Modular Multilevel Converters for HVDC Applications: Review on Converter Cells and Functionalities

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***Abstract*—In this paper, the principle of modularity is used to derive the different multilevel voltage and current source converter topologies. The paper is primarily focused on high-power applications and specifically on high-voltage dc systems. The derived converter cells are treated as building blocks and are contributing to the modularity of the system. By combining the different building blocks, i.e., the converter cells, a variety of voltage and current source modular multilevel converter topologies are derived and thoroughly discussed. Furthermore, by applying the modularity principle at the system level, various types of high-power converters are introduced. The modularity of the multilevel converters is studied in depth, and the challenges as well as the opportunities for high-power applications are illustrated.**

***Index Terms*—Building block cells, converter modularity, high-voltage dc (HVDC) transmission, modular multilevel converters (MMCs).**

I. Introduction

THE first use of direct current for electrical power transmission on a commercial level was in the late 19th century. However, the advent of the transformers and induction machines in around 1890 led to the domination of ac electrical power systems. Over time, there have always been heated arguments between the proponents of dc and ac systems. The acceptance and dominance of ac systems never eclipsed the obvious advantages of dc transmission [1]–[7]. High-voltage dc (HVDC) transmission is considered advantageous and in some cases superior to ac in applications such as long under water cable crossing, long distance bulk power transmission, stable ac interconnection, interties with low short-circuit levels, coupling 50/60 Hz systems, and long-distance underground cable systems [1], [8]–[26]. For such systems, the high-voltage ac needs to be converted to the HVDC when transmitting power, and needs to be converted back to ac at the receiving points. The feasibility and benefits of an HVDC link are thus embedded in the development of suitable converters [27].

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Continuous progress of the high-voltage high-power switching devices has a big impact on power electronic technologies used in power systems. The evolution of HVDC converter topologies versus power device technologies is presented in Fig. 1. Suitable converters appeared to be implemented with Mercury-arc valves first in 1954, which followed by line-commutated thyristor valves in 1967. Thyristor valves are still used today in bulk dc power transmission systems up to 800 kV and toward 1100 kV [28]. The so called turn-off capability which did not exist in the normal thyristors was later implemented in the Gate turn-off thyristor (GTO), followed by the hard driven GTO, and the integrated gate-commutated thyristor (IGCT) [29]–[31]. The metal oxide semiconductor technology (initially used to produce integrated circuits) became available in the 1970s, and created a new field of semiconductor switching devices, including the insulated-gate bipolar transistor (IGBT) invented in the 1980s and widely accepted in the 1990s [32]–[34]. With the development of the IGBT, the voltage source converter (VSC) technology has been developed by ABB for HVDC systems where series connection of IGBTs enables to reach the required high dc transmission voltage [35]–[45]. The VSC HVDC technology, reaching 500 kV today, addresses a number of shortcomings in the classic line-commutated thyristor HVDC converters by offering an independent reactive power control, black start capability, usage of extruded polymer cables, smaller station footprint and the use of standard transformers [46]–[49]. The VSC transmission technology is now in its fourth generation using a modular converter technology that has no filter requirements and has a very low level of converter loss [8]. The HVDC technologies are not only used for conventional point-to-point bulk power transmission, but also exploited on a larger scale to build dc grids for the integration of large scale renewables such as offshore wind farms. A number of HVDC configurations and their emerging applications have been reviewed by [50].

A. *Power Converters for Transmission Applications*

Starting with fundamental network theory, one can distinguish two basic electrical energy source types — the voltage source (VS) and current source (CS). All dc/ac power conversion systems are designed to act either as a VS converter (VSC) or as a current source converter (CSC). If the VSC is connected to an active dc system as shown in Fig. 2(a), this implies the presence of a VS that maintains a given voltage across its ac terminal

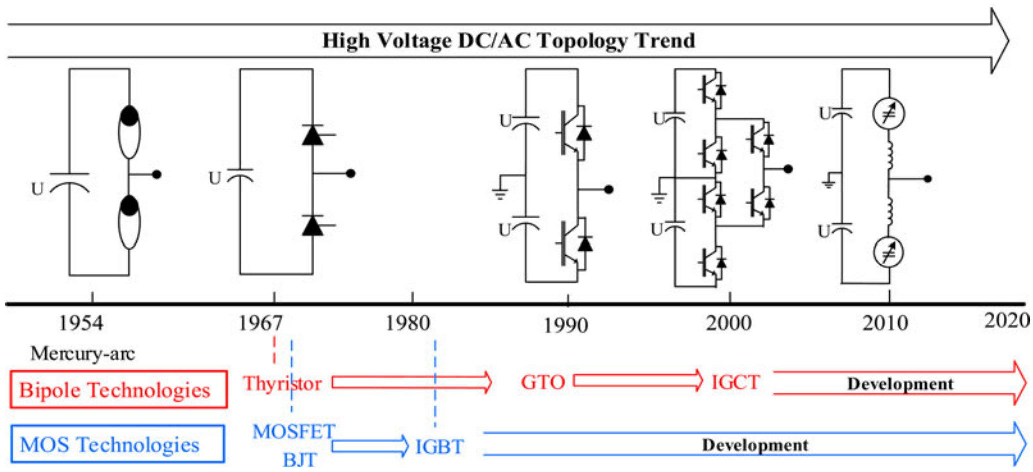

Fig. 1. Evolution of HVDC converter topologies versus power device technologies.

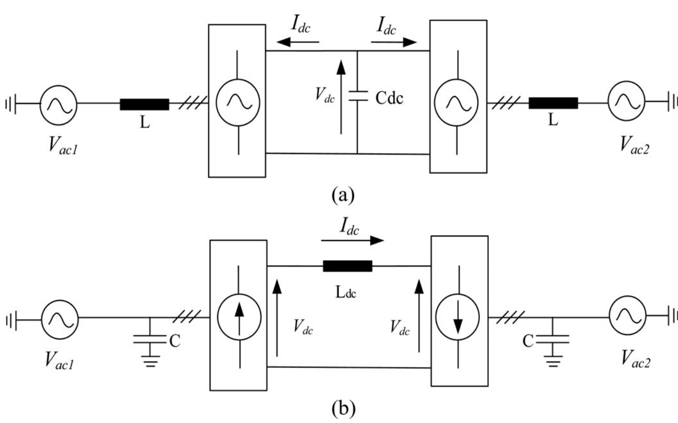

Fig. 2. Point-to-point HVDC system based on (a) VSCs and (b) CSCs.

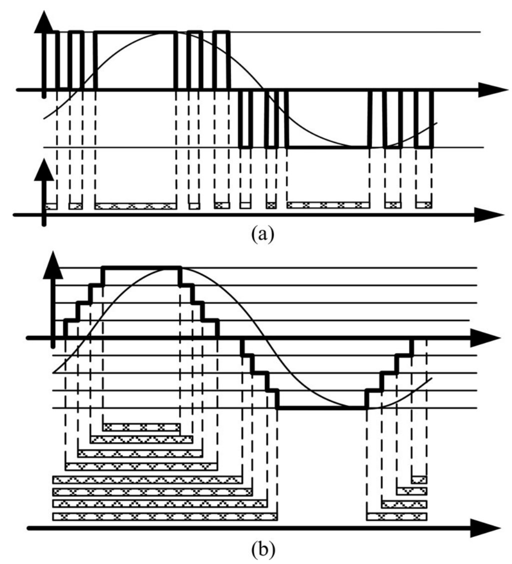

Fig. 3. Waveforms synthesized by (a) a two-level dc source and (b) multilevel dc sources.

irrespective of the magnitude or polarity of the current flowing through the source. Therefore, by controlling the phase angle and magnitude of the ac voltage through the switching methods, the converter acts as an inverter or rectifier, with lagging or leading reactive power. The switches in VSCs normally have bidirectional current conducting or reverse conducting (RC) capability. This allows the power reversal in VSCs by controlling the $I_{\rm dc}$ direction while $V_{\rm dc}$ has a fixed polarity. It is also worth to mention that a VSC cannot be directly connected to a strong ac system. In such a case, a coupling reactance is needed between the converter terminal and the ac system. Another way of connecting ac systems to dc systems is by means of a CSC as a dual of the VSC and shown in Fig. 2(b). The CSC is a current stiff converter at the dc side and is achieved by the connection of a large inductor on the dc side pole. Since the ac system has a substantial inductance, a shunt capacitor at the converter ac terminal is needed as an interface. In contrast to the VSC-based HVDC system, the CSC can only conduct current in one direction while blocking voltage in both polarities. The switches in CSCs normally have bidirectional voltage blocking or reverse blocking (RB) capability. This allows the direct control on phase angle and magnitude of the ac current by a proper switching control strategy. Therefore, power reversal in CSC-based systems is achieved by reversing the polarity of the dc voltage ($V_{\rm dc}$). A two-level VS (CS) converter utilizes only one dc level $V_{\rm dc}$ ($I_{\rm dc}$) to create an average equal to the reference voltage or current in each switching cycle as shown in Fig. 3(a). Therefore, the switching loss and the total harmonic distortion (THD) are relatively high. On the other hand, multilevel converters are able to synthesize a stair case waveform using several independent dc voltage or CSs created by capacitors, inductors, or separate sources (batteries, renewable sources). The conducting angles of each source can be chosen such that the THD of the output voltage or current becomes minimum. Normally, these angles are chosen in order to cancel the predominant lower frequency harmonics, to eventually, synthesize waveforms as close to a sinusoidal as possible. This method is shown in Fig. 3(b). This results in a significant reduction of the filter size used in a two-level converter. However, for the same rated power, the total energy stored in passive components used in multilevel converter structures is considerably higher and is about ten times more than in a conventional two-level converter. The staircase waveform can also reduce the voltage stress (*dv/dt*); which can mitigate the problems associated with electromagnetic interference. The lower switching frequency and the lower voltage stress level on the devices lead to a significant reduction in the switching losses. Therefore, the comparably lower switching losses and considerably higher power quality are, in general, the advantages of multilevel converters compared to two-level converters [52]–[56].

