

Circuit Topologies, Modeling, Control Schemes, and Applications of Modular Multilevel Converters

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Abstract—Modular multilevel converters have several attractive features such as a modular structure, the capability of transformerless operation, easy scalability in terms of voltage and current, low expense for redundancy and fault tolerant operation, high availability, utilization of standard components, and excellent quality of the output waveforms. These features have increased the interest of industry and research in this topology, resulting in the development of new circuit configurations, converter models, control schemes, and modulation strategies. This paper presents a review of the latest achievements of modular multilevel converters regarding the mentioned research topics, new applications, and future trends.

Index Terms—Flexible AC transmission systems, HVDC transmission, medium voltage machine drives, modular multilevel converters, power electronics converters.

I. INTRODUCTION

TODAY, multilevel converters receive wide acceptance in industry and energy systems because they enable the design of medium and high voltage systems with excellent output voltage quality. Compared to the two-level voltage source converter, the simple realization of redundancy, low filter expense, and the reduction of power semiconductor losses and common-mode voltages are important additional benefits [1], [2]. Among the different topologies for multilevel converters, as shown in Fig. 1, multicell converters feature the highest degree of modularity and the lowest expense for redundancy due to the large number of cells they have, as well as the lowest harmonic content due to the large number of output voltage levels they produce. The large number of cells substantially increases the requirement of the converter controller, but each cell offers a simple structure, reducing the manufacturing costs. Currently, multicell

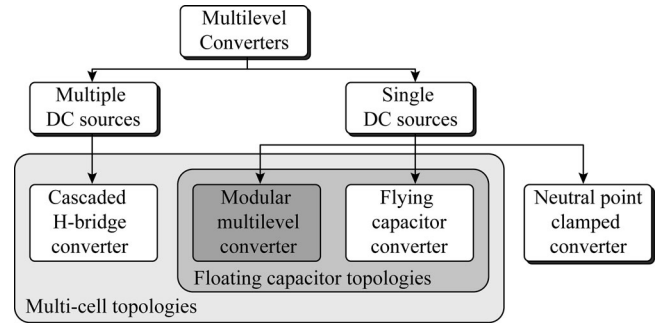


Fig. 1. Multilevel converter topology classification.

converters are used in applications like medium voltage drives (MVD), active filters, integration of renewable energy sources to the electrical grid, and in high-voltage dc (HVDC) transmission systems [3].

Modular multilevel converters (MMC) are a subfamily of multicell converters which have additional features such as the option of a transformerless operation, a completely modular design, and a common DC-bus [4], [5]. The MMC was invented by Prof. R. Marquardt in 2001 [6]. Pioneering publications propose this converter as an interface between a three-phase and a single-phase systems, proposing the use of space vector modulation and a method for the capacitor design [7]. This converter has also been proposed for traction applications with a medium frequency transformer in [5], where technological aspects of the converter were addressed. The first reported prototype was implemented using the latter configuration [8]. Early publications describe an open-loop control strategy based on imposed modulation indices calculated by the required input and output voltages [5]. A closed-loop control strategy was published only a few years later [9]. During the last years, several alternative topologies, models, modulation techniques, and control schemes have been proposed for this converter [10], [11]. Furthermore, they have also attracted the attention of industry, being currently developed as a solution for HVDC transmission by four main vendors [12]–[15], as well as for MVD [16].

II. MODULAR MULTILEVEL CONVERTER TOPOLOGIES AND MODELING

The main feature of MMCs is the cascaded connection of a large number of power cells. These cells are arranged in groups called arms, or branches, which can be connected in several configurations as shown in Fig. 2. In this figure, the interconnection of the arms between the input and output terminals is visible. Depending on the cell topology, as can be seen in next sections,

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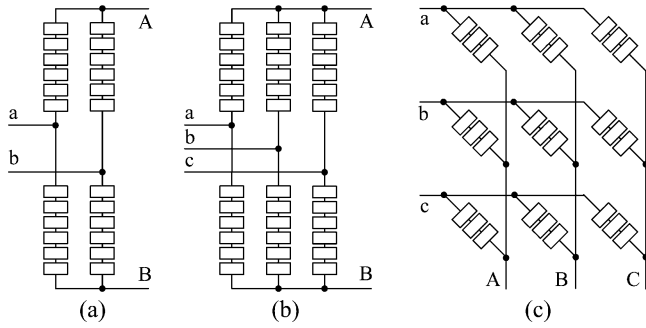


Fig. 2. Modular multilevel converters topologies according to the interconnection function (Each box represents one power cell). (a) Single-phase/single-phase or single-phase/dc. (b) Three-phase/single-phase or three-phase/dc. (c) Three-phase/three-phase (back-to-back).

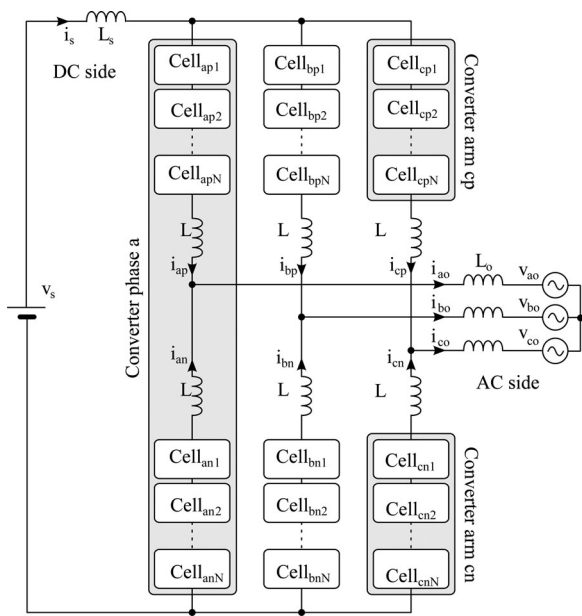


Fig. 3. DC/Three-phase modular multilevel converter circuit topology for HVDC applications.

the configurations shown in Fig. 2(a) and (b) can work with dc or single-phase ac voltages regarding the terminals P and N.

A. Converter and Cell Description

One of the typical configurations of the MMC is the dc to three-phase converter used in HVDC applications, shown in Fig. 3. In this topology two arms form a converter phase, where the dc system is connected to the upper (P) and lower (N) sides of the phase and the three-phase ac system is connected to the middle point of each phase (a, b, c). The arms connected to the positive bar are usually referred as positive, or upper, arms and the arms connected to the negative bar are referred as negative, or lower, arms. The ac and dc systems are usually modeled as voltage sources and the lines as inductors. This figure also shows the arm inductance L which must be connected in series with each group of cells in order to limit the current due to instantaneous voltage differences of the arms.

