

## Review Article

# A Detailed Review of MMC Circuit Topologies and Modelling Issues

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MMC is a promising technology for MTDC systems and would transform into the concept of Supergrids in the near future. The salient features of MMC are modularity, reduced  $dv/dt$  and  $di/dt$  stress on switches, voltage and power scalability, inherent fault blocking capacity, transformerless operation, and improved power quality. However, there are some technical issues and challenges to be critically analysed and addressed. There is room for development of novel and enhanced MMC based on SM configurations to enable higher efficiency, improved power quality, compactness, and DC fault blocking capacity. Moreover, development of efficient and accurate models is required for the studies of MTDC grids during steady-state and transient conditions. Literature review suggests a need for studying and comparing different MMC modelling approaches because no modelling technique can be best suited for all applications. The main contribution of this paper is to provide a comprehensive review of recent developments in MMC in terms of SM configurations. This paper also presents an in-depth review of systematic comparison of different models of MMC, which can enable appropriate selection of model based on target studies and desired accuracy and efficiency. Finally, the associated research challenges and future trends are presented.

## 1. Introduction

Over the years, there have always been heated disputes between the supporters of the DC and AC systems [1–3]. In the 1880s, electricity development experienced major inventions, and the war of currents between Nicholas Tesla and Thomas Edison started, which lasted several years [4]. The earliest electrical system was introduced by Thomas Edison in 1882. His electrical system had DC generators driven by steam engines to supply Direct Current (DC) at 110 volts. However, in the late nineteenth century, the war ended as AC won, and there had been a decline in DC systems. The AC became dominant over DC due to the inventions of the induction motor and AC transformers. AC transformers facilitated cost-effective transmission, and thus High Voltage Alternating Current (HVAC) was considered the most economical choice for decades [5]. DC has reemerged and been preferred over AC after the rapid advancements in the field of power electronic devices and power converters. DC system rebooting started in 1954, when ABB accomplished the High

Voltage Direct Current (HVDC) project between Gotland and the Swedish Mainland [6].

Most countries worldwide have set an ambition to increase renewable energy resources to meet energy targets and combat climate change while increasing energy security [7]. European Union (EU) has set a target for the year 2050 to reduce 80–95% of greenhouse gas emissions compared to 1990 levels [8, 9]. In this regard, European Wind Initiative (EWI) has decided to replace 50% of its nonrenewable power sources with wind power generations [9]. Since most renewable energy resources such as offshore wind farms are situated at remote locations, the requirements for long-distance power transmission and asynchronous interconnections are increasing [6]. HVDC is well-proven technology to meet these requirements and is a promising technology for future power systems [6, 10, 11]. MMC-HVDC for an offshore wind farm is shown in Figure 1.

HVDC can be used for asynchronous interconnections such that technically mismatched systems with different grid frequencies and voltage ratings can be

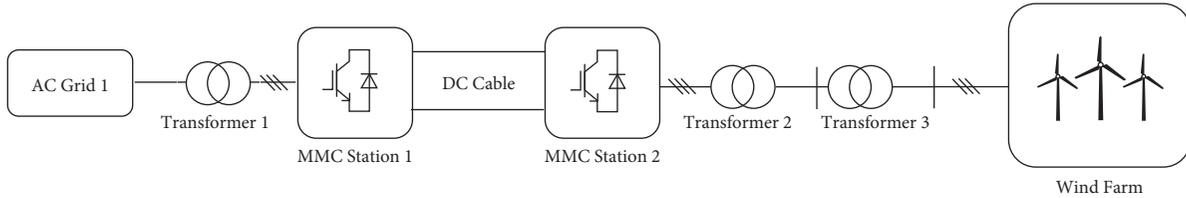


FIGURE 1: MMC-HVDC with the submarine cable for an offshore wind farm.

interconnected [12, 13]. This is one of the significant advantages of HVDC as compared to HVAC. HVDC is preferred over HVAC in applications such as underwater long-distance cable crossing, bulk power long-distance transmission, and underground long-distance cables [1, 14, 15].