B. Monolithic Multilevel Converters

Referring to the aforementioned benefits, multilevel VSCs are appropriate for high-voltage applications. However, for monolithic multilevel VSCs, one of their main drawbacks is the need for a large number of series-connected switching components for high-voltage applications due to their nonmodular configuration, which is called the "monolithic configuration." This imposes additional expenses and further complexity on the overall system design. Several types of monolithic multilevel converters have been proposed based on different structures of a dc-link voltage (or current) to generate staircase output voltage (or current) levels [52]–[64]. The neutral-point-clamped (NPC) [57], and flying capacitor (FC) [61] topologies are widely known in industrial and high-power applications. Different current and voltage control methods and pulse width modulation techniques have been proposed for multilevel converters to achieve a considerably higher efficiency [65]–[71]. The operation of the multilevel VSC under fault and unbalanced conditions has been also studied in [76], [77]. Other multilevel VSC topologies, based on the monolithic multilevel voltage/current injection circuits, are addressed in [78]–[80] for HVDC transmission applications, creating high-resolution output voltage and current waveforms. However, lack of optimum power utilization and extra complexity in converter structure and control are the drawbacks of the proposed methods for transmission applications. In addition, to exploit the advantages of both topology types, a hybrid VSC combined with CSC monolithic system was proposed in [81].

C. Modularity in Multilevel Converters

During the last decade, modular multilevel converters (MMC) have shown a break through and have made their way to commercial high-power applications. Modularity, in general, refers to a technique to develop comparably large systems by combining smaller subsystems. For power converter topologies, this means, a cascaded connection of converter cells, so-called chain links, which seems to be an interesting solution to reach high-voltage and high-quality waveforms [63]. However, in order to transfer active power, isolated dc sources are required by means of a transformer and a rectification stage. This fundamental problem has been addressed in [82], opening a new field of possible new solutions. The solution proposed in [61] eliminates the need of separated sources in high-power converters by means of an intermediate VS or CS, such as a capacitor or inductor, floating with respect to ground potential in the converter circuit. These intermediate sources with passive elements are actively balanced by means of the switching process of the converter. Other circuit configurations including voltage or CSs or their combinations can be tailored in order to make use of the modularity and scalability for high-power applications, as shown in Fig. 4. These solutions require a proper cell or a building block structure. The power electronics building block is an intermediate level toward the modular power converters that incorporate the integration of power devices, passive elements, and other components into functional blocks. Building blocks can be easily added in parallel to increase the current carrying capability or in series in order to handle considerably higher voltages. The objective of this paper is to provide an overview of the MMC topologies from the basic building blocks to the system level modularity, targeting high-power applications and in particular HVDC. Categorized multilevel topologies are shown in Fig. 4. As shown and will be discussed further in this paper, modular multilevel VSCs and CSCs can be built either straightforward by applying the modular building block cells or by a combination of cells with monolithic multilevel topologies. Therefore, this paper summarizes the most recent developments made in this field, covering new promising topologies and operational issues. In addition, emerging trends, challenges, and possible future directions of the multilevel converter technologies are outlined to motivate further work in this field.

This paper is organized as follows: First, a brief review of VS cell structures including forms and functions is presented in Section II to introduce the basic concept of the modularity. This is followed by emerging topologies of the modular/chain-link multilevel VSCs made by the presented modularity concept. Also, the latest development in VSC modular and hybrid modular multilevel generation methods is addressed. Using the duality concept, CS cell structures and the latest development of CSC MMCs are given in Section III. The modularity at the converter phase level is presented in Section IV, where different converter phase connections are addressed, and the corresponding features are compared. Finally, future trends and challenges of the multilevel converter technologies are described in Section V which is followed by concluding in Section VI.

II. Modular VSCs

MMCs are becoming attractive in both industrial applications and academic research. The most distinctive advantage of these converters is the ability to deliver a very high voltage with excellent harmonic performance. Moreover, a relatively low-device switching frequency is achieved by stacking the modular cells that are composed of low-voltage rating components. Thus, the modularity and the scalability of the modular converters allow it to be competitive in high-voltage applications. In addition, the improved high-voltage insulation coordination requirements, simpler mechanical design, and service are other benefits of the MMCs compared to monolithic converters.

A. VS Cell Structure

The building-block cell is the basic unit of any MMC configuration which can basically be either a dc/dc or a dc/ac power

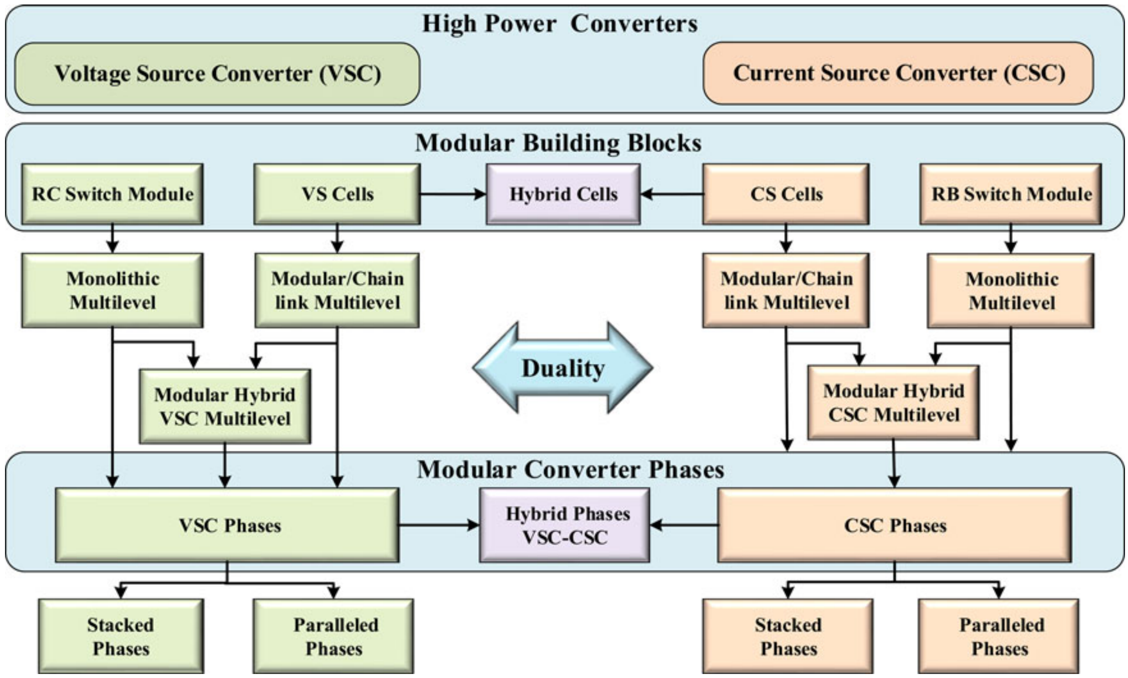

Fig. 4. Categorized topologies for high-power applications.

converter. Cells could be connected in series or in parallel in various topologies in order to meet the requirements for a specific application. The basic form and function of these building block cells are discussed and compared in this section.

1) Half-Bridge Commutation Cells: The elementary three-pole commutation cell, considering forced commutation, is shown in Fig. 5(a). This is the simplest structure to generate a unipolar output voltage by chopping its dc-link voltage [83]. Switch needs to provide bidirectional current flowing and unidirectional voltage blocking. This cell can be operated in two quadrants and can generate only two voltage levels at the output as shown in Fig. 5(a).

2) Full-Bridge Commutation Cells: By parallel connection of two identical cells shown in Fig. 5(a), a double commutation cell, or a full-bridge cell, can be created as shown in Fig. 5(b). This cell can duplicate the operation of the basic commutation cell, thus operate in all four quadrants where both positive and negative cell dc voltages can be obtained at the output terminal. However, the number of the switching devices is doubled compared to the basic commutation cell.

3) Mixed Commutation Cells: Combining the basic cell and the full-bridge cell, a new mixed commutation cell structure can be created in order to achieve both unipolar and bipolar cell benefits. Series connection of the commutation cell and the double commutation cell generates an asymmetric four-level voltage as shown in Fig. 5(c).

4) Asymmetrical Double Commutated Cells: Another way of doubling the commutation cells is shown in Fig. 5(d). This cell is called the asymmetrical double commutation cell as two different voltage levels of the basic commutation cells are connected at the dc side in order to generate an alternative four-level cell structure.

5) Cross- or Parallel-Connected Commutation Cells: The double commutation cell can be connected in a cross [84] or in a parallel way as reported in [84] and [85]. The cross-connected cell is an alternative symmetrical bipolar cell structure as shown in Fig. 5(e). The switching states of this five-level cross-connected structure have been summarized in Fig. 5(e). It is worth mentioning that by cross connecting more intermediate capacitors in the structure shown in Fig. 5(e), a higher number of voltage levels can be achieved [86].

By changing the switch connection between the intermediate cell capacitors as shown in Fig. 5(e), the capacitors can be connected in parallel. Connecting the cell capacitors in parallel helps the capacitors' voltage ripple reduction. An alternative parallel connection of cell capacitors at reduced device current rating is proposed in [87].

