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Modular Multilevel Converters: Recent Achievements and Challenges

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ABSTRACT The modular multilevel converter (MMC) is currently one of the power converter topologies which has attracted more research and development worldwide. Its features, such as high quality of voltages and currents, high modularity and high voltage rating, have made the MMC a very good option for several applications including high-voltage dc (HVdc) transmission, static compensators (STATCOMs), and motor drives. However, its unique features such as the large number of submodules, floating capacitor voltages, and circulating currents require a dedicated control system able to manage the terminal variables, as well as the internal variables with high dynamical performance. In this paper, a review of the research and development achieved during the last years on MMCs is shown, focusing on the challenges and proposed solutions for this power converter still faces in terms of modeling, control, reliability, power topologies, and new applications.

INDEX TERMS Modeling, modular multilevel converters, modulation and control, multilevel converters, power electronics.

I. INTRODUCTION

The modular multilevel converter (MMC) was originally proposed in 2001 in a German patent by Prof. Marquardt [1]. In this patent, the dc to three-phase converter structure with series-connected submodules is shown, as well as, the inductances in each arm and the half and full-bridge submodules.

Early publications introduced several topology variations, including a single-phase to single-phase MMC [2] and a single-phase to three-phase MMC [3]. Both converters were proposed for traction applications transforming the low-frequency voltage from the catenary to a medium-frequency voltage required to power the machine drives. These publications also showed a basic one-phase model with a rudimentary control scheme for ac and dc components, which can be easily extended to the three-phase MMC [4]. To validate the proposed topology and its control, an experimental prototype was implemented and reported [5].

Since then, the MMC has been widely researched in several topics, including the theoretical models to perform steady-state analysis and to establish design guidelines, simulation models to reduce the computational burden, modulation techniques to provide a high-quality arm voltage, control schemes for currents, voltages, and energies, and reliability studies to evaluate different aspects of the MMC implementation. One of the most active research topics is the study of MMC topologies proposing several alternatives configurations of converters and submodules to benefit from a specific feature of the MMC for a given application or to address a specific issue such as reduction of losses or minimization of capacitor voltage ripple [6].

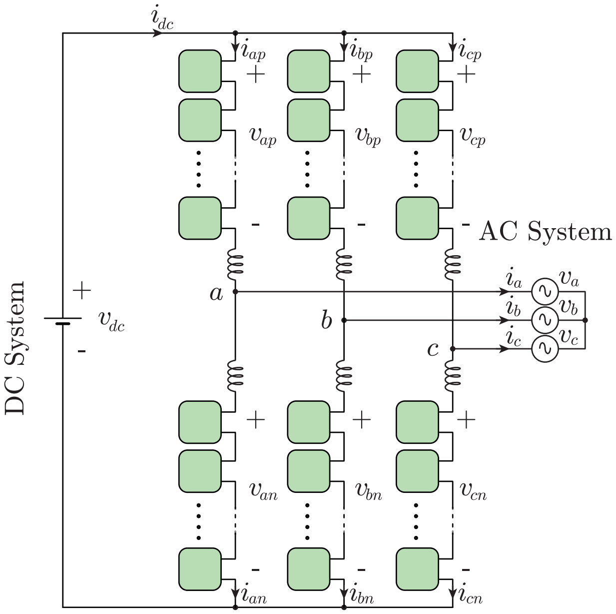

FIGURE 1. Dc to three-phase MMC topology.

Nowadays, as a result of the intensive research and development on the MMC and its technology, this converter has become an important alternative in HVdc applications being successfully employed in China [7], Europe [8], and the USA [9] in point-to-point, multi-terminal and hybrid systems. Several commercial products can be found in the market from manufacturers such as SIEMENS [10], Hitachi-ABB [11], CEPRI [12] and GE (formerly Alstom) [13]. Additionally, motor drives [14], and STATCOM [15] products using this converter topology are also available in the market.

However, there are several issues that are still under research, and they have not been completely solved yet. Some of these issues, or challenges, are required to improve the performance of the control system, managing faults inside and outside the converter, optimize its size in terms of capacitance and cooling requirements, adapt the topology of the converter, and submodule for emerging applications in medium voltage distribution power systems, motor drives and other areas, to name a few [16].

This paper reviews the newest achievements in the previously identified challenges revising proposed solutions that have been recently published [17]. Additionally, future trends regarding these challenges which allow widening the use of MMC in HVdc and motor drives, but also pushing the development of MVdc grids and enabling its use in emerging applications, are given.

II. POWER TOPOLOGY AND OPERATING PRINCIPLE

The basic feature of the MMC is the series interconnection of several submodules, generating a multilevel voltage waveform at its terminals. The submodules can be interconnected following several structures depending on the application, such as the dc to three-phase configuration shown in Fig. 1(a), widely used in HVdc applications. It is important to notice that an actual HVdc system commonly has more than 200 submodules per arm generating a nearly sinusoidal voltage waveform [6]. The series-connected submodules and the decoupling inductance form an arm, and two arms form a phase. The dc system is connected between the upper and lower terminals of the phases, while the ac system is connected to the central point of each phase. Each arm generates a controlled voltage at its terminals, which combined with the dc and ac system voltages, produce the required ac and dc currents [18].

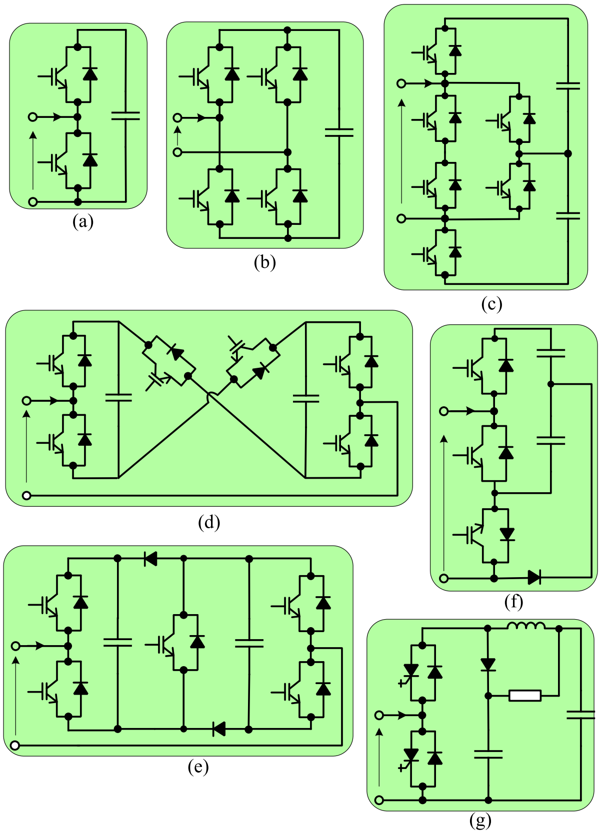

FIGURE 2. MMC submodules: (a) half-bridge submodule, (b) full-bridge submodule, (c) modified ANPC submodule, (d) cross-connected submodule (CCSM), (e) clamped double submodule (CDSM), (f) single-clamped submodule (SCSM), and (g) IGCT submodule.