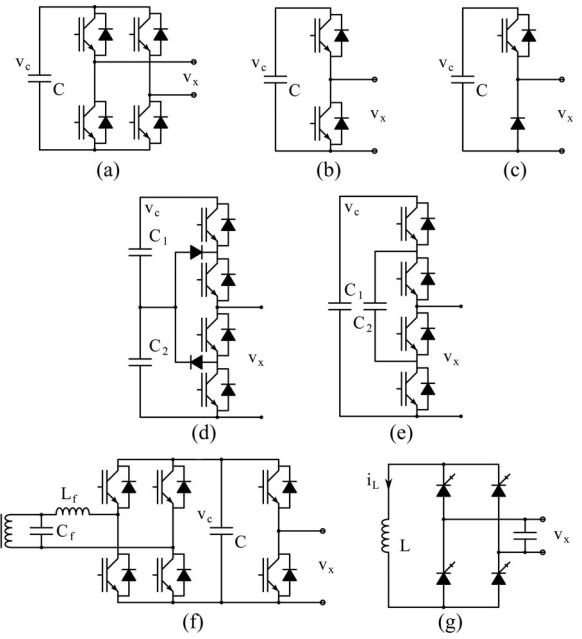


Fig. 4. Power cell topologies. (a) Full-bridge. (b) Half-bridge. (c) Unidirectional cell. (d) Multilevel NPC cell. (e) Multilevel flying capacitor cell. (f) Cell with resonant inverter for inductive power transfer. (g) Current source cell.

There are several power cell topologies proposed in the literature, the known ones are shown in Fig. 4. The most common cells are the full-bridge and half-bridge, of Fig. 4(a) and (b), respectively. The half-bridge cells can generate only zero and positive voltages, so there is inevitably a dc component in the arm voltage. This kind of cell thus only be used when the MMC is connected to a dc system. On the other hand, full-bridge cells can generate positive, zero, and negative output voltages, hence, they can be used when the MMC is connected to either ac or dc systems. One of the drawbacks to full-bridge cells is the higher number of components, compared to half-bridge cells. The unidirectional cell, shown in Fig. 4(c), has been proposed to reduce the number of semiconductors per cell, but the switching states are restricted depending on the current direction [17].

The efficiency of the cells can be improved, replacing the standard cell by multilevel structures, such as neutral point clamped or flying capacitor [18], as shown in Fig. 4(d) and (e), respectively, or by using a twin module [4].

One of the challenges of controlling the MMC is keeping the capacitor voltages balanced. It is possible to modify the power cell connecting an inverter and a resonant circuit, as shown in Fig. 4(f), to balance the capacitor voltages transferring power among cells inductively [19].

Finally, the topology of the cells can be completely modified from a voltage source dc link to a current source dc link, as shown in Fig. 4(g). These power cells have been proposed to achieve a higher voltage and power rating than traditional voltage source cells [20].

B. Converter Modeling and Simulation

The modeling of MMCs could become extremely complex and its simulation could be highly time consuming, due to the

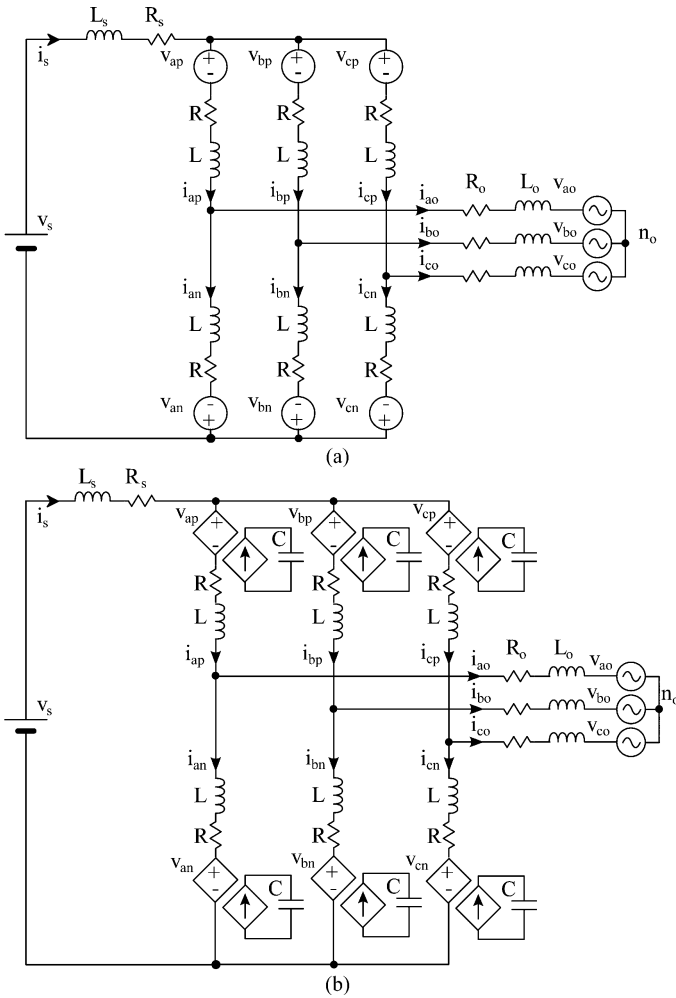


Fig. 5. Models of the MMC. (a) Considering the arms as voltage sources. (b) Considering switching effects and capacitor dynamics.

large amount of cells. To avoid this problem, several approaches have been proposed in the literature to simplify its model. The simplest one is to consider all the power cells in each arm as a single equivalent voltage source [21], as shown in Fig. 5(a). This model is very simple to analyze and to simulate, being also possible to obtain independent dynamical models of currents to further simplify the analysis. To further refine the converter model, switching effects and capacitor dynamical behavior can be included, considering the arms as controlled voltage and current sources [22], as shown in Fig. 5(b). This model provides more accurate results than the previous one, but it requires longer simulation time and the analysis becomes more complex due to coupled dynamics. A matrix representation is usually adopted to simplify the analysis and simulation in both models [23]. The MMC can be also modeled by generic behavioral models such as two-terminal [24] or macroscopic energy [25] models. These approaches can simplify the analysis employing an abstract model of the converter and its cells. A model based on phasors can be also used when the MMC is connected to ac sources [26]. This model allows the graphical representation and analysis of the currents and voltages of the converter, but it is only valid in steady state.

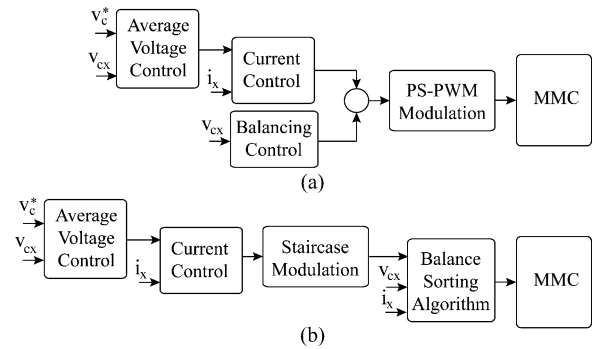


Fig. 6. Control schemes used in MMC. (a) Balancing control prior to modulation adding a component to the modulation index. (b) Post modulation balance sorting algorithm after modulation.