6) Clamped-Double Commutation Cells: An alternative connection of the double commutation cells has been proposed in [88] and shown in Fig. 5(f). Using proper switching states allows a series or a parallel reconfiguration of the cell capacitors. However, additional design considerations should be taken into account for the transition into the full-bridge mode in which two capacitors that may have different voltages will be connected in parallel. As shown, one way of avoiding the paralleling issue is to replace active switches by diodes in the parallel path. However, this limits the full-bridge operation to a three-quadrant cell operation. The voltage levels associated with the different switching states of the clamped double-commutation cell are shown in Fig. 5(f).

7) FC Commutation Cells: Using the commutation cell as the building element, the FC configuration is implemented by connecting the basic commutation cells in a nested configuration, in a single-phase leg structure, as shown in Fig. 5(g). In

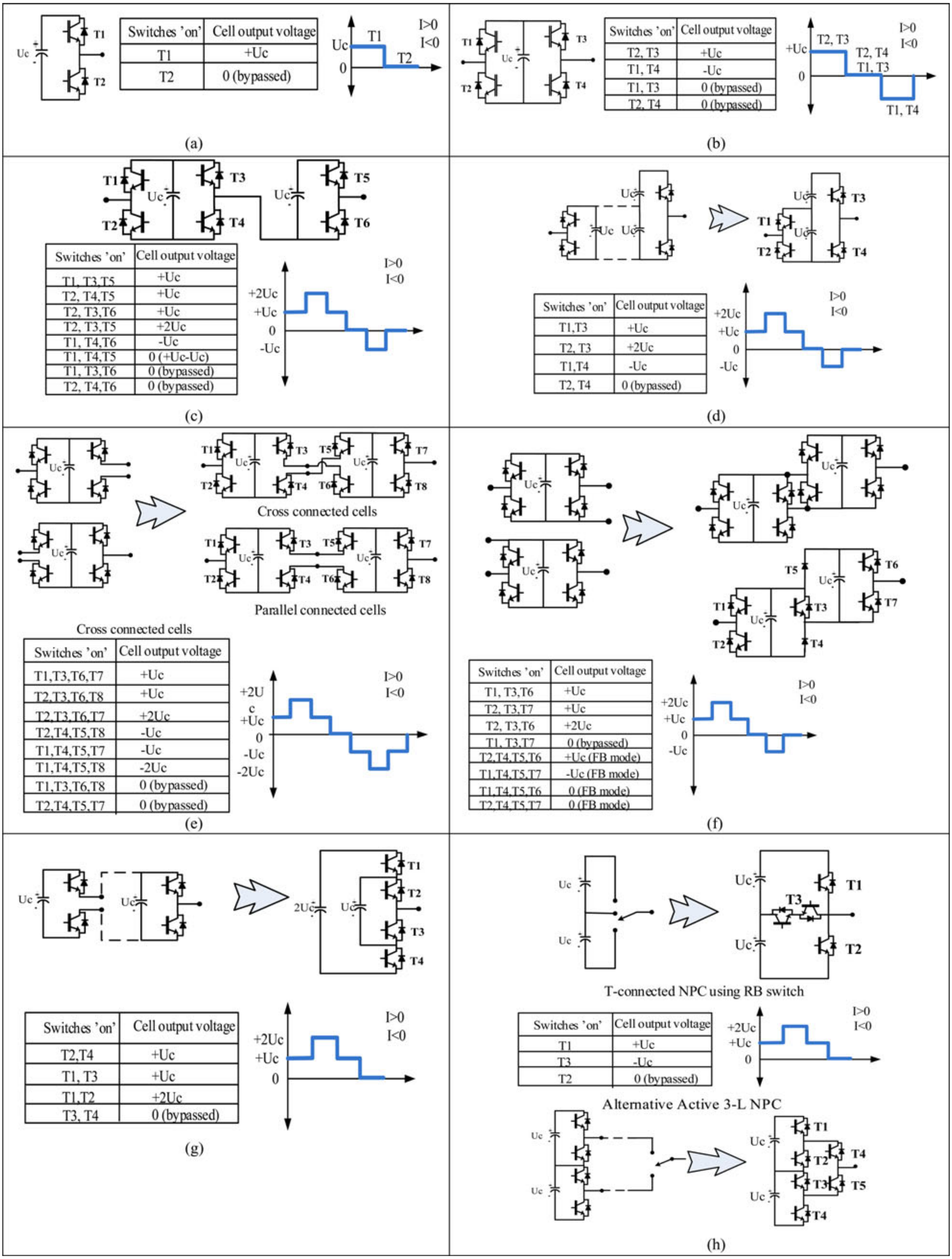

Fig. 5. VS cell structures, switching states and voltage levels. (a) Half-bridge commutation cells. (b) Full-bridge commutation cells. (c) Mixed commutation cells. (d) Asymmetrical commutation cells. (e) Cross-connected commutation cells. (f) Clamped double commutation cells. (g) FC commutation cells. (h) NPC-type commutation cells.

TABLE I
COMPARISON OF THE DIFFERENT VS CELL TYPES

Cell type	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Number of output voltages	2	3	4	4	5	4	3	3
Max. Voltage blocking	Uc	Uc	2Uc	2Uc	2Uc	2Uc	2Uc	2Uc
Total No. of switches normalized Uc	2	4	6	6	8	7	4	6
Max No. Switches in conduction path	1	2	3	3	4	3	2	2
Bipolar operation	No	Yes	Yes	Yes	Yes	Yes	No	No
Cell level design complexity	Low	Low	Low	High	High	High	High	High
Cell level control complexity	Low	Low	Low	High	Low	Low	High	High

the FC topology, the intermediate capacitor voltages should be balanced on half the dc voltage in case of the three-level configuration [61]. An improved configuration of the double FC cell is also addressed in [89] to improve the voltage quality.

8) NPC-Type Commutation Cells: The NPC converter can also be used as a building block of MMCs. Two alternatives of the NPC cells are shown in Fig. 5(h). One of them is constructed by a series connection of two basic commutation cells [57]. As shown in the figure, another NPC configuration can be achieved by a T-connection of switches where the midpoint switch needs to block in both polarities [58]. In the NPC-cell with active switches, all power switches are blocking the same voltage while in the NPC with T-connection, the switches of the upper and the lower leg switches block double the dc-link voltage.

A comparative study on different cells is summarized in Table I with a focus on ratings, features, and the control complexity. In principle, it is desired to achieve a cell structure having a higher voltage blocking capability, symmetrical voltage levels, and in addition a bipolar operation at a minimum cost. The cost is related to the number of devices and losses. As shown in Table I, the penalty for aforementioned characteristics is the higher number of components which eventually leads to a higher semiconductor loss. Moreover, the cell mechanical design, protection systems for internal faults, and the control complexity of the cell capacitor need to be taken into account for high-power applications. Therefore, there is a tradeoff between the cell complexity and the cell functionality/reliability which is the main challenge toward finding the optimum power electronic building block.

B. Modular/Chain-Link Multilevel Converters

Expanding the building block matrices as shown in Fig. 5, various types of chain-link modular converters can be synthesized as shown in Fig. 6. In the chain-link structures, for the same switch and capacitor units, the higher the number of cells, the higher the voltage blocking capability and the output voltage quality is. The total number of components in the chain-link structure is simply proportional to the number of cells (N) and the number of cell components. Even though the switching frequency of the power devices is reduced, by a higher number of cells, the conduction losses are a function of the number of cells inserted in the conduction path. Chain-link structures shown in Fig. 6 bear the same characteristics of their corresponding building block cells. For instance, the chain-link multilevel converters of Fig. 6(b)–(g) are formed based on a bipolar building block cell configuration which offers a bipolar chain-link converter structure. This results in a bipolar staircase voltage synthesized by the chain-link modular multilevel structure which is used in high- and medium-power applications with alternating converter terminal voltages, e.g., STATCOM, matrix converters, etc. [60]. Despite the nonnegative voltage limitation of the unipolar chain link, it will be shown in the following sections that both the bipolar and the unipolar chain-link converters can be used in ac/dc or dc/ac high-power conversion systems. A chain-link MMC can also be used in dc/dc modular multilevel topologies to step down or step up dc in medium- or high-voltage dc applications as proposed in [90]–[92].

C. Modular Multilevel Converter (M2LC)

The first group of MMC which corresponds to the first idea of modular converters for an HVDC application is proposed in [93]–[104] and is called the modular multilevel converter (M2LC). As shown in Fig. 7, this circuit has a similar structure as the conventional two-level converter; however, the series-connected *RC* devices in each converter phase arm have been replaced by a chain of switched capacitor cells shown in Fig. 6(a). In other words, the energy storage elements at the converter dc side have been distributed in the converter arms. This topology addresses, low losses, low switching frequency, slightly above the fundamental frequency, voltage scalability due to the simple cascading of identical cells, negligible ac filters due to the synthesized pure sine voltage waveform (for above 20 cells per arm), and mechanical simplicity. Each converter arm generates a multilevel voltage with a dc offset of the pole-to-ground voltage. A sinusoidal multilevel waveform at the ac terminal is synthesized by devising a proper modulation strategy [98] and creating appropriate insertion indices as shown in Fig. 7.