Three power converter topologies have been historically used for HVDC projects. Initially, a line-commutated converter (LCC) was used; later on, voltage source converter (VSC) was introduced; and currently, modular multilevel converter (MMC) is dominating the HVDC technology [16, 126, 127]. In 1940s, only LCC was used commercially [12]. Before the 1970s, mercury arc valve was used in LCC, but after the 1970s, thyristor technology was introduced in LCC. LCC-based HVDC systems dominate the long-distance and bulk power transmission. Many LCC-based HVDC projects have been installed, and few are under construction [6, 17]. LCCs have relatively high line impedance and thus have the natural ability to slow down the rise of DC fault current, making AC circuit breakers suitable to allow protection [18, 19]. This current limitation feature is missing in MMC with half-bridge topology and VSC [18, 20]. Therefore, DC fault becomes a critical issue. Arm inductors in MMC and transformer leakage inductance in VSC mainly limit DC fault current. Moreover, DC circuit breakers, advanced extruded DC cables, fault blocking submodules, MMC topologies with fault ride-through capability, fault current limiting devices, and MMC control strategies may be used to address critical DC faults in VSC-MMC [4, 18, 21]. Another drawback of VSC-MMC-HVDC is lower current and voltage rating compared to LCC, but in the last decade, these ratings have increased significantly [7]. Previously, LCCs had higher efficiency than VSC-MMC, but with development in power electronic devices, MMC is arriving at efficiencies close to LCC converter. However, LCC technology is not preferred for future power systems due to several limitations such as the need for fast communication, complex control system, use of semiconductor devices that cannot be turned off autonomously, operating at lagging power factor, limited reactive power control, and inability to use it in the isolated system [6, 7]. Another major limitation of the LCC-HVDC system is an inability to change the direction of current such that it needs to reverse voltage polarity to change power flow direction [22]. LCC can conduct current in only one direction while blocking voltage in both polarities. Moreover, the LCC type converter has short-circuit ratio (SCR) of more than two which means

that it cannot be adequately interfaced with weak AC networks such as offshore wind power plants [12].

The real breakthrough came with the invention of IGBTs in 1997, making VSC-MMC-HVDC technology superior to LCC technology. The use of VSC-MMC as compared to LCC offers the following advantages.

- (1) It can eliminate commutation failure problems due to disturbance in AC network [23].
- (2) It offers flexible and independent control of the converter's active and reactive power consumed or generated.
- (3) It can operate with delay and advanced power factor, and it is possible to sink and source reactive power [24].
- (4) It is possible to connect weak AC networks such as offshore wind power plants [25].
- (5) Lower total harmonic distortions (THD) and improved power quality.
- (6) The size of the filter is reduced, or no filter is required.
- (7) It offers black start capability, and there is no need for a transformer to assist the commutation process [26].
- (8) The dynamic behaviour allows AC fault ride-through capability.
- (9) It requires less space and has less footprint and weight of the converter than LCC. Therefore, offshore wind power plants which need a DC cable connection prefer VSC-MMC technology.
- (10) It can change current and power flow direction without reversing the polarity. Power switches in VSC-MMC have bidirectional current carrying ability. Therefore, VSC-MMC technology is ideal for implementing Multiterminal Direct Current (MTDC) power grids [27].
- (11) DC power cables are lighter in weight and have lower installation cost in VSC-MMC. VSC-MMC uses fully controlled power semiconductor devices that can be autonomously turned on and off.