Yet another approach can be adopted, modeling the converter directly in the frequency domain. In this case, the frequency response of the converter can be easily obtained and the design of a controller is straightforward [27].

Combinations of the previous models, for example, using only a few switched cells and a voltage source to model the rest of the arm, can be used to improve simulation performance in terms of speed and accuracy [28].

In summary, simple models can perform faster simulations and provide straightforward analysis but certain effects cannot be investigated. On the other hand, complex models can give more accurate results and satisfy broad application requirements but they are highly demanding [29]. A working model of MMC must therefore be selected according to the objective to be addressed.

III. CONTROL AND MODULATION OF THE MMC

The main control objective in MMCs is the control of voltages, or currents, at its terminals. Depending on the application, it could be required to control the dc and ac voltages or currents. The converter works as an energy interface between input and output using the cell capacitors as energy storage elements. For stable operation in steady state, the average capacitor voltage must be adjusted or controlled. Additionally, there are secondary control objectives such as the influence of circulating currents and equalizing stress on the power cells, low switching losses, etc. Therefore, the control of the MMC can be divided into several classes according to the different control objectives: control of external voltages and/or currents, control of internal currents, control of the average capacitor voltage, and control of the capacitor voltage balance.

Early MMC publications describe the structure of the control [8] and develop an open-loop strategy calculating the required voltages in each arm depending on the input and output voltages [5]. A closed-loop control strategy is proposed to control the dc current, average voltage, and voltage balance [9]. This strategy is shown in Fig. 6(a), where the average voltage capacitor control is located in the outer control loop generating the input reference for the current controller. This current controller generates the modulation index. On the other hand, the balance control adds an additional term to the modulation index depending on the

voltage error and the current sign. This control method has a restricted operating range, which has been later improved, including an arm balance strategy [30].

Fig. 6(b) shows a control system with similar average voltage and current controllers than the previous one, but now the voltage balancing is implemented after the modulation stage [31]. In this case, the modulation stage generates the output voltage level, i.e., the number of cells that must be in ON state in each arm, and the balance algorithm minimizes the difference among capacitor voltages charging the capacitors which are below the voltage reference and discharging the capacitors which are above this reference.

There is a large number of alternative control strategies proposed in the literature to address different control objectives which will be discussed in the following sections.

A. Arm Current Control

One typical way to control the input and output currents and voltages respectively is to control the arm currents. Each arm current is, in turn, controlled by a combination of the arm voltages, depending on the converter configuration.

The basic current control strategy applied to MMCs is based on the calculation of the modulation signals directly from the output and input references for a given operating point [8]. This strategy effectively controls the input and output currents of the converter but it requires a compensation term to eliminate the steady-state error [32]. Although this control strategy does not directly control the internal dynamics of the converter, it has been proven that these dynamics are stable [33].

A closed-loop strategy can be used to calculate the modulation indices based on the error between the arm currents and their references [34]. The references of the arm currents are, like in the previous scheme, calculated based on the output and input current references, but the closed-loop configuration automatically rejects any steady-state error. The closed-loop controller can be implemented with several types of controllers ranging from the simple PI controller in rotating coordinates up to more sophisticated controllers such as LQR controllers [35].

Predictive current control is a powerful control strategy that can be applied to the MMC as well. However, the large amount of states that must be evaluated heavily restricts its use [36]. A control based on Lagrange multipliers can be also used in the MMC but it requires the definition of an integral period [37].

It is possible to define decoupled components for the currents, such as the input, output, and circulating components. Using a decoupled model, controller design becomes simple, because PI controllers can be designed independently [38]. Other transformations can be applied to the MMC in order to obtain decoupled control loops, as such as using dq coordinates [39], using symmetrical properties of the currents in the converter [40] or using positive–negative sequence decomposition [41]. This last transformation is particularly with unbalanced ac grids [42].

B. Circulating Current Control

MMCs produce circulating currents, which are internal currents that flow among the converter arms but do not flow outside

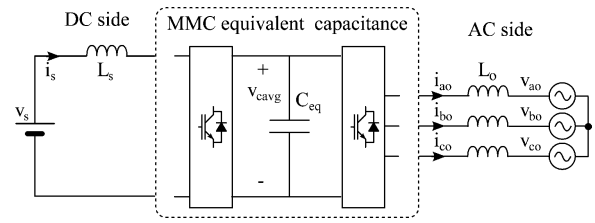


Fig. 7. Model of average voltage of MMC considering a single equivalent capacitance.

the converter [23], [43], [44]. One source of circulating currents is the capacitor voltage ripple, where the frequency of the circulating current is twice the output frequency. The instantaneous changes between voltage levels due to multilevel modulation will also produce circulating currents but at switching frequency.

The controller can, optionally, minimize the circulating current in order to reduce losses and to improve controllability [45], [46]. On the other hand, it can also be maintained at a given value to minimize the capacitor voltage ripple, reducing the required capacitance of the cell [47]. However, this alternative increases the losses and the power rating of the semiconductors.

The circulating currents can be controlled defining them as a part of the input current of each arm [48] or with a completely independent control scheme [49]. Both alternatives have a comparable performance but the use of an independent controller simplifies controller design. The most common method to control circulating currents is the use of one, or a group, of resonant controllers [50], [51].

The circulating currents due to multilevel modulation can be minimized in the modulation stage. For example, a modified carrier disposition modulation can be used to avoid multiple simultaneous commutations [52].

C. Capacitor Voltage Control

In order to make the MMC operate properly, the capacitor voltages must be controlled at a given voltage reference level. The control of these capacitors is usually separated in terms of average voltage and voltage balance. In turn, the voltage balance can be separated into two stages: the control of the imbalance among arms and the voltage balance of cells inside each arm. The first stage can be integrated into the control scheme, distributing the energy among arms by changing the current references. The second stage must balance the cell voltage differences inside each arm by acting on the modulation signal or directly on the switching pattern. This arm balance stage will be analyzed in the next section.

