point 2. Control complexity of thyristors

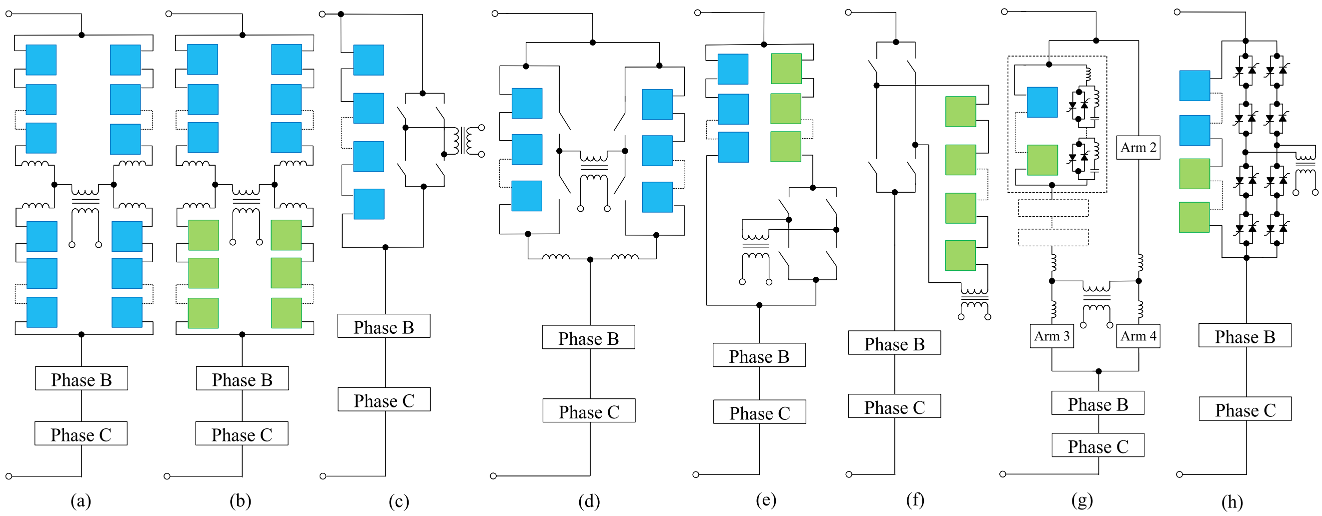

FIGURE 8. Modular series-connected multilevel converter topologies: (a) SC-MMC, (b) SCAH-MMC, (c) SHMC, (d) MDSMC, (e) SBC, (f) series-HBHMC, (g) TAMBC, and (h) METDC.

terminals are used in MMSPC arms, such as the double-H-bridge SMs [50], asymmetrical/symmetrical double-half-bridge SMs [52], [53], three-switch SMs [54], [55] [see Fig. 7(a)–(d)], and each SM connects to its adjacent SM through two output terminals [51]. The parallel connectivity allows sensorless voltage balancing [56], capacitance reduction, arm current sharing, conduction loss reduction [57], and modulation stage simplification [51]. In addition, the MMSPC with bipolar SMs can also handle dc fault as conventional FB-MMC [55].

Nevertheless, such parallel structure increases the number of semiconductor devices in each SM, although the total arm current can be shared by two switches in each SM. Moreover, additional switching states increase the control complexity, while modulation stage can be simplified due to the parallel SM connectivity [51].

IV. SERIES-CONNECTED CONVERTER TOPOLOGIES

Different from PCCs, SCCs are typically designed for lower power ratings and are suitable for HVDC tapping application benefiting isolated rural and small areas located besides the main HVDC stations due to the direct series connection of, typically, three phases [58]. Each phase in SCCs is subjected to only one third of the full dc voltage, while full dc current flows into each phase. This section summarizes SCC topologies and Tables V to VII show the unique characteristics, advantages and disadvantages of the phase series-connected MMC-based, H-bridge-based and other SCC topologies, respectively.

A. PHASE SERIES-CONNECTED MMC-BASED TOPOLOGIES

This type of SCC topologies is originated from the study of HVDC taps for power transmission along the existing HVDC lines. The converter topologies provide two thirds of the power rating compared to the MMC under the same dc voltage [see Figs. 8(a) and (b)]. There are four arms in each phase, and the SMs are connected with an arm inductor in series in each phase for both topologies. The required number of SMs is 66% of an equivalent MMC, hence the power losses are lower.