Although the most commonly used submodules are the half- and full-bridge topologies, shown in Figs. 2(a) and (b), respectively, several alternative submodules topologies to fulfill different objectives have been proposed in the literature [19]. For instance, the modified active-neutral-point-clamped (ANPC) submodule shown in Fig. 2(c) serves as a lower loss submodule option in applications where unipolar voltage output is sufficient [20]. Bipolar submodules such as the cross-connected submodule (CCSM) [19] and the clamped double submodule (CDSM) of Fig. 2(d) and (e) provide general fault blocking capabilities and controllable negative voltages similar to the full-bridge topology with reduced component count [21]. The single-clamped submodule (SCSM) defines a family of submodules with bypass clamping diodes as shown in Fig. 2(f) that facilitates fault-clearing in MMCs [22],

[23] while the IGCT based submodule, shown in Fig. 1(g), features higher efficiency, voltage rating and reliability [24].

III. MODELING AND DESIGN

The increasing integration of the MMC in HVdc systems requires improved models of the converter to reduce simulation time, considering that the power system must be simulated for several seconds or minutes. A simple and reliable model also facilitates the theoretical analysis and consequently, the design of the MMC. Models for theoretical analysis and simulation and design guidelines are discussed in this section.

A. MODELING

The initial approach to model the MMC for control purposes uses a static model in which the ac and dc voltages and currents are modeled without dynamical components [25], generating the ac and dc modulating indices directly [26]. A mathematical model of the MMC, including the capacitor voltage dynamics and balancing algorithm was introduced later [27]. The natural dynamic response of the circulating currents was showed and the need for circulating current control to reduce capacitor voltage ripples demonstrated at this point. The dynamic model of the differential and summative arm currents, i.e., ac and dc currents, was introduced in [28] facilitating the control design and improving its performance. The dynamic model of the circulating current was also added to further improve the performance of the converter control [29]. In the particular case when the ac and dc sides are both grounded, a common-mode current appears through the converter arms. The dynamic behavior of this common-mode current was introduced in [30] completing a mathematical model with six degrees of freedom corresponding to the six controlled arm voltages. The extension of the MMC model using sequence decomposition was proposed to work with unbalanced grid conditions [31]. This model has been recently improved using small-signal dynamics [32] and obtaining a steady-state model to improve the design [33].

The effect of voltage imbalances and signal quantization on the accuracy of reduced simulation models is analyzed, and improved results when using a low number of submodules per arm are obtained [34]. Models to study the harmonic performance of the MMC are introduced such as a steady-state mathematical model which relates harmonics in the arms and line currents [35], and a simplified approach based on harmonic linearization to facilitate the analysis of the MMC in the frequency domain [36]. More sophisticated methods able to capture the internal harmonic dynamic behavior of the MMC have been recently presented. Harmonic linearization theory is used to develop an ac-side impedance model of the MMC [37]. Alternatively, [38] and [39] use the harmonic steady-state analysis to capture the linear time-periodic characteristic of the MMC.

From the standpoint of power system stability, impedance and state-space modeling of MMCs have been developed during the last years. Ref. [40] and [41] are two of the first attempts to develop impedance models of three-phase MMCs valid for power system stability studies. They develop approximated models that neglect the effect of the capacitor voltage ripple in the dynamics of the system. As a consequence, the linearization process required to obtain the small-signal ac-side impedance is simplified. However, the internal dynamics may have an impact on the ac-side impedance. On this basis, the multi-harmonic coupling behavior of the MMC is represented and an impedance model for power system stability studies is obtained. [42] makes use of several dq-transformations at different frequencies to separate the multiple frequency components within the MMC. State-variables that represent the dynamic behavior of the system settle at an equilibrium point. Consequently, a small-signal linear state-space representation of the MMC can be calculated and the state space matrix together with the eigenvalues and eigenvectors that define the small-signal system stability are defined.

A complete HVdc system including converter stations, dc line and ac systems, as shown in Fig. 3, usually requires several seconds, or even minutes, of computational simulation. These simulation times are not achievable if the model is based on switching devices [43]. Several models have been proposed to speed up the simulation, such as the linearized operating curve of insulated-gate bipolar transistors (IGBTs) to avoid the lengthy nonlinear solving [44], a model based on dynamic phasors to directly obtain the steady-state operation [45], and a reduced-order small-signal model that simplifies the model and enhances simulation efficiency [46]. Alternative MMC topologies, such as the alternate arm converter (AAC), have also been modeled in order to make it compatible with multi-terminal dc (MTdc) simulation [47]. Current-source models of the MMC, based on Norton equivalent to study a back-to-back system, can also be found in the technical literature [48].

The converter design has been improved during the last years, incorporating into the control strategy the thermal balance among submodules in order to avoid overheating of a submodule. To provide a simple thermal modeling, several stages of thermal resistances and capacitances are used [49]. However, the main advances shown in this area are related to the simplified power loss model for analytic purposes, both at converter level [50] and at semiconductor level [51] using data from datasheet and linearized energy calculations. Thanks to the simplicity of these models, it is possible to accurately simulate the complete converter in terms of electrical variables, including the thermal behavior.