One of the control objectives is to keep the average voltage of all cells at the reference. In the dynamical model of this voltage, all the capacitors in the converter are considered as only one equivalent capacitance, as shown in Fig. 7. The steady-state power equation of the MMC is

$$\frac{C_{eq}}{2} \frac{d}{dt} v_{cavg}^2 = \underbrace{v_s i_s}_{\text{Input Power}} - \underbrace{v_o i_o}_{\text{Output Power}} - P_{Losses} \quad (1)$$

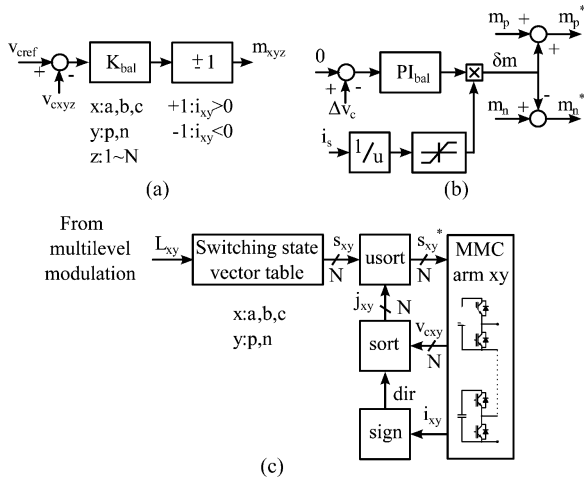


Fig. 8. Voltage balancing control methods. (a) Balance compensation per cell. (b) Balance compensation per arm. (c) Using sorting and a switching table.

where the first term is the variation of average energy in the capacitors expressed in terms of voltages, and the last term represents the losses of the converter [53]. To keep the average voltage at a given level, the input power must be equal to the output power plus the losses in steady state.

The balance of voltages, or energy, among the arms can be performed by modifying the currents in the different arms. In order to minimize the impact on input and output currents, the components of circulating current [54] and common mode voltages [55] are usually employed for this task. There are several strategies for accomplishing this balancing: using only the positive and negative arms [56], improving the balance per phase [57] or with a combination of both methods [58].

D. Capacitor Voltage Balance Control

As shown in the previous section, the voltage balancing can be divided into the two categories: in arm voltage or arm energy balance and voltage balance inside each arm. The latter is, due to the dependency of the arm current, usually implemented in the modulation stage. However, it is possible to include it in the control system by adding, to the modulation signal of each cell, a term which depends on the capacitor voltage error and the arm current [48], as shown in Fig. 8(a). If the error is positive this term charges the capacitor of the corresponding cell and, if the error is negative this term discharges it. Therefore, this additional term also depends on the current direction [59]. It is important to note that this method modifies the modulation index previously calculated by the current controllers, leading to a small deviation from the current references. A similar result, but with lower impact on the current control loop, can be obtained using a single compensation term added to the upper and subtracted from the lower arm modulation index [60], as shown in Fig. 8(b). This method injects a common mode voltage in the arms, and therefore cannot be used in systems with neutral to ground connection.

A second way to obtain capacitor charging/discharging action is injecting an adjustment to switching times directly prior to modulation [53]. When the converter works with low-frequency

modulation such as with SHE or staircase, a similar approach can be also implemented by modifying the switching angles [61]. The voltage balance can be implemented also in space vector modulation by modifying the switching sequence [62].

A completely different balancing algorithm is based on the sorting of all the capacitor voltages in one arm and, depending on the modulation signal and current direction, selecting the higher ones to discharge them or the lower ones to charge them. In this balancing algorithm, which is commonly referred to as a sorting algorithm, only few cells change their state at each sample time, with the result that the capacitor voltages are not exactly balanced but they rather remain within a given tolerance band [43], [63].

The sorting algorithm can be integrated into the modulation strategy [64] or can be implemented using a lookup table to store the possible switching states and selecting the best option depending on the modulation index, current sign, and capacitor voltage error [53], as shown in Fig. 8(c). The required processing time and the high switching frequency it produces in the cells are two main drawbacks of the sorting algorithm. The switching frequency can be reduced avoiding multiple commutations at the same time, using a memory of the previous switching states [65].

It is possible to use the large number of redundant states in this converter to implement an efficient balancing algorithm. However, the analysis and selection of optimal states become very complex with a large number of cells [66].

E. Modulation Techniques for MMC

Modulation at high switching frequencies modulations based on triangular-wave carrier signals with phase shifting [67] and level shifting [68] can be modified for use in MMCs as shown in Fig. 9(a) and (b), respectively. Both of these types of carrier-based modulation are established, well-known techniques, but they have the disadvantage of high switching losses compared to, e.g., fundamental frequency modulation. Space vector modulation can be also adapted to multilevel converters, but as the number of levels increases, the complexity of the algorithm grows exponentially [62].

Low-frequency modulation is preferred in MMCs, due to the high number of output levels of this converter. Selective harmonics elimination (SHE) can be applied to MMCs [69], as shown in Fig. 9(c), but the process of finding the switching angles becomes complex as the number of level increases. Staircase or nearest level modulation are particularly useful for the MMC, because, compared to SHE, the performance is comparable and the implementation is more simple [70], as shown in Fig. 9(d).

As mentioned before, the voltage balancing algorithm can be integrated into the modulation. Phase shifted modulation produces an equal distribution of power among cells, while level shifted modulation requires modifications to achieve the same goal [71]. A low-frequency modulation can be also integrated with the voltage balancing by modifying the switching instants of the switching pattern for each cell [65]. A logical modulation algorithm based on independent higher side and lower side modulations can help to balance the capacitor voltage as well as providing a method to directly generate the switching signals for each cell [72], as shown in Fig. 9(e).

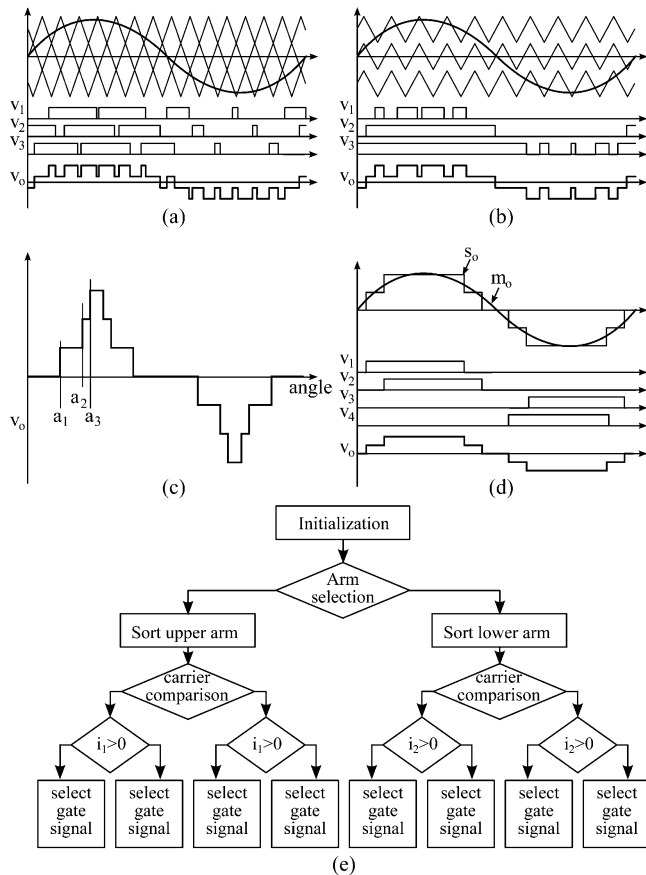


Fig. 9. Modulation techniques. (a) Phase shifted PWM. (b) Level shifted PWM. (c) Multilevel SHE. (d) Staircase modulation.