A certain number of cells in each phase-arm always contribute to maintain the dc voltage. This requires a considerably higher number of switching devices (at least twice) compared to two-level converters. Since fundamental current flows through each converter arm, the energy storage required by each arm is considerably higher (at least ten times higher) [102]. However, there is no need for additional dc-link capacitors and bulky ac and dc filters in this converter. Due to the high quality of the output voltage, which is the result of the high number of cells in each converter arm, the switching frequency of the semiconductor switching device is considerably reduced. Converter semiconductor loss calculation methods corresponding to the

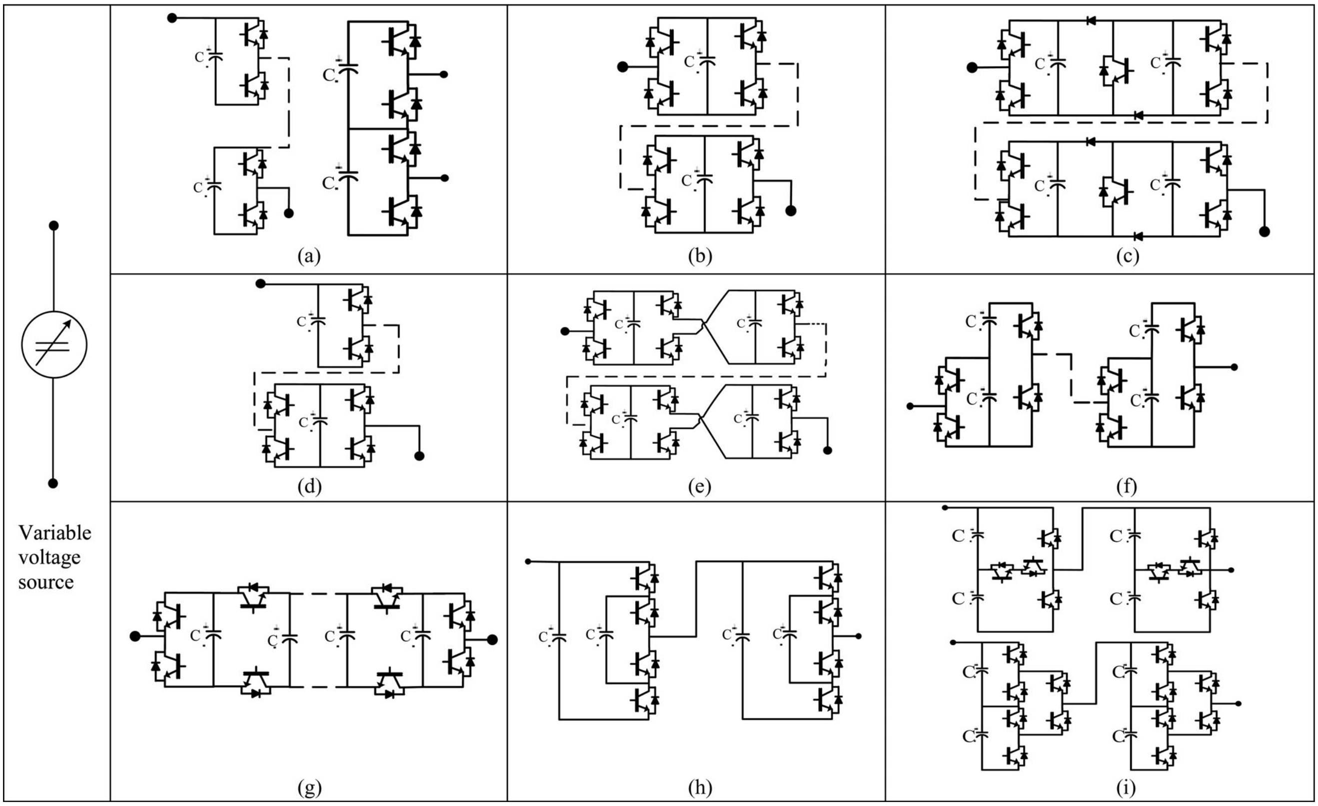

Fig. 6. Chain-link variable VS MMC topologies. (a) Series of commutation cells. (b) Series of double commutation cells. (c) Series of clamped commutation cells. (d) Series of mixed commutation cells. (e) Series of cross commutation cells. (f) Series of asymmetrical commutation cells. (g) Stacked FC commutation cells. (h) Series of FC commutation cells. (i) Series of NPC commutation cells.

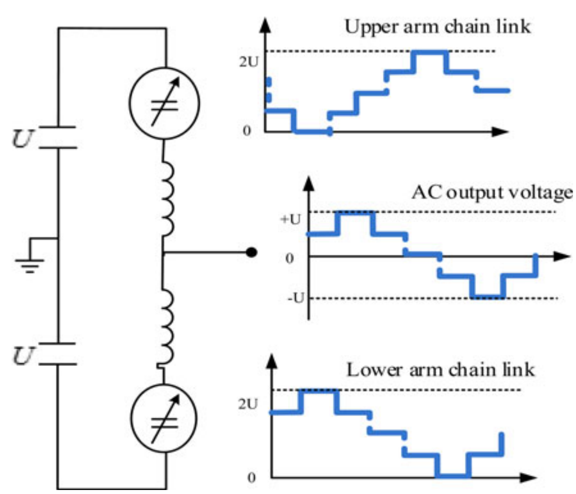

Fig. 7. VS modular multilevel converter (M2LC).

M2LC have been reported in [103]. Theoretically, the switching frequency can be reduced to a unity pulse number [94]–[101]; however, there is a tradeoff between capacitor ripple and switching frequency as the capacitors are actively regulated by the switching process [104]–[109].

Given the important features of this topology, it seems to be an invincible topology for HVDC applications with respect to today's technology. This converter has been developed recently by ABB known as HVDC Light [127] and by Siemens known as HVDC PLUS [128]. However, research activities are addressing the problems associated to M2LC for high- and medium-voltage applications such as HVDC, STATCOMs, and high\medium power drives. One of the main challenges in order to control this type of converter is the energy variation in each converter arm which causes a circulating current [108]–[112]. Another critical challenge which corresponds to the HVDC application requirements is the internal and the external fault tolerance of the converter [114]. Various fault detection methods [113] and cell protection devices have been introduced to deal with critical internal faults. The Press Pack power devices have been introduced by ABB for HVDC applications that employ a built-in short-circuit failure mode capability [115], [116]. The bypass switch using a mechanical or a high-current thyristor valve is another solution proposed for internal cell faults [117], [118]. Since VSCs are not inherently fault-tolerant converters, controlling the converter when subject to internal faults such as dc short-circuit faults or converter ac-bus faults is challenging. Different dc and ac circuit breaker solutions have been proposed in order to prevent the converter feeding the short-circuit faults [119]–[121].

D. M2LC Arm Variants

Alternative M2LC topologies can be generated by altering the cell structure or the chain-link configuration. An alternative chain-link structure in the M2LC topology offers different

TABLE II
COMPARISON OF M2LC TOPOLOGIES PHASE WITH DIFFERENT CHAIN-LINK ARM STRUCTURES

M2LC with chain-link arm	(a)	(b)	(c)	(d)	(e)	(f)	(h)	(i)
Number of cells	$2N$	$2N$	N	N	N	N	N	N
Total No. of switches normalized Uc	$8N$	$16N$	$14N$	$12N$	$16N$	$12N$	$8N$	$12N$
Max No. of switches in conduction	$4N$	$8N$	$7N$	$6N$	$8N$	$6N$	$4N$	$4N$
Bipolar voltage operation of the arm	No	Yes	Yes	Yes	Yes	Yes	No	No
Dc fault short-circuit current limitation	No	Yes	Yes	Yes	Yes	Yes	No	No
Capacitor voltage balancing in M2LC	Yes	Yes	Yes	Yes	Yes	Limited	Yes	Limited
PQ controllability	Yes	Yes	Yes	Yes	Yes	Limited	Yes	Limited

TABLE III
GENERAL ADVANTAGES AND CHALLENGES OF THE M2LC TOPOLOGIES

General Advantages of the M2LC variants:	General challenges of M2LC variants:
• High level of modularity at the cell level	• High number of power device
• Voltage scalability	• High number of cells and capacitor
• Independent PQ control	• Large energy storage
• Ac filters nearly eliminated	• Cell voltage balancing and circulating current control
• Low losses, and low switching frequency	

features corresponding to the cell types. MMCs using different cells are studied in [123]. The chain-link configurations shown in Fig. 6(b)–(g) allow the submodule capacitor to be inserted into the circuit with either polarity. This allows the converter to block the fault current caused by a short circuit between the positive and negative dc terminals (something which is impossible with any of the preceding types of VSCs). This also offers additional flexibility in controlling the converter during the temporary fault in overhead line applications. By decoupling the ac and the dc voltages, using the bipolar chain links in M2LC arms, the dc link of the VSC can now be in either polarity (similar to the line-commutated capacitor (LCC) HVDC scheme). This feature also gives a further possibility to connect the hybrid LCC and VSC HVDC systems. However, the penalties for such a functionality are a higher number of power devices and a considerably higher power loss as compared to the unipolar arrangements [122].

In addition, extra protection and measurement devices as well as cooling system requirements can cause an extra effort in designing the bipolar cells. A comparison between unipolar and bipolar chain-link structures in M2LC arms has been reported in [123]. Using three- or higher level multilevel cells [see Fig. 8(f), (h), and (i)] results in reduction in the number of cells in M2LC arms, for a given voltage level, and eventually the total converter dimension and component counts due to a higher voltage blocking capability. The capacitor voltage balancing methods for FC and NPC cells in M2LC have been addressed in [123]. Besides the complexity of the cells structure, both theoretical and experimental results indicate that NPC has limited operation in M2LC due to the capacitor imbalance issues [123], [124]. This also affects active and reactive power controllability. The M2LC structures associated with different chain-link structures, shown in Fig. 6, are compared in Table II, where N is defined as $N = \frac{2U}{U_c}$. The advantages and challenges of M2LC topologies are also summarized in Table III.