B. DESIGN

Industrial MMCs for HVdc systems have rated powers ranging from hundreds of MWs to a few GWs. Therefore, the design of such systems involves many technical challenges, including sizing reactive components, selecting proper power devices, designing the mechanical structure and cooling system, etc. Since each submodule has a dc bus and there are hundreds of submodules, the MMC integrates many capacitors. Minimizing the capacitance value required in each

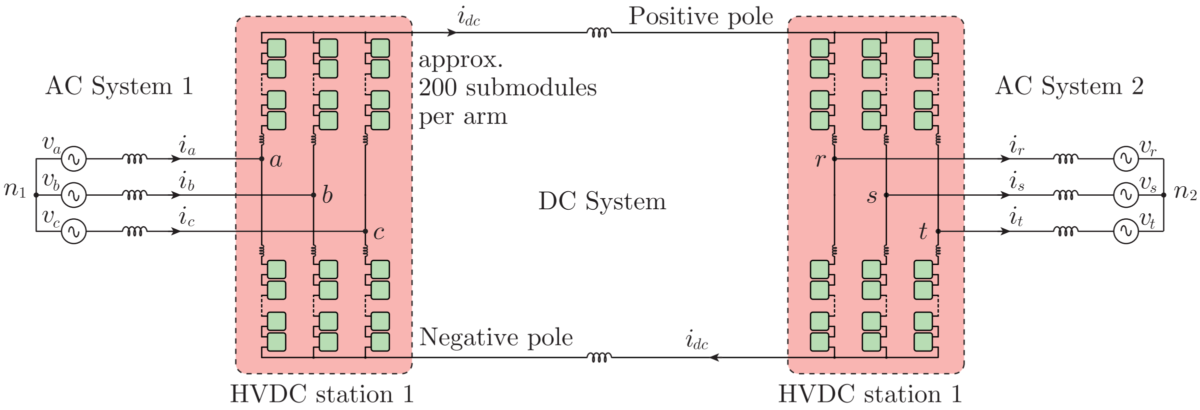

FIGURE 3. HVdc system with two MMC stations.

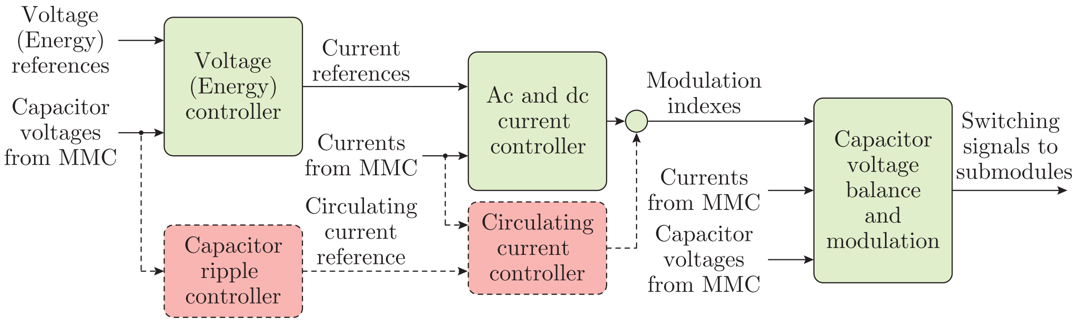

FIGURE 4. MMC control structure.

submodule of the converter is a key target that has been extensively addressed in the literature. Capacitor voltage ripples are intimately linked to the circulating currents in the converter. The information regarding normalized capacitor voltage ripple amplitudes allows the sizing of capacitors for different circulating current strategies considering all the possible operating points of the converter [52]. When half of the submodules of each arm have half-bridge topology and the remaining have H-bridge topology the capacitor size can be reduced. Adding a zero sequence to the reference voltages demonstrated a further reduction in the capacitor size [53].

The design of a fully rated MMC with several hundred submodules where each valve has to meet all conditions in service, the values of the transformer turns ratio, the transformer reactance, and the valve reactance, considering how the ripple that appears on the submodule voltage are calculated [54].

IV. CONTROL AND MODULATION

To benefit from the high power quality featured by the MMC, a suitable modulation technique and controller must be employed. The structure of the control systems, different control methods, control objectives and modulation techniques are described in this section.

A. CONTROL SYSTEM STRUCTURE

Early attempts to control the MMC were focused on the direct generation of arm voltages, i.e. modulation indices, to provide the required ac, dc and common-mode voltages [55]. This control system was improved using dynamical models to drive the ac and dc currents to their references and adding an average capacitor voltage control and a capacitor voltage balance strategy [56]. Since then, a control structure using three stages: an internal capacitor voltage balance, a current control stage, and a voltage, or energy, control stage, as shown in Fig. 4, has commonly been employed [57], [58].

At the innermost control level, the capacitor voltage balance is usually implemented using a sorting algorithm, which requires the value of each capacitor voltage and the current in each arm. A version of this algorithm has been implemented using a current estimator to reduce the number of sensors and the wiring complexity [59]. It is possible to modify the sorting algorithm considering the specific topology of each submodule, for example, for flying capacitor submodules, integrating the capacitor voltage balance into the modulation algorithm [60].

The current control generates the modulation indexes in order to synthesize the required voltages in the converter arms. This control stage is usually designed using the dynamic models of the MMC, but they can be adjusted including the positive and negative sequences in the model to work with unbalanced voltages [61]. It is also possible to take into account the effect of the capacitor voltage ripple in the arm currents using a transformation to obtain the fundamental component of these voltages and feedforward it into the control loop, improving the dynamic performance [62].

The outermost control loop is usually focused on regulating the average arm capacitor voltages [63], or energies [64]. Both alternatives have shown to provide proper regulation, but the energy approach has the advantage of providing a linear relationship between power and currents, keeping the same dynamic behavior even if the operating point changes.

Increasing the number of submodules often necessitates the use of distributed architectures for control methods and hardware design, which include capacitor grouping and intergroup balancing on top of all other balancing and control structures [65].

B. CONTROL METHODS

Most of the control methods proposed in the literature work well with a fixed ac frequency, such as in the case of HVdc systems. However, in motor drive applications, where the ac frequency changes, the capacitor voltage control strategy has to be modified. For example, it can be separated into three different current and voltage injection strategies depending on the motor speed [66] or controlling the ac and dc component of the arms independently using an unsymmetrical arm control [67]. The former has a simpler implementation, but suffers from operating discontinuity produced when the control strategy changes, while the latter has better performance, but increased complexity.

To improve the control performance when the ac frequency changes, sliding mode control has been proposed for this converter, providing faster dynamical behavior than linear proportional-integral (PI) controllers without increasing the processing time [68].