IV. OPERATIONAL ISSUES IN MMC

Several operational issues of the MMC such as alternative converter topologies, component design, loss analysis, fault operation, and capacitor precharging will be discussed in this section.

A. Alternative Converter Configurations

Several alternative topologies of MMC have been proposed in literature; a few examples are shown in this section.

In Fig. 10(a) the middle-cell MMC is shown, where the output phase is connected at the center of a cell located in the middle of the phase leg. This structure can reduce the number of cells and the complexity of the control system because the balancing of power among the arms is performed only by this cell [59]. The alternate arm MMC has an additional switch connected to each arm as shown in Fig. 10(b). This switch controls the conduction period of each arm and could reduce the number of cells per arm [73]. The hybrid MMC uses two three-phase power units connected to the upper and lower bars as shown in Fig. 10(c). These power units control the interchange of power among the arms [74]. Although these topologies improve some aspect of the MMC, they sacrifice modularity, reducing the reliability of the whole converter.

The interconnection of two ac networks can be performed using a back-to-back configuration or directly by a matrix MMC as

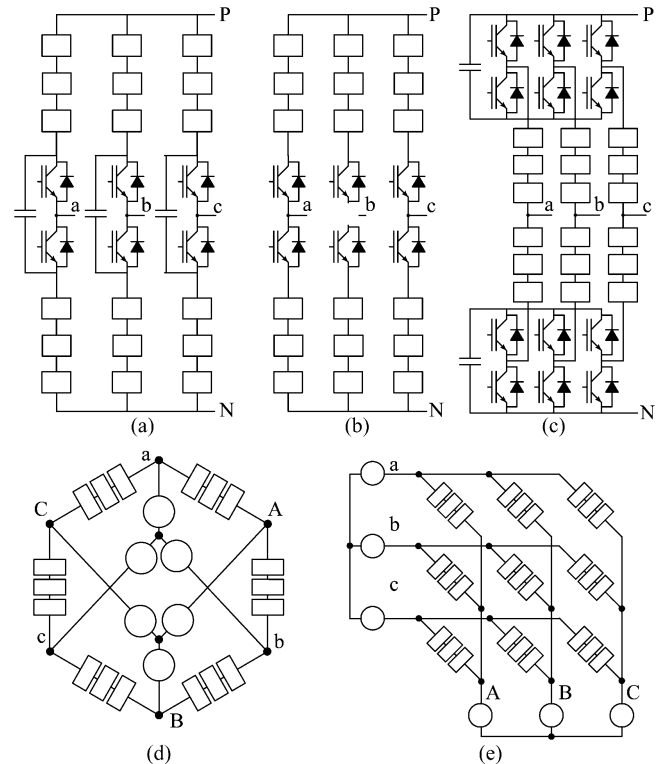


Fig. 10. Advanced topologies of MMC. (a) Middle-cell MMC. (b) Alternate arm MMC. (c) Hybrid MMC. (d) Hexagonal MMC. (e) Matrix MMC.

shown in Fig. 10(d). The main advantage of this configuration is the reduced number of arms required for the interconnection. However, the control becomes more complex due to the existence of two ac components in the arm currents [40]. An interesting alternative topology is the hexagonal MMC, which is shown in Fig. 10(e). This configuration can interconnect two three-phase ac systems using only six arms, but the control actions are restricted compared with matrix MMC, particularly for unbalanced grids, because each output phase is generated by a combination of only two input phases [75].

B. Design and Implementation

There are several methods to design the passive components of the MMC, i.e., the capacitor in each cell and the inductance of each arm. The most common procedure is to design the cell capacitor for a given ripple at twice the output frequency [76] and the arm inductance to provide attenuation to the switching components of the circulating current [77], [78]. It is possible to reduce the common mode inductance without modifying the differential inductance using coupled inductance between positive and negative arms [79].

The design of MMC components must be adjusted depending on the application. For example, when the MMC is used as a power electronics transformer, the design of the arm inductance must take into account the high-frequency arm currents [80].

An isolated power source to feed the internal electronic devices of the cell directly from the capacitor voltage has been proposed to simplify the implementation of the MMC [81].

If a sorting algorithm is used to balance the capacitor voltages, the sampling frequency becomes an important issue to guarantee the stability of the converter. It is possible to optimize this frequency taking into account the required controller speed and the distortion in the arm voltages [82].

The large number of cells which must be controlled imposes a heavy restriction on the communication system which must be fast enough to achieve the bandwidth required by the controllers. Several alternatives for communication protocols have been evaluated, but they must be still improved for utilization in the MMC [83].

C. Losses and Semiconductor Technologies

Several studies indicate that the MMC has higher efficiency than other multilevel topologies, mainly because it is possible to control the internal current components to minimize losses [84].

The losses in the MMC can be analyzed using several methods: using piecewise adjustment of switching waveforms [85], calculating the energies in the semiconductors, and using linear interpolation [86], or using real-time waveforms and temperature feedback to adjust the switching losses model [43].

From the semiconductor point of view, IGCT-based power cells have lower losses than IGBT-based cells [87]. Next generation NPT-IGBT and SiC semiconductors have been evaluated for use in MMC cells and it was found that they could further reduce the losses, improving the efficiency [88].

D. Fault Operation of MMC

One of the features of the MMC is its fault tolerance due to the high number of redundancies that exist. Additionally, the control system can be used to detect failures and to modify the structure of the converter minimizing the impact of the failure on overall converter operation [89], [90]. Due to the high current dynamics these converter exhibit, a short circuit current limitation strategy using the converter itself can be implemented to manage dc faults [91], [92].

E. Capacitors Precharging Methods

During normal operation, the capacitors of all cells must be charged to the nominal value. However, the charging process at converter start-up or after a fault can lead to high inrush currents due to the high equivalent capacitance of this converter [93]. To avoid this problem, several precharging strategies have been proposed. The simplest one is using a resistor which is temporarily connected in series to the converter, as shown in Fig. 11(a). This solution is not energy efficient and can lead to large and bulky resistances operating at high voltages [94]. An alternative strategy is to delay the charging of each capacitor to charge them one at a time in a staggered sequence, as shown in Fig. 11(b). This solution does not require external hardware but it requires a more complex control system, which must operate even if the cells are completely discharged [95]. A combination of both methods can be implemented reducing the precharge resistor and the control complexity [78], as shown in Fig. 11(c).