E. Hybrid Modular Multilevel Converters (HM2C)

In general, a hybrid modular multilevel VSC can be created by a combination of monolithic converter topologies and modular chain-link converter topologies discussed in the previous sections. This will result in different configurations of modular converters while inheriting both the advantages and the disadvantages of the monolithic converters. The major advantages are the minimum number of power devices, comparably the higher level of modularity and the considerably high power quality, though it suffers from the disadvantages such as the high-voltage stresses and the series connection of devices. This section is dedicated to the different configurations targeting hybrid modular converters.

1) HM2C With Monolithic Director Switches: As shown in Fig. 8(a)–(c), the series-connected commutation cells (chain link) can be connected to different points of the monolithic two-level converter such as the converter leg, the ac side, or the dc midpoint, respectively [129]–[133]. The main purpose of using chain links at the dc or ac side of the monolithic converters is to filter out the square-shaped waveforms generated by a series connection of devices, usually called director switches. Therefore, these series-connected devices are switched fundamentally and possibly at zero voltage to minimize the switching loss and to reduce the voltage stresses on the devices. By examining the waveforms shown in Fig. 8(a), it can be understood that the chain-link modular multilevel is able to inject a bipolar multilevel voltage waveform in order to filter out the output voltage creating a sinusoidal waveform at the ac output terminal. Therefore, the higher the number of commutation cells in the chain link of the monolithic converters, the higher the quality of the output voltage is. It is important to highlight that due to the bipolar voltage requirement; only bipolar chain-link converters are used in those structures [see Fig. 6(b)–(g)].

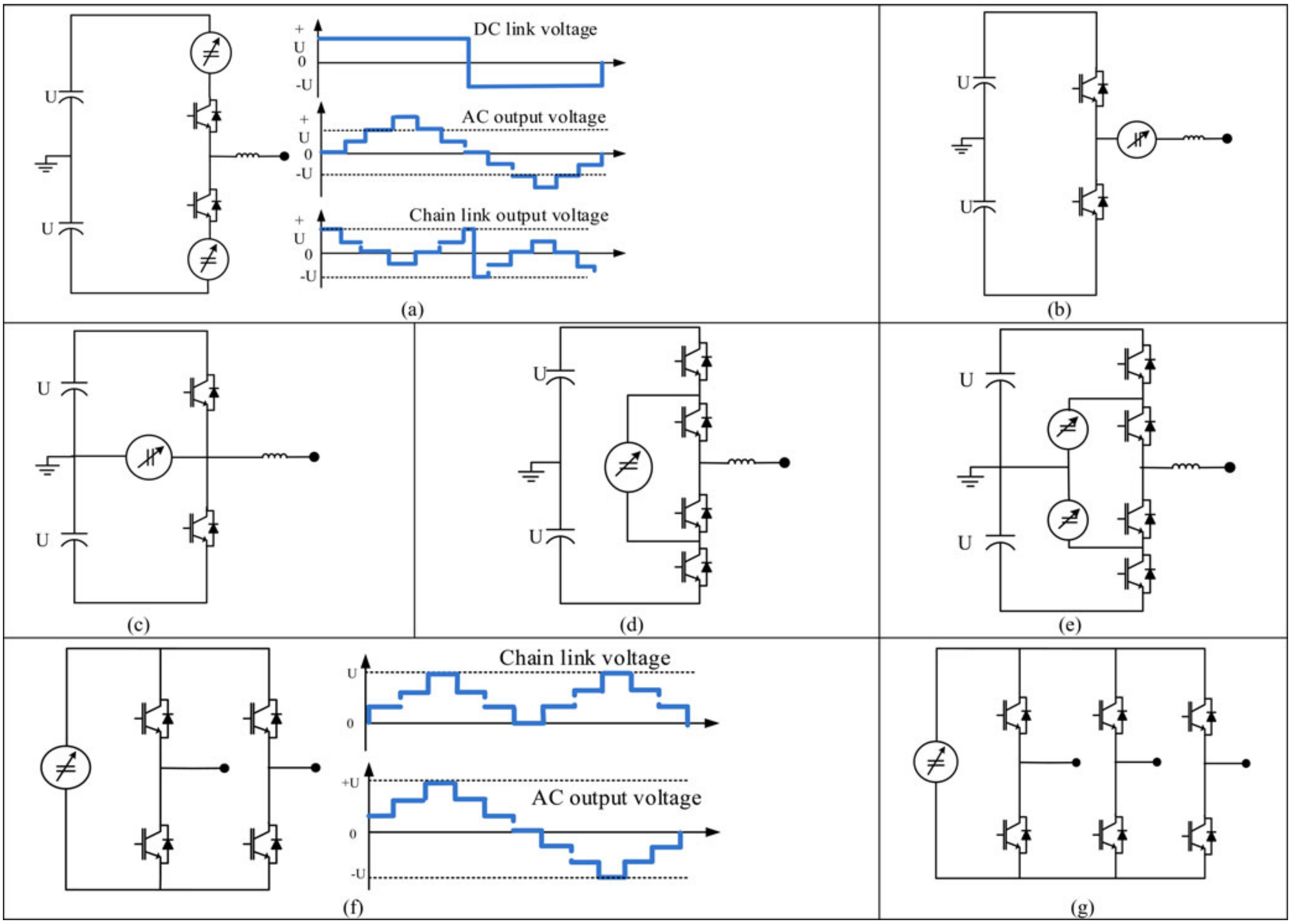

Fig. 8. Hybrid modular VSCs. (a) Hybrid two-level with arm chain link. (b) Hybrid two-level with ac-bus chain link. (c) Hybrid two-level with midpoint chain link. (d) Hybrid three-level FC with midpoint chain link. (e) Hybrid three-level NPC with arm chain link. (f) H-bridge hybrid with parallel chain link. (g) Three-phase hybrid with parallel chain link.

Since the total dc voltage is now shared by the director switches and the chain of cells in the hybrid solutions, a reduction in the number of required cells and consequently the number of the required power devices is expected. However, forcing the director switches to have zero voltage or fundamental switching brings a limitation to operation of hybrid converters. This limitation is the specific required relation between the ac and the dc voltage. Keeping this relation is essential to maintain power in the chain link of the modular multilevel cells, i.e., to have an average power of zero in these chain links [131]. This requirement limits the independent active and reactive power control as the dc and the ac voltages cannot be controlled independently.

Different methods are proposed to decouple the ac and the dc power; however, this will considerably increase the converter's voltage rating. The dc fault ride-through capability and STATCOM operation of the HM2C has been proposed in [132], [133]. A method of capacitor voltage balancing for a three-phase system considering full-bridges in the converter arm has been described in [134]. It is also feasible to use three-level monolithic converters (NPC and FC) as director switches in hybrid converters as shown in Fig. 8(d) and (e) [126], allowing more flexibility to decouple the ac and the dc voltages. However, this may increase the complexity of the mechanical design and the control.

2) HM2C With H-Bridge Director Switches: The HM2C can be created by a combination of H-bridge or a three-phase bridge monolithic converters and the chain-link structures [135]–[142]. The concept is to synthesize a rectified half-wave multilevel voltage using the chain link of commutation cells while the director switches adjust the polarity of the synthesized voltage as shown in Fig. 8(f) and (g). Consequently, a bipolar multilevel waveform can be generated as shown in Fig. 8(f).

As shown in Fig. 8(f) and (g), the chain links are connected in parallel with two-phase or three-phase bridges, respectively. In order to gain soft switching in the director switches, their switching is occurred at zero voltage. In order to have a sinusoidal voltage in the ac terminal of the director switch bridges, the commutation cells in the chain link of Fig. 8(f) generates a 100-Hz rectified sinusoidal voltage at the dc terminal of the H-bridge director switches [135], [136], while in Fig. 8(g), a six-pulse rectified voltage needs to be generated for the three-phase director switch bridge configuration [79]. This can reduce the overall switching losses of the converter and reduce the voltage stress sharing on series connection of director switches during

TABLE IV
COMPARISON OF HYBRID MODULAR MULTILEVEL PHASES

Hybrid topologies	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Number of cells	*N* (FB)	*N*/2 (FB)	*N*/2 (FB)	*N*/2 (FB)	*N*/2(FB)	*N*(HB)	*N*(HB)
Number of director switches	(4/pi)∗*N*	2*N*	2*N*	3*N*	2*N*	4*N*	6*N*
Total No. of switches normalized by Uc	5.27*N*	4*N*	4*N*	5*N*	4*N*	6*N*	8*N*
Max No. of switches in the conduction path	3.27*N*	3*N*	3*N*	4*N*	3*N*	3*N*	4*N*
Zero switching in director switch	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dc faults short-circuit current limitation	Yes	Yes	No	No	Yes	No	No
PQ controllability	Limited	Limited	Limited	Limited	Limited	Limited	Limited

TABLE V
GENERAL ADVANTAGES AND CHALLENGES OF HYBRID MODULAR CONVERTERS

General Advantages of hybrid modular converters:	General challenges of Hybrid modular converters:
• Lower number of active and passive components	•· Limited PQ controllability
• Reduced number of cells	• Series connection of power devices
• AC filters nearly eliminated	• Higher conduction loss
• Low switching loss and zero voltage switching	• Possible need for a dc filter
• Compact structure	

the turn-off. In these converter topologies, the main current flows through director switches, and as a result, the conduction loss of the director switches is the dominating part of the converter losses in these specific converter structures.