However, a number of issues accompany series connected converters. A typical issue is the third harmonic current caused by the single phase structure and the secondary side of the three separated transformers [59]. The three separate dc voltages should be balanced under unbalanced grid conditions, especially under asymmetrical ac faults.

1) SC-MMC

The basic converter of SM-based series-connected converters, the series-connected MMC (SC-MMC), uses HBSMs in all arms [see Fig. 8(a)]. Therefore, the SC-MMC cannot self-interrupt fault currents under dc faults [59].

2) SCAH-MMC

The series-connected asymmetrical hybrid MMC (SCAH-MMC) is an improved topology of the SC-MMC, achieving dc fault tolerance capabilities by introducing FBSMs in the lower two arms [see Fig. 8(b)]. However, it also inherits the drawbacks of the SC-MMC due to the similarity in the topology structure [60].

B. H-BRIDGE-BASED TOPOLOGIES

Similar to the H-bridge-based PCC topologies, this type of SCC topologies also requires fewer SMs compared to the MMC, while the three phases are connected in series in the dc-link. This type of SCC topologies combines different SMs and an H-bridge in each phase (Fig. 8). The number of SMs for these topologies is reduced due to the alternate switch operation in the three H-bridges. Fewer SMs in the arms means lower losses which are, however, negated by the losses in the H-bridge switches. In addition, the SM capacitor energy storage requirement per MVA is also reduced due to lower maximum energy deviation. It is noted that the parallel-connected SM arms allow possible ZVS for H-bridges [see Fig. 8(c)–(e)]. Nevertheless, these topologies have a fixed energy balancing point due to the strong coupling of the ac and dc sides that the ac and dc currents cannot be controlled independently.

1) SHMC

Parallel connection of an HBSM arm and an H-bridge per phase are adopted in the series hybrid multilevel converter (SHMC) [see Fig. 8(c)]. The SHMC uses HBSMs to synthesize a multilevel ac voltage, but such a converter with HBSM arms has no capability to ride through dc faults [61].

2) MDSMC

Unlike the SHMC, there are two parallel-connected HBSM-based branches in the modular directed series multilevel converter (MDSMC) [see Fig. 8(d)]. The MDSMC provides lower current rating for the two branches via arm current division. Similar to the SHMC, the MDSCM also uses HBSMs, hence the converter is not able to handle dc faults [62].

3) SBC

Starting from the topology structure of the SHMC, additional FBSMs are connected with an H-bridge in series per phase to derive the series bridge converter (SBC) [see Fig. 8(e)]. The FBSM arms provide dc fault handling capability of such topology and assist with harmonic filtering generated by HBSM arms. The energy balancing between the HBSM and FBSM arms should be considered similar to the PCUB [63] of Section III-C2.

4) SERIES-HBHMC

The series-HBHMC is a series-connected variant of the parallel-HBHMC [see Figure. 8(f)]. It has dc fault handling capabilities and operates in the overmodulation range. However, soft-switching of the arm switches cannot be achieved, increasing the voltage stress and losses of the converter [44].

C. OTHER SCC TOPOLOGIES

In order to further reduce the power losses of the aforementioned two types of SCC topologies, some other converter topologies are introduced by reconfiguring the SM-based SCCs using antiparallel thyristors [see Fig. 8(g) and (h)].

1) TAMBC

For reducing the conduction losses of the SMs in the SC-MMC and providing dc fault tolerance, the thyristor augmented modular bridge converter (TAMBC) is developed by partially replacing HBSMs with FBSMs and connecting antiparallel thyristors in parallel [see Fig. 8(g)]. The operating principle of the TAMBC is different from the SM-based SCC topologies, since only two arms generate the output voltage and the remaining two arms are bypassed via the thyristor path. Also, the TAMBC has a lower total energy deviation, hence a lower capacitive energy storage requirement per MVA [64].

2) METDC

The modular embedded thyristor directed converter (METDC) is an improvement of the SHMC, which uses antiparallel thyristors to replace the IGBTs in three H-bridges and adopts hybrid HBSMs and FBSMs in the arms [see Fig. 8(h)]. In addition to the aforementioned benefits of the SHMC, the thyristors in the METDC drive the loss reduction of switches in H-bridges. The topology can also ride through dc faults. However, the ac and dc sides are still coupled, and thyristor commutation needs to be considered as part of the converter operation [65].