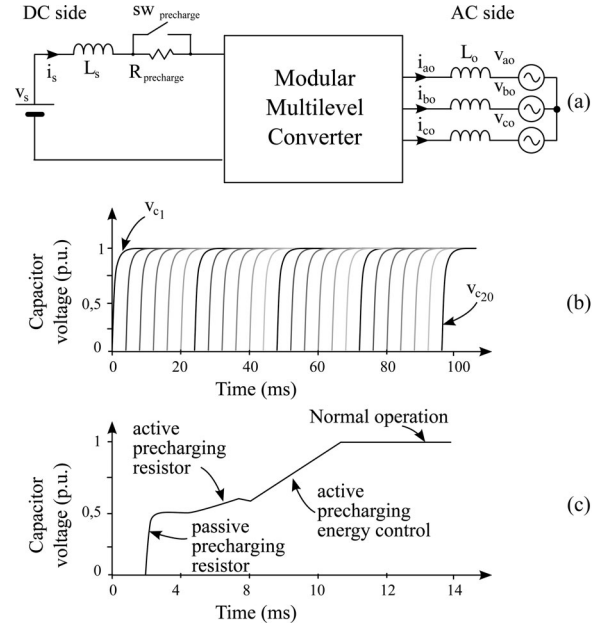


Fig. 11. Precharging of capacitors. (a) Using resistors. (b) Staggered sequence precharge. (c) Controlled precharge.

F. Voltage Ripple

The interaction between arm currents and modulation signals causes the ripple in the capacitor voltage [96]. The relation between this voltage ripple and the circulating current has been intensively studied in order to use this current to minimize the ripple [97]. It has been found that this ripple minimization has a limited operating range given by the maximum circulating current allowed by the converter [98].

V. APPLICATIONS

Due to the high voltage capability and the high power quality provided by MMCs, their main application is in HVDC transmission systems. Other applications such as medium voltage drives and active filters have been proposed in the literature.

A. HVDC Transmission Systems

The transmission of electrical energy using high voltage dc (HVDC) systems has proven to be more efficient than ac systems particularly when the transmission distance increases. On the other hand, the cost of the conversion stations for HVDC is higher due to the extensive use of semiconductors. Therefore, combining the previous aspects, there exists a distance above which the selection of HVDC systems has economical benefits over ac systems. During the last years, developments in semiconductor technology and the consequent fall in costs have reduced this break-even distance, enlarging the participation of HVDC systems in the electrical grids. If underground or submarine cables must be used to transmit energy, ac transmission systems have major restrictions while HVDC can be used regardless of the length of the cable. Additionally, HVDC systems have several additional operational and environmental benefits such as high controllability, low electromagnetic interference,

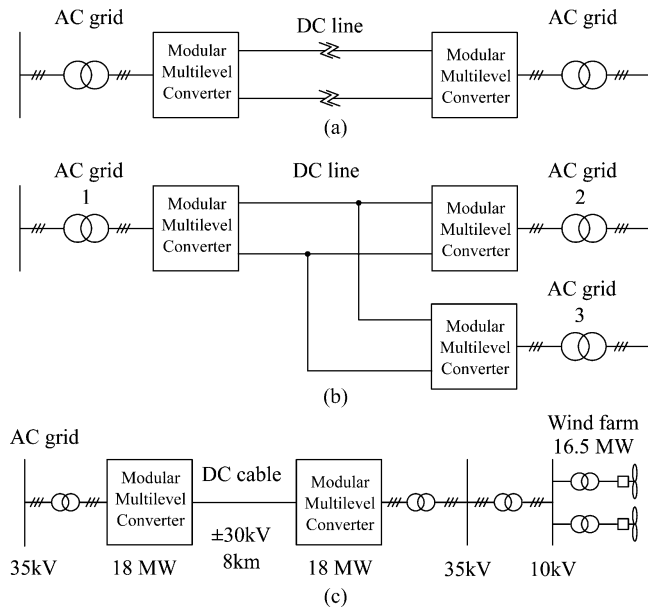


Fig. 12. HVDC applications of modular multilevel converters. (a) Long distance HVDC with overhead line. (b) Multiterminal HVDC. (c) HVDC with submarine cable for off-shore wind farms.

low acoustic noise, and smaller right of way (RoW) than ac systems [99].

High-voltage dc systems can be implemented based on line-commutated current source converters (CSC) or self-commutated voltage source converters (VSC). A preponderance of the currently installed HVDC systems are CSC, because they work with well-known SCR semiconductors, achieving higher power and voltage ratings than IGBT-based VSCs. However, voltage source converters overcome important disadvantages of CSCs, such as reduced harmonics distortion at the dc and ac sides, a substantial reduction in the size of filters, improved dynamic performance, independent control of active and reactive power, black-start capability, operation with passive and weak ac networks, and the possibility of implementing a multiterminal connection [100].

There are several configurations of HVDC-VSC stations using two-level (2L) converters, three-level NPC (3L-NPC) converters, and MMCs. Compared to 2L and 3L converters, the MMC provides a substantial increase of output voltage levels and output switching frequency, enabling a further reduction of filter size. Although the output switching frequency is high, the switching frequency in each cell can be as low as a few hundred Hertz, further reducing the switching losses. The output voltage waveform in the MMC is composed of small voltage steps compared with 2L and 3L converters where the voltage steps are the whole or half dc link voltage, respectively. This feature reduces high-frequency emissions because of the reduction of the voltage time derivative. Finally, the MMC provides distributed energy storage and has a modular structure which offers higher availability and fault tolerant operation. The main drawback of the MMC, compared to the other alternatives, is that the controller is more complex and the control hardware requires a larger processing capability [101].

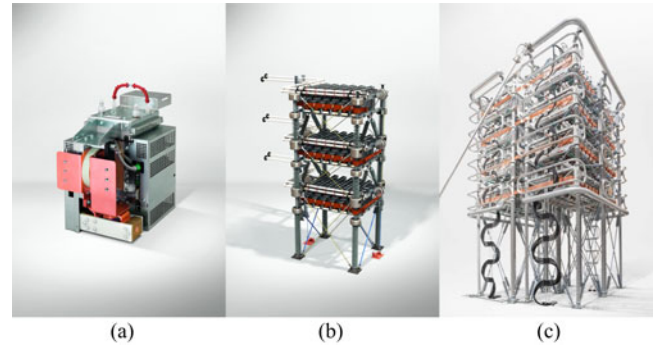


Fig. 13. MMC for HVDC applications (pictures obtained with permission of Siemens [12]). (a) cell of the MMC converter. (b) Arm of the MMC converter. (c) Complete structure of the MMC.