Model predictive control (MPC) is a simple and powerful alternative to control power converters which can be also applied when the ac frequency changes. One of the first examples of this type of control applied to MMCs was on a single-phase to single-phase MMC topology, in which the input, output and circulating currents are controlled simultaneously [69], and a back-to-back HVdc system [70]. Despite the fast performance of MPC, the large number of possible switching states becomes one of the main weakness of this control method in MMC applications due to the high processing power required. To overcome this problem, several alternatives have been proposed such as modulated MPC, in which a continuous optimization is employed and the resulting modulation index is then modulated with phase-shifted pulse-width modulation (PWM) [71]. In addition to reducing the processing time, the modulated MPC approach also reduces the steady-state error [72]. A predefined switching sequence can be used to reduce the circulating current [73]and pulse-pattern control in order to reduce the harmonic content on the currents [74].

It is possible to reduce the universe of possible switching states by preselecting the available states [75], or grouping them depending on the operation conditions [76]. Both alternatives reduce the processing time by evaluating only a fraction of the total switching states, but the result corresponds only to a local optimization. Also, clustering the submodules for voltage balancing and linearizing the objective function reduces the computational burden [77]. It is also possible to reduce the processing time by separating the optimization process into two stages: one to calculate the insertion index, and a different stage to calculate the inserted submodules [78]. Recent MPC algorithms proposed in the literature employ three different stages to control the grid side current, circulating current and voltage balancing [79]. The first two stages do not depend on the number of submodules, and only the last one has a processing time that increases with the number of submodules. Unbalanced grid voltages can be controlled with MPC using a per-phase approach in which each phase is controlled separately [80], or using a three-phase approach that requires more calculations but improves the converter performance [81].

With the increased interest on the development of control techniques to improve the inertial response and primary frequency control in grids with high penetration of power converters, several grid-forming control algorithms have been adapted to operate together with MMCs [82], [83]. A virtual synchronous machine control technique for MMCs with inertia response has been introduced later [84]. Different inertia emulation strategies for an MMC-based HVdc transmission link have been evaluated taking into consideration the energy stored in the submodule capacitances [85]. A droop control for MMC performs active power support as well as parallel operation with other voltage sources and islanding operation [86]. It has been demonstrated that the internal energy control of the MMC impacts the dynamic behavior while operated with grid-forming control [87].

C. ADDITIONAL CONTROL OBJECTIVES

The circulating current is one of the distinctive features of the MMC, which represents the current that circulates among the arms of the converter, but it does not circulate through the converter terminals. An early approach to control and eliminate the circulating currents in PWM-based MMCs obtaining the circulating current reference from a control loop based on PI controllers [77], [88], using a current controller based on double-frequency rotational synchronous frame [89]. The low-frequency harmonics of the circulating currents concentrate the losses; hence the effort has been focused on design a controller to eliminate them [90]. Although the main control objective regarding circulating currents initially was to suppress them completely, it has been recently proven that the injection of a specific circulating current can be used to reduce losses [91] and also capacitor voltage ripples [92].

The combination of arm currents and modulation signals generates several harmonic components in the capacitor voltage of each submodule. This capacitor voltage ripple can usually be reduced by a proper design of submodule capacitance. However, in a motor drive, where the ac operating frequency can be lower than the grid, the capacitor voltage ripple increases and impacts the performance of the whole control system [93]. There are several approaches from the topology perspective to deal with the capacitor voltage ripple, for example modifying the circuit topology by using half- and full-bridge submodules to redistribute the power among submodules [94]. Another approach is using a middle cell with bidirectional power capability [95], or using a multipulse diode bridge to change the dc voltage when the drive operates at low speed reducing, at the same time, the capacitor voltage ripple [96]. From the control perspective, it is possible to use asymmetric control canceling either the upper or lower arm current for half a period, reducing the current through the capacitor and consequently the voltage ripple [97]. It is also possible to use a discontinuous modulation to inject common-mode voltage and reduce the most important frequency components of the capacitor voltage ripple [98]. Circulating current paths inside the MMC, particularly the second and fourth order current harmonics, can be implemented to reduce capacitor voltage ripples [99], [100]. Optimization methods can be used when the circulating current control parameters, capacitor voltage ripple and limits defined by the converter operation are treated as an integrated problem. By considering appropriate criteria, the problem can be converted to a convex optimization problem, which leads to global optimum solutions for combinations of voltages and currents that minimize capacitor voltage ripples [101]. When the MMC operates under unbalanced voltages, a fundamental frequency appears in the ac power and, due to the interaction of the arm currents, increases the amplitude of the capacitor voltage ripple [102]. In this condition it is possible to use zero-sequence voltage injection to reduce the ripple amplitude [103].

D. MODULATION

Due to the large number of voltage levels the MMC can generate, the Nearest-Level Modulation (NLM) provides a simple implementation and calculation of gating signals while ensures a nearly sinusoidal arm voltage. A combination of NLM and PWM, in which only one submodule per arm is modulated, can reduce the low-frequency current distortion generated by NLM without increasing the modulation complexity [104]. The NLM also produces unbalanced capacitor voltages, which can be balanced again using a rotation strategy in order to periodically change the modulated submodule [105]. It is also possible to use a series of logical functions to force the insertion of submodules improving the balance of capacitor voltages [106]. Both previously proposed methods do not increase the power losses because only one submodule is switching, while the remaining ones are at a fixed state.

The duty cycles can be modified during the sample time to reduce the effect of voltage ripples on the output voltages. The voltage drop in the power devices and parasitic resistances can also be considered [107]. On the other hand, the capacitor voltage ripple can be reduced by using a square-wave modulation for some submodules of the arm, and phase-shifted for the remaining [108].

V. FAULT-TOLERANT OPERATION AND RELIABILITY

Fault-tolerant operation of the MMC has received attention during the last years, mainly due to the increment of industrial applications in HVdc systems. This section shows the main contributions regarding dc and ac faults, submodule faults and reliability assessments.

A. DC AND AC FAULTS

The analysis of HVdc faults has shown that capacitances along the dc line can produce large fault currents across the converter. This issue has been addressed by using dc breakers as in conventional HVdc systems and communication between both systems in order to improve the protection performance [109]. Nonetheless, one of the most common practices to reduce the fault current in MMC-based dc systems is the use of the converter itself to manage this current, hence reducing the complexity and cost of the protection system [110].

The blocking of a dc fault in an MMC can be achieved when the total voltage of connected submodules along the fault current path is greater than the line-to-line ac voltage [111]. This can be achieved by hybridization of the MMC arms using combinations of unipolar and bipolar submodules. At the simplest form, an arm with 50% half-bridge and 50% full-bridge submodules can provide such functionality. In bipolar HVdc systems, hybridization can be done at arm level rather than a submodule level. This leads to converter designs where the arm on the ground pole is configured with unipolar submodules while the other arm only includes bipolar submodules [112].