The classification of voltage source power converters is shown in Figure 2. Two-level VSC suffers from high switching losses as it generally requires a high switching frequency to operate [28]. Two-level VSC suffers from poor power quality and high total harmonic distortions. Therefore, it demands a large filter size; hence, filter losses are increased, and overall

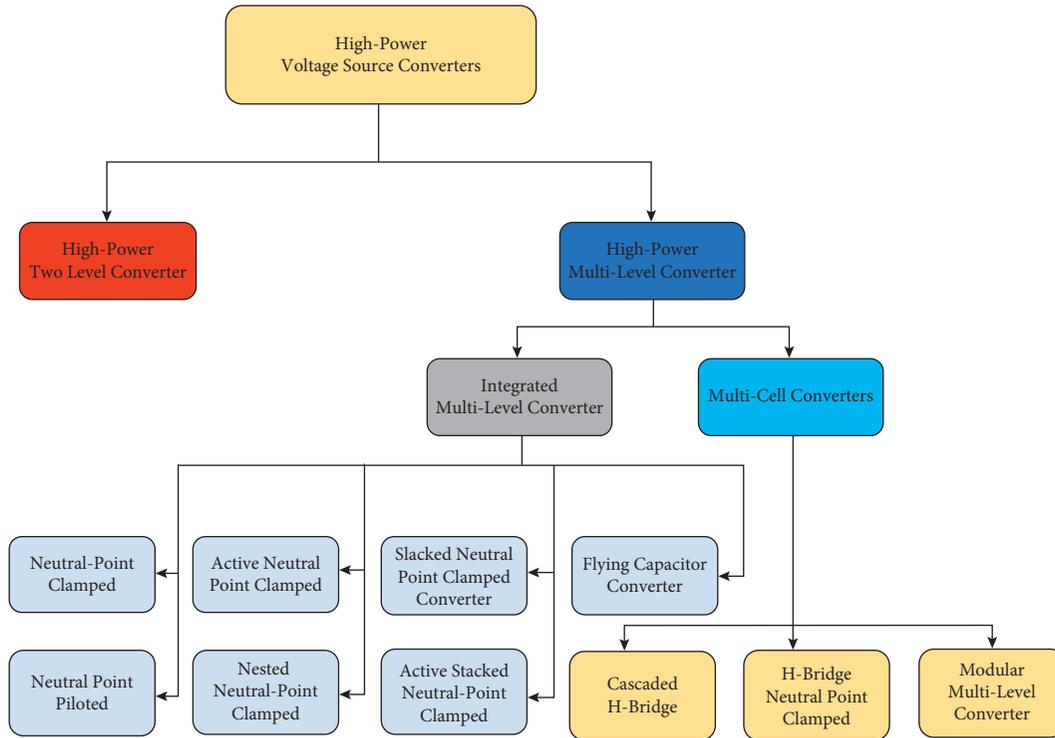


FIGURE 2: Classification of high-power voltage source converters.

efficiency is compromised. It also suffers from electromagnetic interference problem, high  $dv/dt$  and  $di/dt$  stress, and over-voltages in power switches [29]. Moreover, two-level VSC cannot block DC fault current in the case of DC pole to pole fault. The integrated multilevel converters are not preferred, requiring significant modification to increase operating and output voltage levels. Moreover, these converters need to be shut down during internal and external faults, resulting in huge production loss in the industrial process.

To solve these critical issues, multicell VSC such as cascaded H-bridge, neutral-point-clamped (NPC), and flying capacitor (FC) topologies have been recommended in the literature review [4]. However, the main drawback of these topologies is the lack of modularity, such that a large number of series-connected power switches are needed for HVDC applications. Therefore, the cost and overall complexity of system design are increased.

The VSC technology is now in its fourth generation using MMC, which was introduced by Lesnicar and Marquardt in 2001 [1], as shown in Figure 3.

MMC has been recognised as invincible topology for high-power and medium/high-voltage applications [30]. The modularity and scalability features of MMC make it an attractive topology for HVDC applications. Combining smaller subsystems to make a large system is generally known as modularity. In MMC, hundreds of converter cells such as half-bridge and full-bridge cells are cascaded to achieve desired voltage ratings. The modularity of MMC targeting HVDC application in depth is reviewed in [4]. The MMC has several other benefits as compared to two-level VSCs and different converter topologies such as reduced  $dv/dt$  and  $di/dt$  stress on switches, improved power quality and

lower THD without the need for any filter, fault tolerance and inherent fault blocking capability, lower switching frequency, and power losses. MMC has become the basic building block of HVDC and MTDC systems with these salient features. MMC-based HVDC system is shown in Figure 4.