A three-phase series connection of modular multilevel H-bridges is proposed in [139]–[142]. In the case of series hybrid topologies, the fundamental switching pattern of the director switches causes a limitation on controlling the active and the reactive power independently. Another drawback of this topology is the generation of a half-wave sinusoidal voltage at each single-phase bridge which increases the voltage ripple at the dc link. A method to minimize the ripple has been proposed in [140] by injecting odd triplen harmonics. This method also increases the controllability of the active and the reactive power, but it will affect the converter rating. A cell capacitor voltage balancing method for the HM2LC with H-bridge director switches has been reported in [141]. In addition, other monolithic converter topologies such as NPC and the FC converters can be used as the H-bridge director switch in HM2LCs. Although the different chain-link structures shown in Fig. 6 can be used together with the H-bridge director switch, unipolar chain-link modular converters [see Fig. 6(a), (h), or (i)] are sufficient since the director switches are acting as a voltage reversal unit. A comparison between the different series and parallel hybrid modular multilevel structures with chain link shown in Fig. 6(a) and (b) is presented in Table IV. Assuming that the cell and single switch in the director switch has a same voltage blocking, it is shown that the number of cells in the hybrid topologies is reduced compared to the MMCs. Moreover, the converter size is reduced due to the partially removal of large and bulky capacitors. In order to achieve the inherent dc fault blocking capability in hybrid HM2Cs, bipolar cell chain links need to be placed between the main dc and ac current paths. Therefore, only the HM2C presented in Fig. 8(a) and (b) can offer this feature. Generally, the soft-switched director switch reduces the switching losses of HM2Cs; however, this will limit the active and reactive power generation. A summary of the advantages and the challenges of HM2Cs is presented in Table V.

III. MODULAR CSC TOPOLOGIES

One general feature for CSCs is the external short-circuit fault tolerance. This is because the large energy-buffering inductors in CSCs can limit the fault current rise, and the switches in CSCs normally have bidirectional voltage blocking capability. Such a fault tolerance feature makes this category of converters interesting for grid applications. Most of the modular CSC topologies can be derived from their VS counterparts by applying the circuit duality principles, provided that the circuit topologies are planar. It is found that dualities can be applied to most of the cell and single-phase circuit structures, but this is not always true when it comes to a three-phase topology. This section discusses some selected modular CS concepts from cell structures to system-level topologies.

A. CS Cell Structures

Following the circuit duality principles, CS cells can be created from the VS cells of Fig. 5. Different CS cells are discussed in this section.

1) CS Half-Bridge Cells: The CS commutation cell [143], shown in Fig. 9(a), is dual to the VS commutation cell shown in Fig. 5(a). In CS cells, the switches must have bidirectional voltage blocking capability and can conduct current of at least one direction. The switching table of this cell is exactly the same as that of the VS commutation cell. T1 and T2 are complementary switches and one of them must be ON to conduct the inductor current.

2) CS Full-Bridge Cells: The CS double commutation cell [143], as shown in Fig. 9(b), allows four-quadrant operation. This cell can output bidirectional current and block bidirectional

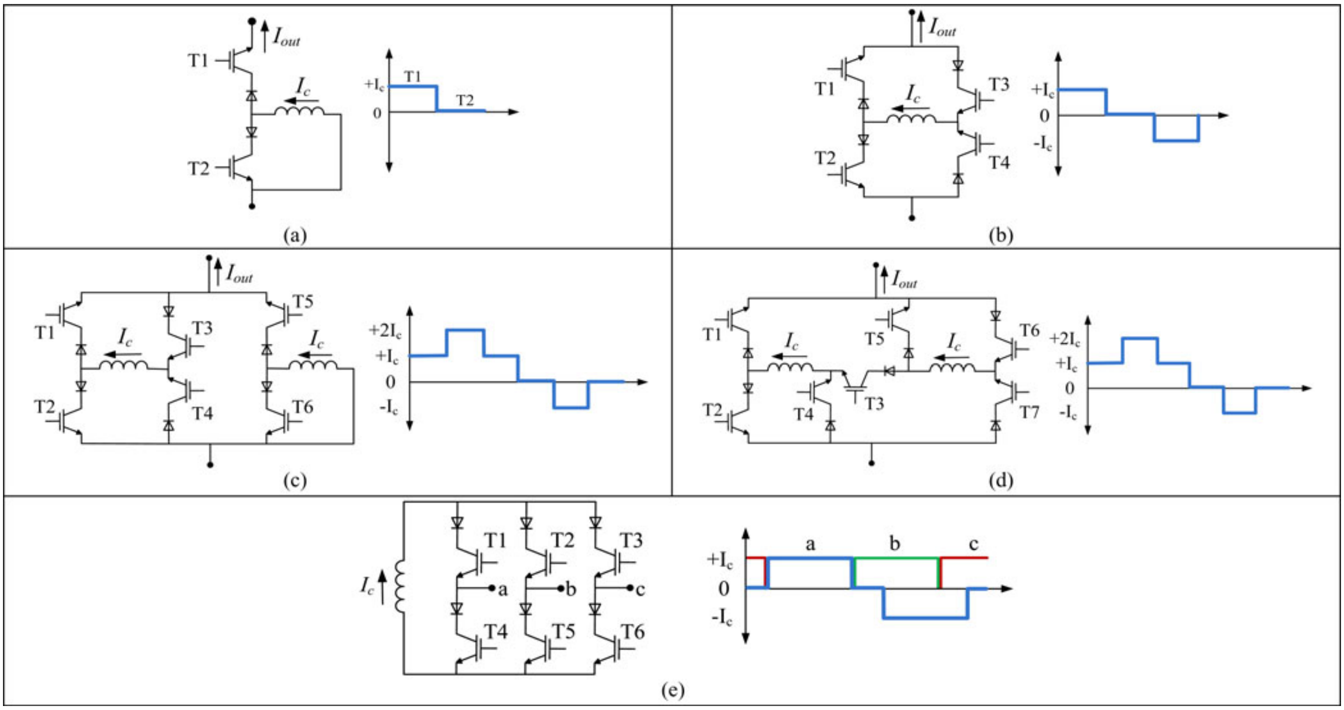

Fig. 9. CS cell structures. (a) Commutation cell. (b) Double commutation cell. (c) Mixed commutation cells. (d) Clamped double commutation cell. (e) Three-phase commutation cell.

voltage. T1 and T2, as well as T3 and T4, are complementary switch pairs.

3) CS Mixed Cells: The CS mixed cell is created by parallel connecting a half-bridge and a full-bridge CS cells, as shown in Fig. 9(c). By mixing the half-bridge and full-bridge cells, one can reduce the total semiconductor rating when a dc bias is desired in the output current waveform.

4) CS-Clamped Double-Commutation Cells: The CS dual of the clamped double commutation cell is shown in Fig. 9(d). When T3 is turned OFF and T4 and T5 are turned ON, this cell is equivalent to two CS half-bridge cells connected in parallel. When T3 is turned ON and T4 and T5 are turned OFF, this cell is equivalent to a full-bridge cell with two inductors connected in series. It results in an interesting feature of extra inductance in the current loop to limit *di/dt*. However, additional design considerations should be taken into account for the transition into the full-bridge mode during which two inductors that may have different currents will be series connected.

5) CS Three-Phase Cells: A CS three-phase commutation cell [see Fig. 9(e)] can also find applications where only parallel-connected CS cells are required. In this cell, T1, T2, and T3 are complementary switches, and one of them must be ON at any given time (each switch conducts for one-third of a fundamental cycle). The same applies to switches T4, T5, and T6. The waveform of phase "a" has been shown in Fig. 9(e) and for simplicity other phases have not been drawn. A comparison of the aforementioned cell types is listed in Table VI.

TABLE VI
COMPARISON OF THE DIFFERENT CS CELL TYPES

Cell type	(a)	(b)	(c)	(d)	(e)
No. of output current levels	2	3	4	4	3
Max output current	I_c	I_c	$2I_c$	$2I_c$	I_c
Total No. of RB switches	2	4	6	7	6
No. of switches in conduction	1	2	3	4	2
Bidirectional current	No	Yes	Yes	Yes	Yes
Cell level design complexity	Low	Low	Low	High	Low
Cell level control complexity	Low	Low	Low	Low	High

B. Modular CSCs

1) Modular CSCs Using Cells With Common DC Connection: Because of the nature of current synthesis, a modular multilevel CSC requires CS cells to be connected in parallel. A three-phase CSC can be constructed by three single- phase CSCs, or parallel connecting three-phase cells. The conventional modular multilevel CSCs (see Fig. 10), that are widely studied in the literature [144], [145], consist of parallel-connected full-bridge or three-phase CS cells. The dc side of cells is opened, and connected through inductors, which are required to minimize circulating currents between the cells. In principle, with a high enough number of cells, each valve can be switched at fundamental frequency. However, a full ac line-to-line voltage blocking capability is required for each valve. Series connection of a large number of semiconductor switches is generally required to scale these CSCs for high-voltage applications.