V. CONTROL SCHEMES

Various control methods can be used to achieve multiple control objectives in extended MMC topologies. Classical closed-loop control approaches are commonly used in these topologies, although other control methods, such as open-loop control [66], [67], conventional model predictive control (MPC) [68]–[70], and machine learning (ML)-based MPC [71] are also being developed to deal with the additional complexity of new converter structures. Fig. 9 shows the classical closed-loop control structure of extended MMC topologies, including high-level (converter station) and low-level (internal converter) control. The active/reactive power, node voltages/currents and frequency in the high-level control are regulated based on references. The low-level control regulates the *i*) arm energy, *ii*) SM capacitor voltage, *iii*) circulating current, *iv*) modulation, and *v*) other control targets in specific converter. Detailed control function description will be provided in this section.

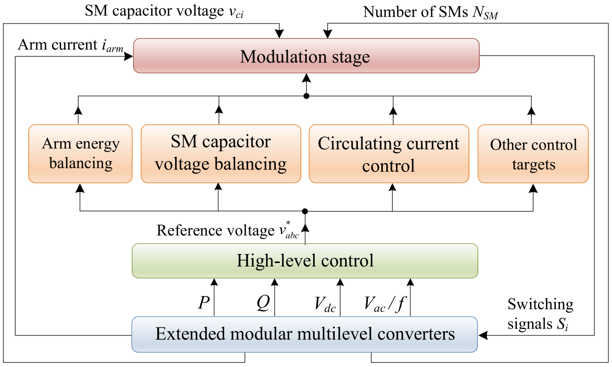

FIGURE 9. Classical close-loop control structure for extended modular multilevel converter topologies.

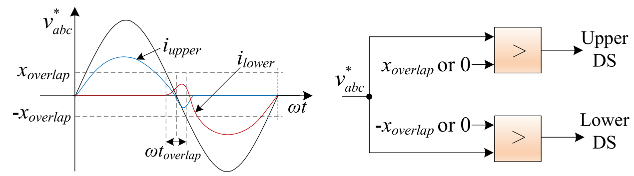

FIGURE 10. DS control of the AAC considering overlap period.

A. COMMON CONTROL FUNCTIONS

1) HIGH-LEVEL CONTROL

As all topologies are VSCs derived or inspired from the MMC, most high-level control schemes used in MMCs can be used, usually with no or minor modifications, in extended MMCs. Commonly applied high-level control schemes, such as vector current control (VCC) with fast current response characteristics are used. Such control can be achieved in three different frames with corresponding control algorithms and associated benefits/drawbacks [72]. These include: *i*) proportional-integral (PI) control in dq synchronous rotating frame, *ii*) proportional-resonant (PR) control in $\alpha\beta$ stationary frame, and *iii*) deadbeat control or hysteresis control in *abc* stationary frame [73], [74].

The PI control algorithm in dq frame is widely applied in the extended modular multilevel converters, which consists of an outer and inner control loop [72]. The outer control loop most commonly generates decoupled output current references for inner control loop to calculate the final output voltage reference. Since PI controllers only show satisfactory performance in dc variable regulation, PR controllers can be used to obtain zero steady-state error when controlling fundamental and higher order harmonic components. It is also possible to arrange three independent controllers in *abc* stationary frame, and nonlinear controllers, such as deadbeat and hysteresis controllers, can be used in applications which require high dynamic responses [75].

2) LOW-LEVEL CONTROL

In addition to high-level control loops, other internal control units are required for the operation of extended MMCs. As all extended MMCs are modular and based on SMs, either in different arms or the ac side, it is necessary to equip them with SM-based controllers. These typically achieve different control targets, which include SM sorting and SM capacitor voltage balancing. Moreover, arm energies should be balanced and circulating current between phases should be regulated for improving the quality of output waveforms [18].

The required number of SMs for each arm is determined in the modulation stage. Different modulation techniques are used to determine the switching states of SMs based on expected modulation waveform. The conventional "sort and select" algorithm can be used to balance the SM capacitor voltages, although such stage can be greatly simplified in the MMSPC due to the parallel SM capacitor connection. The basic process of conventional SM capacitor voltage balancing algorithm can be separated into *i*) sorting SM capacitor voltages, *ii*) measuring arm current directions, and *iii*) selecting SMs to be inserted/bypassed based on arm current directions and instantaneous values of SM capacitors [76]. This algorithm, while simple and efficient, can lead to high switching frequency. Various improved methods are reported in current literature for reducing switching frequency [10], [77]–[79]. Such methods typically employed to MMCs can be readily used to the extended topologies.