Further optimization in the design of a hybrid converter can be achieved by injection of zero sequence harmonics [113], nested operation of low and high switching frequency submodules [114], or even integration of Si and SiC devices in one arm [115]. A key consideration for the fault clearance process is the number of commutations that may occur and need to be accounted [116]. Further improvements for hybrid MMCs can also be achieved through integration of thyristors in the submodules, or the arm design [117].

Multiterminal HVdc, which becomes a natural extension of deploying the MMC, will require a much more complex fault management system to provide a stable and reliable fault clearance strategy. A combination of dc circuit breakers with the MMC itself, operating as a voltage source has been proposed to clear the dc fault [118]. The dc circuit breakers can be replaced by high-speed switches and, using full-bridge submodules in the MMC the fault current can be drastically reduced [119]. However, as mentioned in the literature, this topic is still open and several initiatives are currently focused on it [120].

Faults in the ac side produce unbalanced voltages in the grid, which can be managed by modifying the arm voltages in the MMC in order to shift the neutral point and keep the line-to-line voltages balanced. This strategy is combined with suppressing the circulating current to mitigate the double frequency current that appears in the arms [121]. A similar neutral point shifting strategy, but using a control based on power feedforward, can be applied to already implemented MMCs without requiring any additional hardware [122]. Under single-phase to ground faults, the unbalanced currents generate different thermal stress among phases, which can be avoided using the neutral-point shifting with minimal impact on the circulating currents [123]. Moreover, using the shifted neutral point combined with a dc shift strategy, it is possible to extend the fault response capability maximizing the line voltages [124]. Is important to have a proper ac fault management strategy to avoid the large dc fault currents generated by single-phase-to-ground failures that are not properly managed [125].

B. SUBMODULE FAILURES

Faulty submodules can be dealt with different redundancy strategies such as: (i) not including any additional submodules and using the remaining ones with an overrated voltage ratio, (ii) including redundant submodules which are permanently working or (iii) using spare submodules that are connected when some submodules fail. A reliability model is used to assess the different redundancy strategies resulting on a large dependency on the control system reliability [126]. Additionally, these strategies also perform differently in terms of voltage and currents stress, resulting in competing behavior between losses and dynamic [127].

The operation of redundant submodules which are activated when a submodule fails can be easily implemented using a phase-disposition PWM (PD-PWM) with a selection algorithm to evaluate which and when the submodule has to be activated [128]. On the other hand, phase-shifted PWM (PS-PWM), can also be used with the same purpose, but it requires carrier rearrangements [129] or rotative carrier selection [130].

An MMC typically requires one voltage sensor per submodule and such a large number of voltage sensors impacts the converter reliability. A capacitor voltage measuring system with reduced number of sensors can be implemented, where the minimum number can be as low as two voltage sensors per arm [131]. This technique can be used as a complementary measuring system to further improve converter reliability by providing fault tolerance to voltage sensor failure. The proposed measurement technique can also be used to detect submodule failures, including both, open- and short-circuit semiconductor faults [132]. Other solutions to detect faults without additional sensors have been previously proposed in the literature [133]–[135]; however these solutions can only detect open-circuit semiconductor faults.

In Table 1 a comparison of different types of faults and the causes identified is shown.

TABLE 1. **Classification of Faults in MMC**

Type of fault	Possible solutions
DC Faults	Converter blocking Common mode voltage injections Use of bipolar SMs Hybrid Modular Topologies DC breakers DC grid coordination
AC Faults	LVRT / HVRT grid code requirements Common mode voltage injections Neutral point voltage shift Circulating current control AC side breakers
SM failures	Active Redundancies Passive Redundancies Converter Overrating Operational Underrating Control / Modulation approaches
Measurement and Sensing	System redundancies Sensorless methods Predictive maintenance

C. RELIABILITY

A reliability model assuming periodic preventive maintenance is proposed in [136]. The model is derived by the reliability function and described by the indices of equivalent failure rate and forced outage rate. The reliability in terms of submodule redundancy and maintenance interval is analyzed to provide information for operation and planning, which is especially valuable for offshore utilities. The submodules within the converter can be constructed with either individual IGBT modules or with series-connected IGBTs. Case studies have been conducted to compare the reliability characteristics of converters constructed using the two-submodule configurations [137]. It is found that the reliability of the MMC with series-connected IGBTs is higher for the first few years but then decreases rapidly. By assigning a reduced nominal voltage to the series valve submodule upon IGBT module failure, the need to install redundant submodules is greatly reduced.

A precise reliability model is useful to employ statistical tools, combined with information of submodules and components, to extend the availability of the MMC by properly designing the number of redundant submodules and defining management schedules [138]. There is a trade-off between submodule redundancy and cost, which should be evaluated for each project to define redundancy design and operation strategy [139].

A reliability analysis performed on the circulating current and common-mode voltage control strategies shows the thermal stress of semiconductors depends on where they are physically located in the circuit hence the cooling design can be optimized [140].

VI. TOPOLOGIES AND APPLICATIONS

The most extended topology of the MMC is the one shown in Fig. 1, where the submodules can be implemented by half- or full-bridge converters. Many topology variations have been presented in the literature, each of them targeting the improvement of certain features or addressing some specific applications. Several of these converter topologies and applications are discussed next.

A. MMC TOPOLOGIES

Among the topologies recently proposed for MMCs, the star- and delta-channel ones, shown in Figs. 5(a) and (b), respectively, are very interesting for motor drives due to the reduced capacitor voltage ripple they achieve. These topologies have