A typical MMC-based HVDC system is shown in Fig. 12(a). There are several examples of this system reported in the literature, implemented for example by standard half-bridge [102] or diode clamped [103] cells. To simplify the control system, a proposed alternative is to build a medium voltage MMC with a reduced number of cells, connected to a step-up transformer. This converter structure simplifies the control system but it has higher losses due to the transformer [104].

A multiterminal HVDC configuration, as shown in Fig. 12(b), is difficult to implement using CSCs. However, due to the voltage source nature of the dc link, it becomes a real possibility when using the MMC. This multiterminal scheme will allow the interconnection of different HVDC systems creating an HVDC grid with a higher controllability, efficiency, and reliability than ac grids [105]. A future electrical supergrid will combine ac and dc systems. The flexibility of the MMC is a feature enabling the integration of these two systems [106].

A very interesting application of the MMC is the connection of off-shore wind farms to the coast using dc transmission as shown in Fig. 12(c). Due to the submarine cable, the power rating of wind farms and the space required to build a marine platform for the converter station, the MMC has several advantages over ac and HVDC-CSC transmission in terms of efficiency and costs [107]. One reported example of this application is an offshore wind farm located in Shanghai, China [108].

High-voltage dc systems can also be used to interconnect two asynchronous ac systems using a back-to-back configuration. When using this configuration, the MMC can provide high-quality sinusoidal voltages, avoiding the filters in the dc and ac lines [109]. It is also possible to use the MMC in a matrix configuration, to interconnect two ac systems as reported in [40].

Four types of MMC-based HVDC systems have already been commercialized by three major companies in Europe and one in China: HVDC Plus [12], Maxsine [13], HVDC Light Gen. 4 [14], and HVDC Flexible [15]. Fig. 13 shows the details of the HVDC Plus implementation which was the first MMC topology introduced on the market.

Today, there are several MMC-HVDC projects underway at different stages of development:

- 1) *Trans Bay Cable*: This project was the first commercial HVDC system implemented using MMC technology;

TABLE I
TENNET OFF-SHORE WIND FARM COMPLEX

Wind Park	Power (MW)	Voltage (kV)	Cable length (km)	Commissioned by	State
Helwin 1	576	+/- 250	130	Siemens	Started operation in 2013
Dolwin 1	800	+/- 640	165	ABB	Tested during 2013
Borwin 2	800	+/- 300	200	Siemens	Tested during 2013
Sylwin 1	864	+/- 320	205	Siemens	Started operation in 2014
Dolwin 2	900	+/- 640	135	ABB	Started operation in 2015
Dolwin 3	900	+/- 320	162	Alstom	Started operation in 2017

it connects the California cities of Pittsburg and San Francisco by a submarine cable. The dc cable works at ± 200 kV and is designed to transmit 400 MW, which is 40% of the San Francisco City energy requirement. The project was commissioned by Siemens and has been in operation since November, 2010 [110].

- 2) *Tennet Off-Shore Wind Farm Complex*: This wind farm complex is located in the North Sea, near to the German coast. It is composed of several wind parks with different transmission technologies and commissioned by different providers [111]–[113]. The projects, ordered by date, are shown in Table I.
- 3) *Nanhui Off-Shore Wind Farm*: This HVDC system was commissioned by the C-EPRI and has been operating since May, 2011. It is designed to transmit 20 MW at ± 30 kV from an off-shore wind farm located 8.4 km off to the coast of Nanhui, Shanghai, China [114].
- 4) *South-West Link*: This project will interconnect the cities of Barveryd and Hurva in Sweden with a MMC-HVDC. The transmission power is 1440 MW and the distance is 250 km, and the project is commissioned by Alstom and will be in operation in 2015 [115].
- 5) *Dalian City Infeed*: Due to the growth of space and energy requirements of Dalian City, China, it is required to feed the city center by underground dc cables. The project was commissioned by C-EPRI and it will transmit 1000 MW over 43 km by using a ± 320 kV cable. The project was planned to start in 2013 [15].
- 6) *France-Spain Electrical Interconnection*: This interconnection between Spain and France through an underground cable of 65 km is under construction. The project will consider two dc links, each transmitting 1000 MW and operating at ± 320 kV. The project was commissioned by Siemens and it is planned to be operative in 2015 [116].
- 7) *Zhoushan Multiterminal DC Interconnection*: In this project, a group of small islands near the coast region south of Shanghai, China, will be interconnected by an MMC-HVDC, creating a multiterminal connection. The voltage of this dc link will be ± 200 kV and the total power will be 400 MW. The total length of the dc link will be

134 km. The project is commissioned by C-EPRI and it will begin operation in 2015 [15].

B. Medium Voltage Drives

Recently, the MMC was introduced for industrial medium voltage drives (MVDs) [16]. Compared to conventional MVD topologies, the MMC offers the following advantages:

- 1) simple voltage scalability using a series connection of cells, e.g., $V_{LL} > 4$ kV);
- 2) simple construction and less engineering effort due to modular cells;
- 3) low expense for redundancy;
- 4) operation of standard line motors without output filters;
- 5) operation as grid-side converter without output filters or transformer;
- 6) drastically improved dynamic characteristics due to substantially higher switching frequency.

Obviously the MMC is attractive for line side converters, e.g., to couple MVDs or regenerative energy sources to the grid [e.g., Fig. 14(a)], in shaft generator systems, variable high speed drives as well as general drives. MMCs have been also reported in ship applications as shown in Fig. 14(b) [117].

One important disadvantage of the MMC in drive applications is the high expense required for capacitive energy storage at low and zero speed. Thus, the application of the MMC in drives with these requirements (e.g., in hot and cold rolling mills) is unlikely. However, it is possible to implement a drive using an MMC in matrix configuration. With this topology, the converter can be operated at low and zero speed at rated torque without unduly large capacitive energy storage [118].

Another application is in medium frequency traction application as a power electronic transformer. In this case the low-frequency, high-voltage, single-phase line is connected to a variable-frequency, medium-voltage, three-phase machine by a medium frequency transformer which is fed by an ac/ac single-phase MMC [119], as shown in Fig. 14(c).

C. Power Quality

The modular multilevel converter has a high degree of modularity which can be used to develop distributed energy storage systems. A large storage device can be integrated in parallel with the capacitor as shown in Fig. 15(a), to build a distributed battery energy storage system (BESS) [120]. An additional advantage provided by the MMC in this application is the possibility to interface the energy storage system directly with medium or high voltage grids [121].