Moreover, the energy of different SM-based arms in all topologies should be further balanced. Although the main function of FBSMs in the HC-MMC, PCUB and SBC is harmonic cancellation, the energy distribution between the FBSM and HBSM arms should be managed as well to avoid arm energy unbalance.

Circulating current regulation is also a major control target for modular VSC topologies, which can be specifically applied to suppress arm harmonic currents [10], [11], although additional third harmonic currents have to also be eliminated for SCCs. Current literature also explores relationship approximation between circulating current references and capacitor voltage ripples via ML [80]. A third harmonic voltage component can be included to suppress the inherent third harmonic currents in SCCs. It is worth mentioning that third harmonic injections are common approach for modular VSCs to increase dc voltage utilization ratio, decrease SM capacitance, reduce phase energy deviations, etc [81].

B. SPECIFIC CONTROL FUNCTIONS

Due to the different SMs and arm arrangements, the introduction of IGBT or integrated gate-commutated thyristor (IGCT)- and thyristor-based switches in some topologies, there are specific control functions necessary for the correct operation of certain extended VSC topologies in addition to the common controllers.

For the AAC family, additional control of DSs has to be used in order to achieve alternate arm operation as shown in Fig. 10, which is also necessary in the HCMC. The AAC can operate away the inherent energy balancing point causing energy surplus or deficit. Overlap period control is employed to achieve energy balance in the AAC family [82].

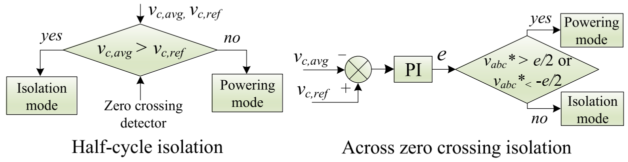

FIGURE 11. **Two isolation modes in the HBHMC for balancing energy distribution between the ac and dc sides.**

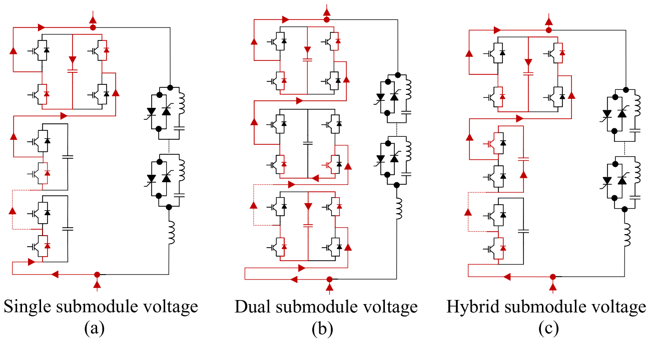

FIGURE 12. **Arm current paths in three SM control methods for reducing the size of thyristor snubber circuits and power losses: (a) single submodule voltage (SSMV), (b) dual submodule voltage (DSMV), and (c) hybrid submodule voltage (HSMV).**

Moreover, zero sequence current injection [83], overlap onset control [84] and circulating gradient current control [85] can be used to balance arm energy. ZCS should also be ensured to avoid increasing switching losses in series-connected IGBTs. It can be achieved by proper circuit modification or different control methods such as the introduction of LC resonant circuit [86] or double-band hysteresis current control [87].

Similar to the AAC family, the fixed energy balancing point limitation of the HCMC and all H-bridge-based converters should be addressed. Therefore, energy balancing strategies are adopted when the energy exchange between ac side and dc side is not zero. In the HBHMC, two isolation operation modes called half-cycle isolation (HCI) and across zero crossing isolation (AZCI) are introduced with corresponding control block diagrams to make zero net energy exchange when the actual modulation index is less than the standard modulation index (Fig. 11) [44].