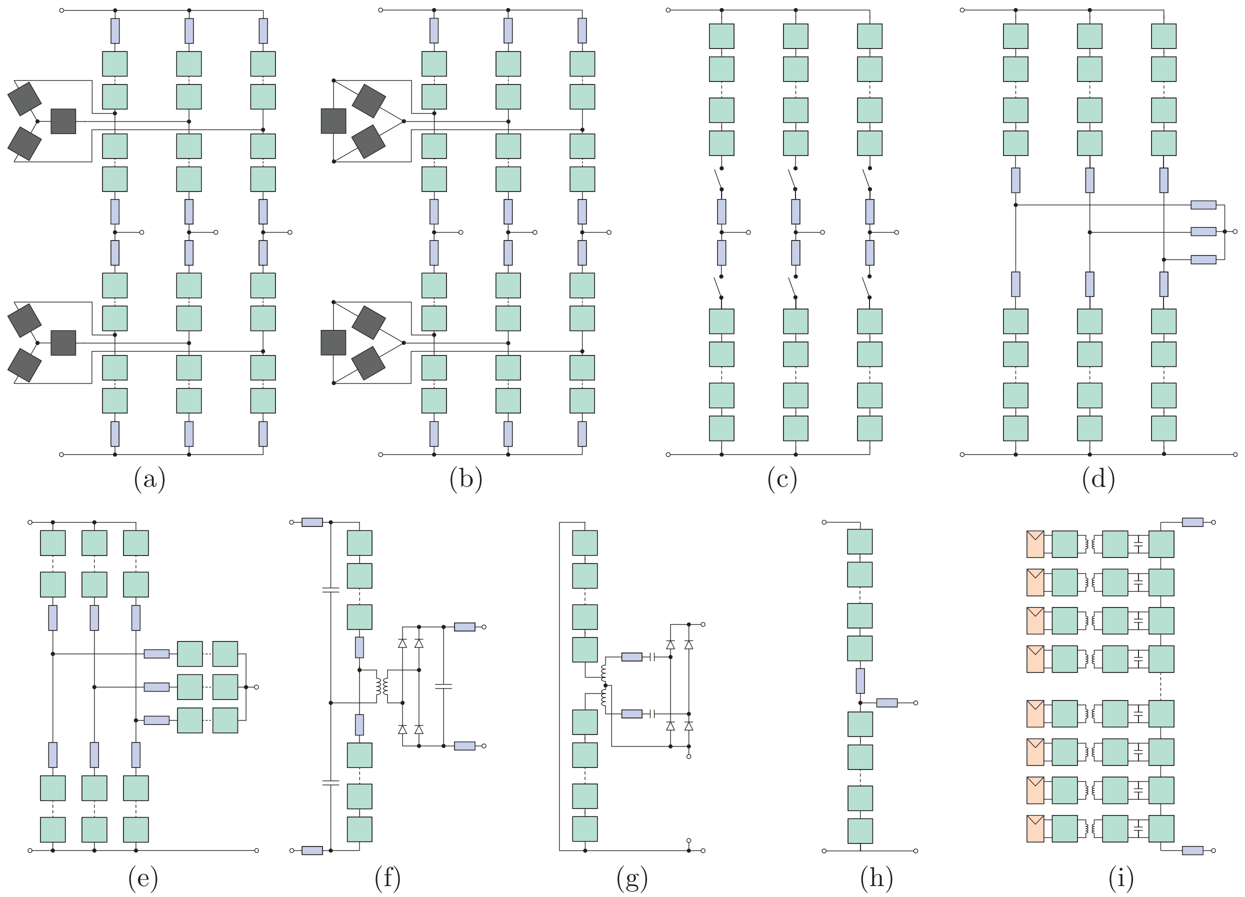

FIGURE 5. MMC topologies: (a) Star-channel MMC, (b) delta-channel MMC, (c) alternate arm converter, (d) dc-dc MMC, (e) dc-dc MMC with output submodules, (f) dc-dc MMC with high frequency transformer, (g) dc-dc push-pull MMC, (h) dc-dc buck/boost MMC, and (i) single-arm MMC.

a set of additional submodules, shown as gray boxes, that are connected to the arms of different phases allowing the exchange of power among the arms, and hence helping to minimize the capacitor voltage ripples even when operating at low frequency. The main drawback of these topologies is the large number of submodules [141], [142].

The Alternate Arm Converter (AAC) topology, in which the arms are connected in series with a high voltage switch, as shown in Fig. 5(c), allows the activation or deactivation of the complete arm. Therefore, it provides better performance than the standard MMC in terms of circulating current, power losses, and capacitor voltage ripple [143]. Additionally, it is possible to define an overlap period in which both arms in the same phase are active at the same time to help capacitor voltage balance and control [144]. It is also possible to inject circulating current to achieve zero current switching in the high-voltage switch reducing the losses [145].

The high performance, in terms of efficiency and controllability, showed by the MMC on HVdc systems, have pushed the development of medium-voltage dc (MVdc) systems for power distribution in which the MMC becomes and essential element [146]. Several topologies providing dc-dc conversion are described in the following.

The standard three-phase MMC topology can be used as a dc-dc converter connecting all the outputs to a common point, as shown in Fig. 5(d). In this case, the control system has to generate a controllable dc output voltage, while a circulating current is forced to circulate among the arms in order to balance the capacitor voltages [147]. The previous topology can be improved by connecting three additional arms between the middle point of each phase and the output, as shown in Fig. 5(e). By adding these submodules, the complexity of the control is reduced, while the effect of the internal circulating current can be decoupled from the input and output dc currents [148]. The tolerance to faults can be increased as well because the output power can be redirected if one of the submodules fails.

Using a single-phase MMC in a half-bridge configuration, a high-frequency transformer and a single-phase diode rectifier, as shown in Fig. 5(f), a high step ratio dc-dc converter to enable HV and MV grids interconnection is achieved [149]. The arms operate with square wave, which further increases the efficiency. Using only one-phase MMC, two auto-transformers, LC filters and a diode rectifier, as shown in Fig. 5(g), provides a low step-up ratio dc-dc conversion [150]. The auto-transformer leakage inductances are used as arm inductances,