The modularity of the MMC can be also used in photovoltaic applications, providing distributed energy sources which could reduce the fluctuation of energy in large scale PV plants [122]. The PV panels, or strings, are directly connected in parallel to the capacitor in each cell as shown in Fig. 15(b). This scheme can reduce the losses of the plant because the converter works at higher voltage than standard PV systems. The maximum power point tracking (MPPT) strategy can be directly integrated with the cell controller, reducing the number of converter stages [123]. Similarly to the previous application, the MMC can provide a

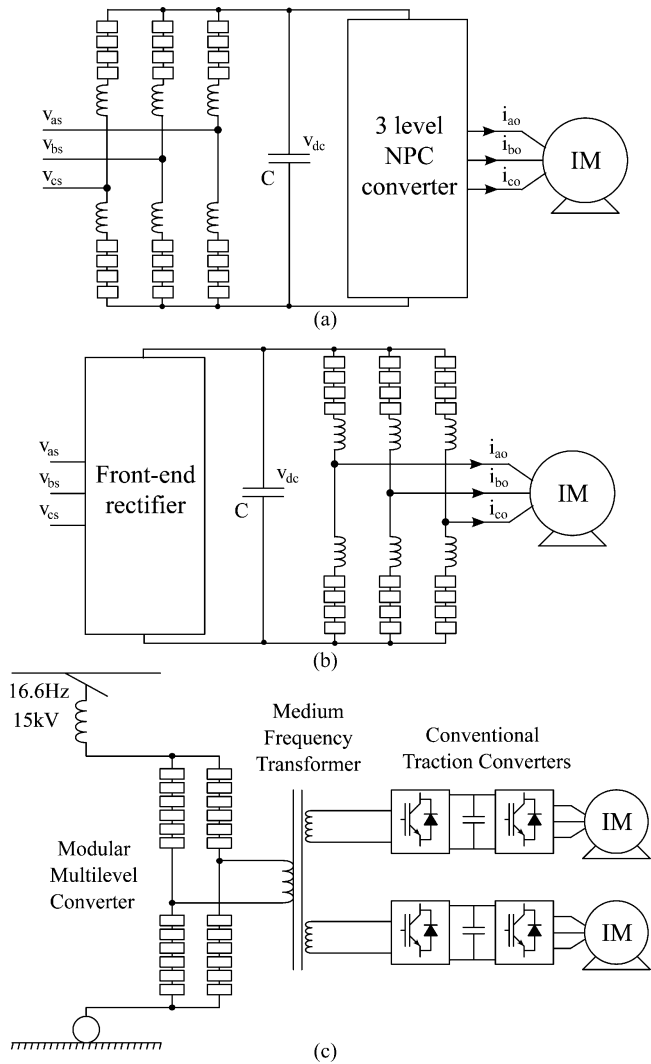


Fig. 14. MMC machine drives applications. (a) Front-end converter for a medium voltage drive. (b) Machine drive for marine applications. (c) Interface converter for trains.

direct connection of the PV plant to medium voltage or high voltage ac or dc grids [124].

Further benefits of the MMCs are the high-quality waveforms and the fast current control. A unified power quality conditioner (UPQC) can take advantage of these two features providing high-performance active filtering. The UPQC is composed of two stages of compensation: series and parallel, and both can be implemented with a back-to-back MMC [125], as shown in Fig. 15(c). The direct connection to medium voltage grids is an advantage in this application.

VI. FUTURE TRENDS

During the last years, there was a large-scale development of modular multilevel converters in terms of topologies, control, modulation, and other features. However, there are several aspects that should still be addressed in order to overcome main drawbacks and to expand its utilization.

One of these drawbacks is the high expense of capacitors required to minimize the voltage ripple. To face this problem, it

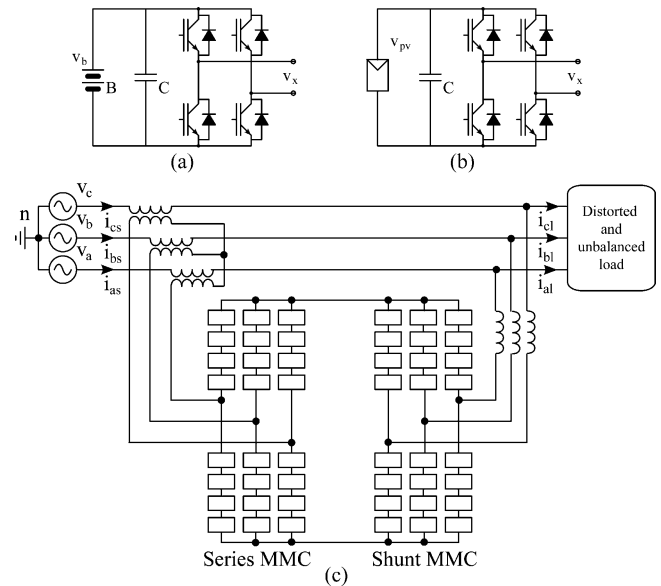


Fig. 15. Flexible ac transmission systems. (a) Cell with an integrated battery for BESS systems. (b) Cell with an integrated photovoltaic-panel to provide distributed energy generation. (c) Unified power quality compensator.

is necessary to design and implement high-performance control schemes.

The intensive use of communication channels for control and monitoring is still a practical restriction, particularly when the number of cells is very large. Therefore, it is necessary to develop a high-speed communications network to provide a high controller bandwidth. Another alternative is to develop distributed control algorithms in order to reduce the communication requirements.

To make this topology competitive with traditional HVDC converters it is necessary to increase its power and to further reduce the losses. Basically, it is required to develop new power semiconductors and cell topologies and to investigate the serial and parallel connections of MMCs.

Considering this technology as a key element for building the future electrical ac–dc supergrid, the internal and external fault management must be investigated. The converter must exploit its modularity to provide fault tolerant operation even with several faulty cells. The converter controller must be also designed to provide fast current control capable of managing dc faults while avoiding costly and bulky dc breakers.

Regarding new applications, several productive processes can obtain benefits from the MMC characteristics. For example, the modularity this converter exhibits can be used in PV energy plants to increase the energy storage so that the plant can supply energy to consumers even during the night. It is possible to take advantage of the high-voltage capability of the MMC to connect machines directly to medium voltage grids. Low-voltage applications can also obtain benefits from the MMC, particularly due to the power quality.

VII. CONCLUSION

Modular multilevel converters have attractive operational features in terms of high voltage operation, power quality,

efficiency, redundancy, and modularity. These features have attracted the interest of the research community, resulting in a large number of new configurations, models, control schemes, and modulation strategies. On the other hand, this converter is also interesting for industry, where several commercial products have already been developed for HVDC and medium voltage drives applications. This work presented a review of the latest achievements regarding modular multilevel converters in terms of modeling, control, modulation, applications, and future trends.

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