2) CS M2LCs: Following the circuit duality transformations, a CS arm and a single-phase CS M2LC can be derived from their VS counterparts, as shown in Fig. 11. Other types of CS cells may also be used in the CS arm. It should be noted that the complementary arms in the single-phase CS M2LC are the two that are connected to the same dc terminal, i.e., the sum of the currents going through the "CS Arm Ap" and "CS Arm An"

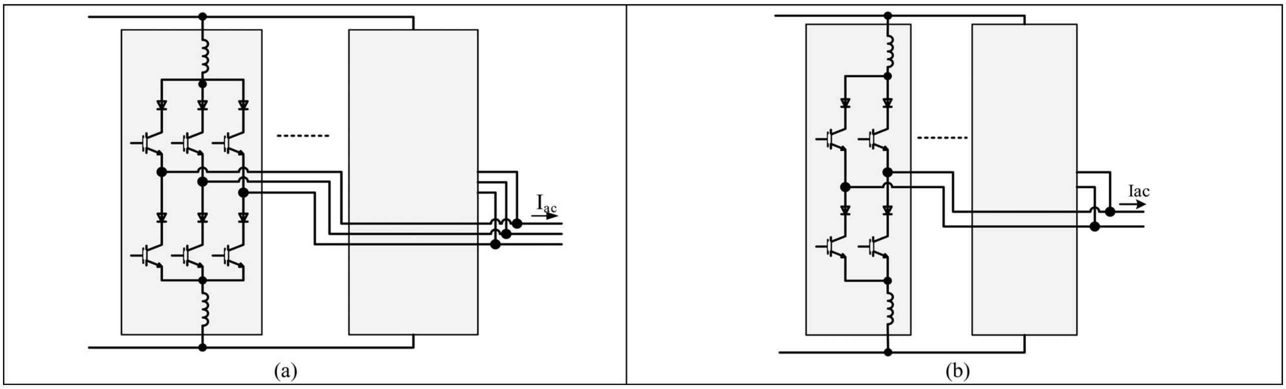

Fig. 10. Modular CSCs using cells with a common dc connection. (a) Three-phase modular CSC. (b) Single-phase modular CSC.

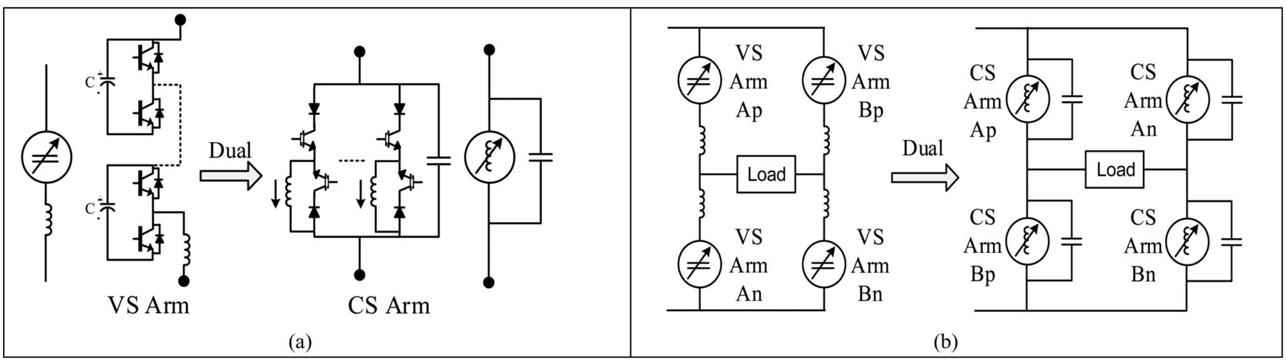

Fig. 11. Single-phase CS modular multilevel converter (CS M2LC). (a) CS dual of M2LC arm. (b) CS dual of single-phase M2LC.

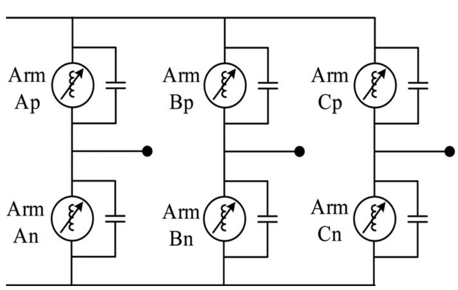

Fig. 12. Three-phase CS M2LC.

equals to the dc current. The desired ac output current is equal to the difference of the currents synthesized by the “CS Arm Ap” and “CS Arm Bp”. When half-bridge cells are used (see Fig. 11), the CS arm current must be unidirectional, and thus, the voltage across each CS arm must be bipolar to ensure zero average arm power.

When conceiving a three-phase CS M2LC, the duality transformations cannot be applied, because a three-phase VS M2LC supplying a three-phase load is not planar. One way to construct a three-phase CS M2LC has been discussed in [146]–[148], and shown below in Fig. 12. This topology copies the higher level circuit structure of the three-phase VS M2LC, and thus, the operation of this CS M2LC also somewhat copies that of the VS M2LC. Each CS arm directly synthesizes 1/3 of the total dc current and 1/2 of the ac phase current.

C. *Hybrid Modular CSCs*

The CS arm can be used as a current shaper to refine the ac current steps generated from a monolithic CSC, as shown in Fig. 13 [143], [149]. For the three-phase hybrid CSC, the shaper may consist of three single-phase CS arms as shown in Fig. 13(b), or consist of parallel-connected three-phase commutation cells. For both circuits, the current shaper can only be used to synthesize quadrature and/or harmonic currents in order to maintain zero average power. A new type of hybrid modular CSCs can be constructed by using the CS arms as current sharpers on the dc side. Fig. 14(a) shows a hybrid modular CSC by series connecting a CS arm with a monolithic full-bridge CSC. The CS arm synthesizes a rectified sinusoidal current, and the monolithic full-bridge CSC converts this rectified current into a sinusoidal ac current. Fig. 14(b) shows another hybrid modular CSC by parallel connecting a CS arm with a monolithic full-bridge CSC. The CS arm in this circuit synthesizes the current difference between a rectified sinusoidal current and the phase dc current. Table VII provides a comparison on the advantages and challenges between the VS modular converters and the CSs modular converters.

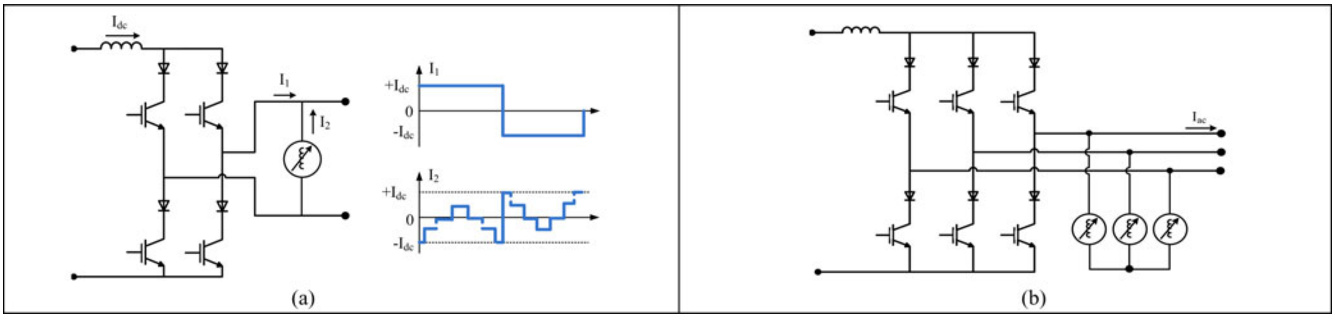

Fig. 13. Hybrid modular CSC with ac current shapers. (a) Single-phase hybrid modular CSC. (b) Three-phase hybrid modular CSC.

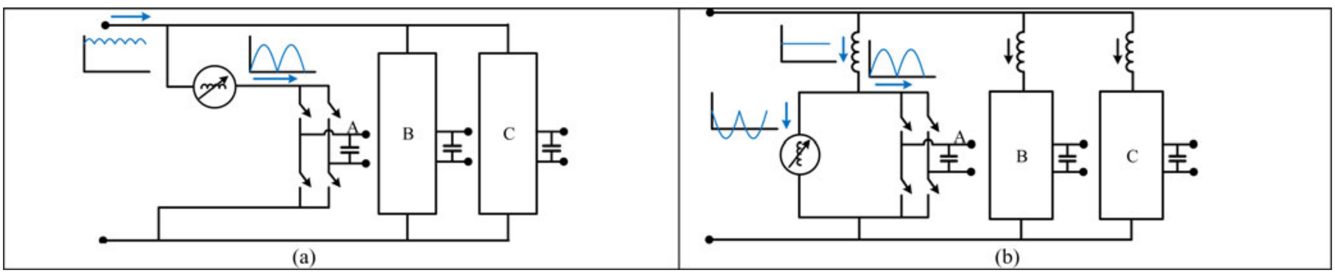

Fig. 14. Hybrid modular CSC with dc current shapers. (a) Series hybrid modular CSC. (b) Parallel hybrid modular CSC.

TABLE VII
COMPARISON OF VS AND CS MODULAR CONVERTERS

	VS modular converters:	CS modular converters:
Advantages	• PQ controllability • Voltage scaling by series connection cells • Well defined voltage across semiconductors • Nearly pure sine-wave output voltage	• PQ controllability using self-commutated devices • Current scaling by paralleled cells • Short-circuit fault tolerance • Nearly pure sine-wave output current
Challenges	• Large energy storage in capacitors • Protection against internal and external dc short-circuit faults • Limited current scaling capability	• High loss due to inductors and RB devices • Large footprint for inductors • Protection against open circuit faults and overvoltage across devices • Limited voltage scaling capability

IV. MODULAR CONVERTER PHASES

In HVDC systems, the three-phase converter is normally connected to the ac system through the transformer as it can provide several advantages such as isolation, zero sequence harmonic cancelation, and offering a tap changer functionality. Therefore, using a single-phase modular VSC, a higher voltage\current can be achieved by a series or parallel connection of phases. Two general multiphase converter structures for converting the dc voltage to an ac voltage using a series or parallel connection of single-phase converters are shown in Fig. 15. Increasing the number of phases can result in the reduction of either the voltage or the current rating of the converter for the same power rating.