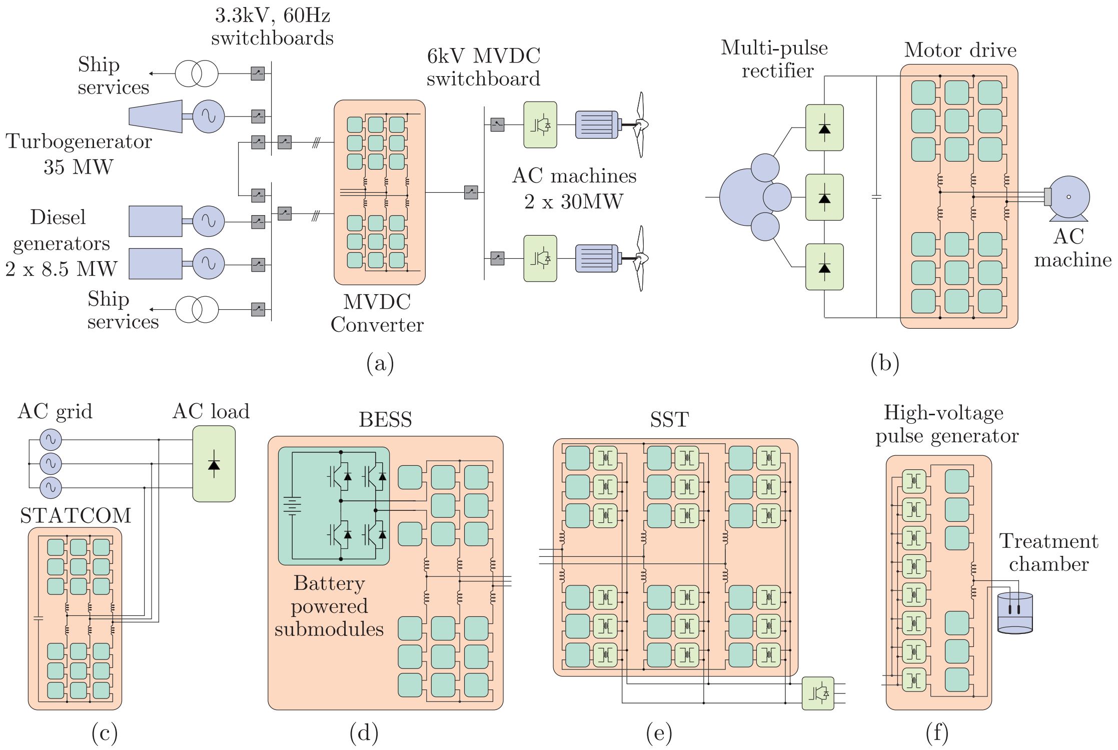

FIGURE 6. **MMC applications: (a) MVdc for shipboard, (b) three-phase motor drive, (c) modular multilevel STATCOM, (d) distributed BESS, and (e) solid-state transformer, (f) high-voltage pulse generator.**

providing resonant operation with soft switching while the circuit interconnection between the upper and lower arms allows to circulate current through the arms to balance the capacitor voltages.

A very simple alternative to implement dc-dc conversion is using one MMC phase with the load connected between the upper and lower arms, as shown in Fig. 5(h). This topology mimics the operation of a dc-dc buck or boost converter working with square-wave modulation for high efficiency, achieving a drastic reduction in submodule capacitance [151].

A dc-dc converter using only one single MMC arm, in which each capacitor submodule is connected to a high-frequency isolated dual active bridge (DAB), as shown in Fig. 5(i), has been proposed to connect a photovoltaic plant to a high voltage dc grid [152]. This topology provides modular interconnection, ground isolation of each submodule and independent maximum power point tracking (MPPT).

B. MMC APPLICATIONS

The MVdc systems mentioned in the previous section can be found in shipboards, as shown in Fig. 6(a), where the reliability of the MMC is an important factor to consider. Designing the on-board converter with redundant submodules, the converter reliability is improved [153]. Moreover, this converter can be used in combination with energy storage and active filtering functionalities in order to improve the availability of the complete on-board system [154]. Regarding fault tolerance, it is not recommended to use dc circuit breakers to clear the fault currents, but instead integrating full-bridge submodules in the MMC and implementing a proper control strategy to operate the converter itself during the fault [155].

One of the early applications of the MMC was as a motor drive, as shown in Fig. 6(b). However, the large increment of capacitor voltage ripple and the reduced controllability at low speeds, slowing down the development of this application [66]. These disadvantages have recently been addressed by several researchers using for example discontinuous modulation to reduce the capacitor voltage ripples [98], or eliminating the common-mode voltage to extend the machine lifetime by using a flying capacitor submodule [156]. Decreasing the operating capacitor voltage also reduces the voltage ripple allowing to reduce the capacitance [157]. A recent trend to improve the performance of the MMC as a motor drive is the incorporation of the machine model into the control system and using vector control to manage both, the converter and the machine at the same time [158]. Additionally, a back-to-back MMC structure implementing a control strategy to provide a controllable current source in the grid converter, allows to drive the machine at very low frequencies [159].

The MMC enables direct connection of a static compensator (STATCOM) at distribution level and even at transmission level avoiding the use of transformers, as shown in Fig. 6(c). Recent investigations have determined that negative sequence compensation capability is a key performance indicator for STATCOM devices; hence the diode-clamped [160] and delta-connected MMC show better performance in terms of efficiency [161].

TABLE 2. MMC Topologies Comparison

Application	Topology	Features
HVdc transmission	Half- and full-bridge submodules (Figs. 2(a) and (b), respectively)	Basic topologies, but the most common one for HVdc
	AAC (Fig. 5(c))	Low circulating currents, power losses and capacitor voltage ripples rating
MVdc grid	Basic topology with half- or full-bridge submodules (Figs. 6(a))	Applied in dc shipboards because of high reliability (using extra submodules), and potential functionalities of energy storage and active filtering
Motor drives	Basic topology with half- or full-bridge submodules (Figs. 6(b))	Large capacitor voltage ripples and reduced controllability at low speeds. Can be mitigated using discontinuous modulation, decreasing capacitor voltages, etc.
	Star- and delta-channel MMCs (Figs. 5(a) and (b), respectively)	Reduced capacitor voltage ripples, but a large number of submodules required
Dc-dc conversion	Half- and full-bridge submodules (Fig. 5(d))	A circulating current has to circulate among the arms to balance the capacitor voltages
	With additional output submodules (Fig. 5(e))	Control complexity is reduced. Decoupled internal circulating from the input and output dc currents. Increased fault tolerance
	Single-phase MMC in a half-bridge configuration with a high-frequency transformer and single-phase diode rectifier (Fig. 5(f))	Possible high step dc-dc voltage ratio
	Single-phase MMC with two auto-transformers, LC filters and a diode rectifier (Fig. 5(g))	Low step ratio. High efficiency because of soft switching
	Single-phase MMC with the load connected between the upper and lower arms (Fig. 5(h))	Reduced submodule capacitances
	MMC arm where each capacitor submodule is connected to a high-frequency DAB (Fig. 5(i))	Can be used to connect a PV plant to a HVdc grid. Modular interconnection, ground isolation of each submodule and independent MPPT
STATCOM	Basic MMC topology but with a floating dc-bus capacitor (Fig. 6(c))	Direct connection of the STATCOM to an MV or HV grid. Negative sequence compensation limitations.
Energy storage	Embedded energy storage in the submodules (Fig. 6(d))	Direct connection to a distribution or transmission grid. Power provided by each battery pack can be different (with some constrains)
Solid-state transformer	With a high-frequency dual active bridge connected to each submodule (Fig. 6(e))	High transformation ratio with isolation
HV pulse generator	MMC phase-leg fed from a single low-voltage source (Fig. 6(f))	Able to release high voltage/power. Can be used in water disinfection