Thyristors are broadly applied in some of the topologies, since they can offer significantly lower losses compared to the full-controlled devices such as IGBT and IGCT. The introduction of thyristor valves in the AT-AAC and TAMBC reduces the conduction losses of SMs [36], [64]. Additional single SM voltage (SSMV), dual SM voltage (DSMV) and hybrid SM voltage (HSMV) control methods can be used for decreasing the power losses and the size of thyristor snubber circuits [88], [89]. Fig. 12 provides current paths flowing into HBSMs and FBSMs in three SM control methods. Also, thyristors are used in the MEMC and the METDC to drive loss reduction by replacing full-controlled devices [38], [65].

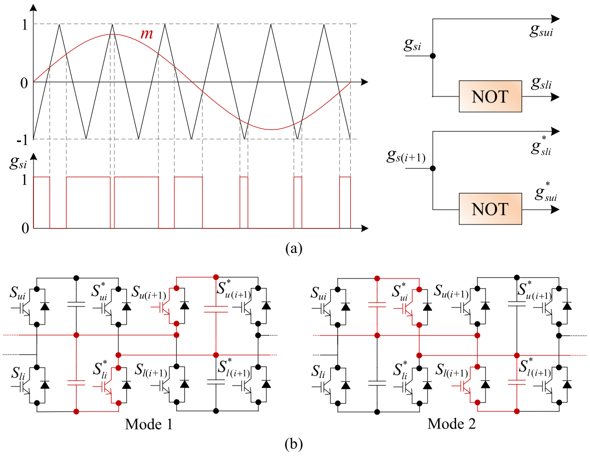

FIGURE 13. **Modulation scheme and different parallel operating states in symmetrical double-half-bridge SMs: (a) Modulation scheme and (b) two possible operation modes of parallel states.**

In H-bridge-based converter topologies, four switches in a H-bridge are controlled to coordinate with corresponding SM-based arm to generate multilevel ac waveforms. The switches in the HMMC and the MEMC turn on/off in one fundamental period depending on the actual output voltage (positive, negative or zero voltage). In addition, four sets of switches in the MVHP-MMC are turned on/off based on two operation modes (modulation index above/below 0.5) [49].

SM parallelization in the MMSPC offers reduced control complexity in the modulation stage. Mass sensors in SMs are eliminated and all SM capacitor voltages can be regulated if the capacitor voltage in one SM is controlled. Figure. 13(a) demonstrates the modulation scheme in the MMSPC with symmetrical double-half-bridge SMs. The generated gate signals (g_{sui}, g_{sli}, g^*_{sui}, g^*_{sli}) are sent to corresponding switches (S_{ui}, S_{li}, S^*_{ui}, S^*_{li}). Of particular note is that the gate signals g^*_{sui} and g^*_{sli} come from a neighbouring SM, which is designed for simultaneous on-off action of diagonal switches [see Figure. 13(b)] [51], [53].

Different from the PCCs, the dc voltage in the SCCs has to be balanced under unbalanced ac grid conditions, since each single-phase keeps the dc voltage as constant as one-third of the total dc voltage. A feasible approach is developed for the SC-MMC and SCAH-MMC, where a zero-sequence component is utilized to realize power balance, and a negative-sequence component is added to the arm modulation signals to offset negative-sequence voltages at the converter side [59], [60].

VI. APPLICATION FIELDS

The extended PCC and SCC MMC topologies are modified from the conventional MMC structure to be applied in different application scenarios. The main application field of these topologies still remains that of HVDC, including use in transmission, multi-terminal systems and tapping applications. The AAC family, and converters such as the HMMC,

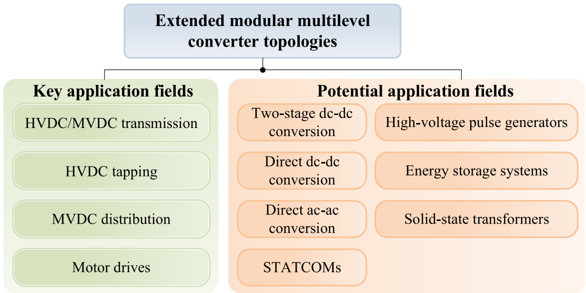

FIGURE 14. Classification of application fields in extended modular multilevel converter topologies.