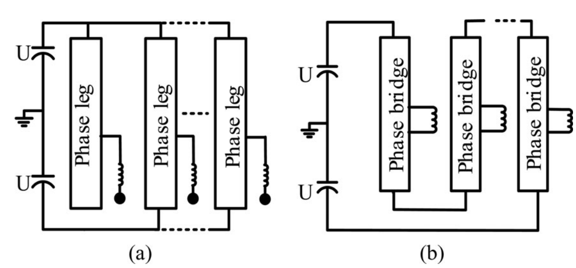

Fig. 15. Modular phases. (a) Parallel and (b) series connection of phases.

A. Parallel Phases

By connection of any kind of single-phase M2LCs configurations or hybrid structures in parallel to the dc poles, a modular high-power converter can be generated. In these structures, all phases are connected in parallel to the dc link. The ac side of the phases can be connected to the ac grid through a transformer. Other alternatives of paralleling converters are the parallel converter arms or parallel two- or three-phase converters. A proper current control is essential to ensure the current sharing between the converter arms and/or phases. At the same power, a parallel connection of phases offers a considerably lower current and a higher voltage rating in the converter valves. Therefore, this is an effective solution to transfer more power when the device current rating and dc cable voltage rating is limited.

TABLE VIII
COMPARISON OF THE SERIES AND PARALLEL CONVERTERS

System level modularity	Series-connected phases	Parallel-connected phases
Power device voltage rating	Low	High
Power device current rating	High	Low
Number of components	Low (2*N*/3 for H-bridge series phases)	High (*N*)
Transformer's level of complexity	Complex(dc insulation)	Simple (normal Design)
Independent PQ control	Yes	Yes
Controller's complexity	Complex	Less complex
Resilience to ac Fault	Not so good	Good

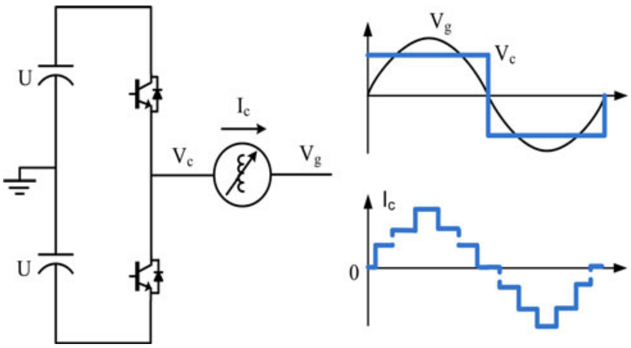

Fig. 16. Hybrid two-level molithic VSC with CS cells.

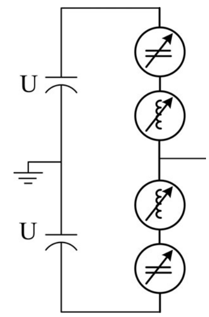

Fig. 17. Hybrid CS-VS M2LC.

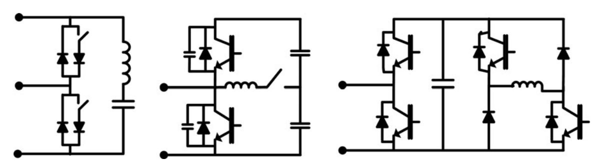

Fig. 18. Example of hybrid VS/CS cells.

B. Stacked Phases

The phase of the modular converter topologies (M2LC configurations or hybrid structures can be also connected in series with a three-phase system. This will divide the total dc link voltage between the phases equally, while each phase is independently connected to the ac side through transformer connections. Therefore, assuming the same power transfer rating, the series connection requires a considerably lower voltage and a higher current rating in the converter valves. The series connection can offer comparably a compact converter solution for a lower power range; however, it comes with the cost of more complex controller when handling the transients due to the lack of current circulating between phases. In general, more phases can be connected in series or in parallel through a magnetic coupling forming a three-phase system. Therefore, any of these structures can be used in order to optimize the valve rating. The advantages and challenges of the stacked converter structures over the parallel phases are summarized in Table VIII.

C. Hybrid Current and VSC Phases

In principle, the CS arm can also be connected to a VSC, and *vice versa*. In the hybrid converter shown in Fig. 16, the CS arm directly synthesizes the desired fundamental current. To maintain zero average arm power, the two-level VSC output voltage must ensure that the fundamental voltage across the CS arm is either zero or 90° out of phase with respect to the CS arm current. Following this same concept, a hybrid M2LC can be constructed by using hybrid CS-VS arms, as shown in Fig. 17. The inductor cells directly synthesize the desired current waveform, while the capacitor cells change the voltage across the CS arms. More analysis is needed for these hybrid single cell designs; typically with additional switches, one can derive new families of converter cells. Additional features are resonant operation, soft switching, etc. Without going into detailed categorization, these cells are generally grouped into the "hybrid cells" category in this paper. Some examples of these cells are shown in Fig. 18 [150], [151].

V. FUTURE TRENDS IN MODULAR MULTILEVEL TOPOLOGIES

The evolution of MMCs over the last decade has advanced several commercial applications such as HVDC and flexible alternating current transmission systems (FACTS). From this technology, as summarized in this paper, some insight on future trends can be extracted. In addition, despite industrial presence, the technology has not stabilized yet and there are still several challenges for further development of this technology. Some of these trends and challenges are discussed in this section.

The role of the next-generation power converter topology becomes significantly important to reduce the total energy consumption by processing the power in electrical transmission systems. The average device switching frequencies are below 300 Hz (for IGBTs and IGCTs) for high-power applications. The main reasons for this choice are the device limits and practical limitations on the cooling system. The switching loss is important in terms of low-order harmonics reduction and can be improved by the modulation technique; however, the conduction loss would become dominant, and once the topology is chosen, not much can be done to lower it. As mentioned in the text, some hybrid converters can reduce the overall conduction losses of the converter; moreover, employing the zero voltage switching techniques can significantly reduce the converter switching loss. Therefore, a trend is to achieve the efficiency of line-commutated thyristor valves converter topologies while gaining valuable insights and overcoming the challenges of the newer topologies.

Reliability and availability at lowered cost is also a key trend in the future development of MMCs for high-power applications [152]. One important application could be better utilization of the modular building blocks to limit the critical faults in power systems. As discussed earlier in this paper, some multilevel converter topologies have capability to operate under dc fault conditions. The fault detection methods are of vital importance for this ability. As addressed, bipolar cell structures and converter reconfigurations are definitely challenges for further research and development in this field. Another trend to have fault-tolerant converters is to move toward the modular CSCs or hybrid VSC/CSC topologies.

Price trends reveal that semiconductors are becoming cheaper while energy is becoming more expensive, and grid codes are becoming more restrictive [153], [154]. Therefore, the use of MMCs becomes more and more attractive for high-power applications, as the long-term operational cost reduction justifies the higher initial costs. The existing and future grid codes and the continued increase of power demand of various applications will be the central focus in MMC development. The reduction of the required energy stored in the passive components is highly important. Moreover, the energy consumption in power converters should be minimized [154]. These necessities motivate the trends toward designing building block cells with more functionalities or creating modular converters with paralleled phases.

Currently, the dominating semiconductor technology for high-power modular multilevel topologies is the IGBT. This approach has been very successful in modular multilevel topologies due to the low switching frequency and is expected to exist in the upcoming years in high-power application fields. On the other hand, the development of mature widebandgap devices such as silicon carbide (SiC), gallium nitride (GaN), and diamond power devices would benefit the establishment of multilevel converters, by drastically reducing the switching losses and minimizing the cooling system requirement [155]. Therefore, it is expected that, in the future, high-voltage SiC devices would affect the building block cells and accordingly modular multilevel topologies for high-power applications [156]. This needs to be further evaluated with a proper modeling of the device and considering practical issues in HV applications [157].

MMCs used for high-power applications contain a large number of semiconductors, capacitors, and inductors within their structures, which increases the size and weight of these converter topologies [158]. For some applications such as offshore wind, it is vital to have a compact converter topology. As discussed, a converter with stacked phases is one solution to reduce the volume of these converters. However, a further development is required to minimize the volume of the converter topologies.

Although transformers provide galvanic isolation and voltage matching in grid-connected high-power applications, a transformerless topology is still a desirable feature. The elimination of transformers provides a significant reduction in the cost, volume, and weight, system complexity, and losses. The new MMC topologies using bipolar cells are good candidates for transformerless topologies as they can offer extra level of freedom to control voltage mismatching in the grid connected applications. However, addressing the transformerless modular multilevel topologies is a topic for future research. An alternative solution to further increase the functionality and efficiency of the grid is to replace the conventional passive transformers by solid-state transformers. This concept also encounters different challenges, such as very high switching loss when using the silicon devices and special considerations required to both core and winding losses, especially for high-power applications [159].

VI. Conclusion

This paper has reviewed the state of the art in MMCs by discussing the most recent modular multilevel voltage and CSC topologies. The modularity concept from the cell to the system level has been investigated on different modular converter families. Using the proposed modularity concept, different modular converter topologies have been synthesized and categorized. In addition, the duality concept has been used to develop the new modular CS topologies. A thorough comparison of topologies versus the main criteria of high-power applications has been presented for each modular converter category, which was followed by general trends and challenges in the field. It is clear that the development of power semiconductor devices and new demands and regulations will drive and shape the future of MMC technology.

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