The high-voltage rating of the MMC allows to connect a dc battery energy storage system (BESS) directly to the distribution or transmission grid, and the modularity of the MMC can also be used to interconnect distributed energy storage [162], as shown in Fig. 6(d). In this configuration, each storage module can be controlled independently in order to work at different operating points, increasing the overall efficiency [163]. Furthermore, the high power quality provided by the MMC enables its use in distributed energy storage systems of electric vehicles, where electromagnetic interferences should be minimized [164]. A decoupled power control is proposed to improve the overall stability of distributed energy storage units [165].

The MMC has been proposed to build a solid-state transformer (SST) using a single transformer and employing the MMC to generate the high-voltage at the primary side [166]. This configuration simplifies the operation of the MMC but it lost the modularity provided by the MMC. Using a high-frequency dual active bridge with isolation transformers is possible to operate each submodule to provide power transfer independently, and hence, improving the reliability [167]. Additionally, the structure of this modular SST can be configured as shown in Fig. 6(e), where all the primary stages are connected in series providing high voltage rating, and the secondary stages in parallel providing high current rating [168], mimicking the feature of a distribution transformer.

Due to the high voltage capability of the MMC it can be used as a high voltage pulse generator for water disinfection [169], as shown in Fig. 6(f). One MMC phase is used to store energy from the low voltage input into the floating capacitors and then release it in the form of a high-voltage short-time period pulse [170].

VII. CONCLUSION

The MMC is an interesting power converter topology currently used in several industrial applications and commercial products. A large amount of literature has been published on the MMC addressing the main issues this topology presents, such as current dynamical models, capacitor voltage balancing using sorting algorithms, control structure, and topologies for conventional applications such as HVdc, motor drives and STATCOM.

TABLE 3. Challenges in MMC and Prospective Solutions

Challenges	Prospective solutions
Unbalanced grids	Small-sigmal models Control in sequence decomposition
Power system stability	Small signal ac-side impedance
Simulation time	Linearized curves of IGBT Reduced-order small-signal models
Thermal design	Linearized energy calculation
Design of MMC	Considering capacitor voltage
Nearest Level Modulation	Hybridization with PWM
Capacitor voltage balance	Integrated sorting modulation Rotating modulation
Circulating current control	Low frequency harmonic control
Variable frequency control	Sliding control Model predictive control Integrated vector control
Model predictive control	Grouping and clustering
Capacitor voltage ripple	New submodule circuits New power topologies Circulating current control
Virtual Inertia	Distributed capacitance Grid forming
Dc faults	Using MMC to manage fault current
Ac faults	Neutral point shifting
Submodule failures	Submodule redundance
Voltage sensor reliability	Voltage observers
MV grids	Requires dc-dc conversion
Motor drives	Low frequency operation
Dc-dc conversion	New topologies
Niche applications	Water disinfection Other high voltage applications

In this review, several challenges that have not been completely solved are identified and the prospective solutions have been summarized. A list of these challenges is shown in Table 3. To ensure the proper operation of the MMC in unbalanced grids, precise small-signal models are required and the development of current and energy controllers considering the additional harmonic components that appear in this condition. To study the interaction between the MMC with the power system, a suitable model of the ac side impedance is required. In this regard, small-signal models also provide simple results that can be used to study the system stability based on the eigenvalues analysis. Power systems require dynamical simulation with a time scope of several seconds or even minutes. MMC simulation models need to be accurate and simple to simulate the MMC into a power system. A proper thermal model is also an important challenge due to the significant economic implications; hence the use of linearized energy calculation using data from datasheets can provide accurate results.

Due to the large number of submodules per arm, nearest level modulation is still the preferred option, but it needs to be combined with PWM to eliminate low-frequency harmonics. A future trend is to adapt NLM to work with a low number of submodules for MV applications. Capacitor voltage balancing usually uses a sorting algorithm to identify the cells that must be charged and discharged. This sorting algorithm can be integrated with the modulation to simplified it. However, open-loop balancing methods such as the rotation of the modulation signals still have potential due to the reduced computation time required compared with any sorting algorithm. Due to the nature of circulating current, its control considering several frequency components is an interesting tendency. Most of the published control schemes are intended for HVdc with fixed output frequency. However, for variable frequency, the control scheme must be developed in rotating coordinates or using a frequency-independent strategy such as sliding control or MPC. However, applying MPC requires grouping or clustering to reduce the large number of possible states to be evaluated. The minimization of capacitor voltage ripples leads to reducing the submodule size, given that approximately half of its volume is the capacitor. This minimization can be performed by topological changes at the submodule and converter level or by injecting a circulating current and common-mode voltage. When the MMC is placed in a distribution grid, the virtual inertia provided can be optimized, considering the large amount of distributed capacitors, and particularly for micrograms, a grid forming methodology must be developed.

The MMC itself can be used to manage the dc fault currents simplifying the protection system. This alternative requires further investigations in terms of practical results. The ac faults can usually be handled by shifting the neutral point to reduce the asymmetric currents. Although this method has been studied previously, the implementation in MMC requires more research. There are several alternatives to implement mitigation strategies when a submodule fails, which must be evaluated thoroughly. The large number of voltage sensors needed for control purposes impacts the MMC cost and reliability. These voltages can be reconstructed using the arm voltage and modulation indexes, but these observers must be precisely tuned.

Several dc-dc conversion alternatives have been proposed in terms of topologies, and it is expected this trend continues. Although the main application of the MMC is still HVdc systems, recent research findings allow its use on standard applications such motor drives and STATCOM but also on emerging applications including BESS systems, MVdc systems, and high-voltage pulse generators.

Addressing these challenges can not only improve the reliability of the MMC and its performance, reduce its cost and size, widening its use in HVdc and motor drives, but also pushing the development of MVdc grids and enabling its use in non-conventional applications.

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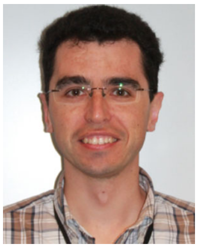

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