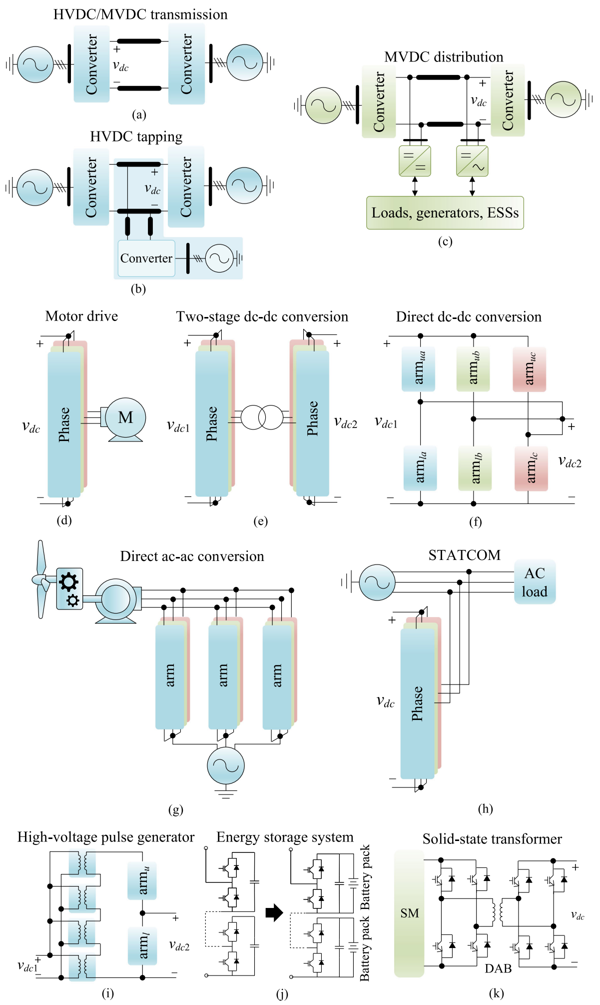

FIGURE 15. Application fields of extended modular multilevel converter topologies: (a) HVDC and MVDC transmission system, (b) HVDC tapping, (c) MVDC distribution system, (d) motor drive, (e) two-stage FTF dc-dc conversion, (f) direct dc-dc conversion, (g) direct ac-ac conversion, (h) STATCOM, (i) HV pulse generator, (j) ESS, and (k) SST.

MEMC, PHMC, PCUB, parallel-HBHMC, CTFB-HMC, HC-MMC, RFB-MMC and HCMC were all originally proposed for HVDC transmission systems [see Fig. 15(a)]. Despite no dc fault self-clearing capability in some converters, dc breakers can be arranged to interrupt transient fault current at the cost of high investment [20]. SCC topologies are more suitable to HVDC tapping solutions due to the lower power rating under the same dc voltage as the main HVDC converters [see Fig. 15(b)]. Although each phase in the SCC topologies has to regulate the dc-side voltage to one third of the total dc voltage, the required number of SMs and power losses can be reduced compared to fully rated MMCs.

In addition to the converter topologies for HVDC applications, the AC-MMC and PC-MMC are specifically proposed for MV motor drives [see Fig. 15(d)], and MVHP-MMC serves for MVDC systems [see Fig. 15(a) and (c)]. The AC-MMC and PC-MMC can operate in a wide frequency operation range, and the issue of arm energy imbalance under low frequency operation mode can be solved via introducing a cross-connected arm or flying-capacitor in the conventional MMC. It is noteworthy that topologies designed for HVDC can also be applied in MVDC systems with decreased number of SMs. Moreover, the size of capacitors in some converters (SO-AAC, SAAC, IAAC, HMMC, RFB-MMC and HCMC) can be reduced with the decrease of dc voltage level enabling expanded applications from HVDC to MVDC. However, the increased number of SMs in the AC-MMC leads to high cost, hence limits its further expansion to higher voltage application scenarios. The MVHP-MMC is also difficult to be ported in HVDC systems due to the complicated coordination regulation of the three arms and four switched in single-phase. The additional parallel operating states lead to capacitor voltage ripple reduction and capacitance saving, which enables the MMSPC to be applied in STATCOMS and low-frequency scenarios such as motor drive [51], [57], [90]. Moreover, current literature also reports the application of different converters based on SM parallel connectivity in BESSs [91]–[93].

Beyond the main application areas of extended MMCs, summarised above, many of these topologies show potential in other use cases, predominantly in applications where the modular structure offers some critical advantages. Such applications include HV dc-dc and ac-ac conversion systems, STATCOMs and FACTS for grid support applications, HV pulse generators, BESSs, SSTs, etc [7]. The classification of application fields in extended modular multilevel converter topologies is demonstrated in Figure. 14.

The dc–dc conversion can be categorized into *i)* two-stage dc–dc converters with intermediate transformer and *ii)* direct, transformer-less dc–dc converters [94]. By constituting front-to-front (FTF) structures with a medium/high frequency transformer, extended MMCs can achieve dc-dc conversion and provide galvanic isolation. Fig. 15(e) shows a typical PCC-based FTF structure [95], while an equivalent SCC configuration would require three individual transformers. Such structure can also be used in SST solutions [96]. PCCs can also realize direct dc–dc conversion by on or more outputs into a common point [see Fig. 15(f)] [97] and appropriate control modifications. Different arms based on SM series and parallel connection can be applied in matrix converter to achieve direct ac-ac conversion without using a dc-link [51], [98]. A possible ac-ac structure for the wind energy conversion based on a permanent magnet synchronous generator is shown in Fig. 15(g) [99], [100].

As these converters all have independent reactive power control capability, they are capable to operate as STATCOMs providing/absorbing reactive current at the point of connection to a grid [see Fig. 15(h)] [101]. In this case, SCCs might not be an preferable choice because the inherent third harmonic current introduces control complexity when regulating the voltage at the point of grid connection.

HV pulse generators are more commonly applied in water disinfection systems and are shown as promising application field for extended MMCs. The purpose of HV pulse generator is to obtain a high-voltage output with pulse duration of a few microseconds from a low-voltage input [102] where the SM capacitors release the stored energy from low voltage side to generate short-time period HV pulses [103]. The modularity of extended MMCs offers redundancy and robustness in the pulse generation operation [102], [104]. Fig. 15(i) shows a single-phase pulse generator structure with SM-based arms.

Interconnection of distributed energy storage systems, such as the one shown in Fig. 15(j) can also be achieved using extended MMCs, for instance through a distributed battery across multiple SMs or as the part of a dc power source [105]. In the field of SSTs, modular topologies possess multiport power transfer capability compared to direct FTF structures with a large high frequency transformer [106], [107]. Fig. 15(k) shows a typical modular SST structure that a dual active bridge (DAB) is used to inject/drag power from connected SM [106]. It has to be noted that not all SM-based arms can be modified into modular ESSs or SSTs. For instance, FBSMs arranged in the HC-MMC have no active power transfer capability, hence they cannot participate into such modification.

Nevertheless, extended MMCs are still limited by the high number of semiconductor devices and complex control logic making them less suitable for use in LV applications, such as remote telecommunication stations, electric vehicle (EV) charging stations, data centers, illuminating systems, etc. Miniaturization and light weight are two major characteristics for LVDC converters, and it is less beneficial to arrange cascaded SMs in each arm for applications where low voltage levels (hundreds of volts) can be met by single devices [108], [109].

VII. CONCLUSION

From the conventional PCCs to SCCs, various modular dc-ac multilevel converters inspired by the MMC have been proposed and further studied in the literature. These extended MMCs all deliver distinct benefits in their respective application fields. This paper provides a comprehensive review of these converters from the aspects of topology structure, characteristics, advantages/disadvantages, control schemes and application fields.

The main driver for development of extended MMCs is to optimise the converter structure, required number of SMs and further reduce power losses, which providing additional functionalities such as handling dc faults and achieving arm energy balancing across all fundamental frequencies. However, the reduction of the required number of SMs and power losses comes at the cost of complex control schemes and the introduction of more semiconductor devices such as IGBTs, thyristors and diodes. Also, there are many challenges that have to be settled for these topologies including the wide modulation index range, soft switching, dc fault self-clearing capability, fault protection, SM structure simplification in the MMSPC, etc. Although the high-level control and low-level functionalities (e.g. SM sorting, SM capacitor voltage balancing, arm energy balancing, and circulating current regulation) used in MMCs can be directly applied in extended MMCs, the structural difference also determines specific control methods required in extended MMCs. Such cases have also been considered in this work. Nevertheless, each controller needs to be designed for specific converter and application. Addressing these challenges is an open question for future work in this field.

In summary, this work *i*) provides a comprehensive overview and rationalises the various extended MMCs currently developed in the literature, *ii*) helps to avoid repetition and rationalize the claims made in multiple articles, *iii*) allows a qualitative comparison of the topologies, and *iv*) offers design references for derivation of new extended MMCs.

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