MMC is one of the most promising technologies for MTDC grids. Over the past years, several studies have been conducted to address technical issues and challenges for MMC-based MTDC grids. This paper presents a comprehensive review of the recent development of MMC topologies. The other main contribution of this paper is to provide a detailed systematic review of MMC modelling techniques. Section 2 discusses MMC-based HVDC/MTDC projects worldwide. In Section 3, recent developments in MMC in terms of the SM configurations are reviewed comprehensively. Section 4 presents an in-depth review of modelling issues and challenges of MMC for MTDC grids. Associated research challenges and future trends are presented in Section 5. Section 6 concludes the paper's outcomes.

## 2. Developments of MMC-Based HVDC/MTDC Systems Worldwide

At present, the debate is not about the selection between AC and DC but how to best integrate both systems. The AC and DC systems can be best integrated using MTDC systems. The successful implementation of point to point HVDC systems suggested the concept of the MTDC system. MTDC system can potentially improve the reliability of the AC and DC systems and enhance flexibility and economy of power by

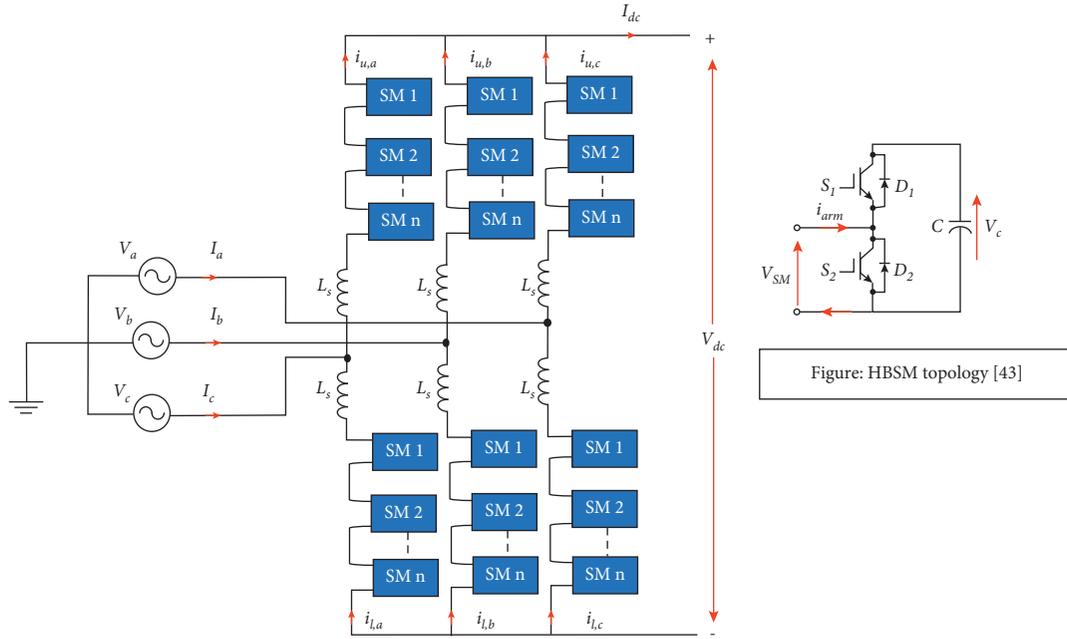


FIGURE 3: Three-phase MMC-HVDC with HBSM topology.

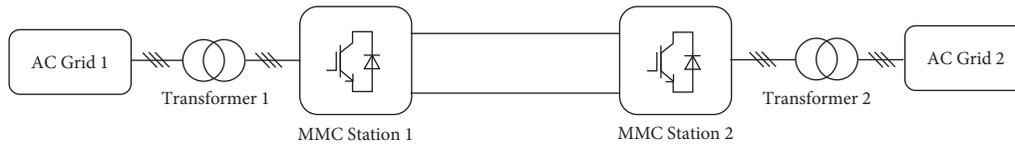


FIGURE 4: MMC-based HVDC system.

interconnecting multiple converters through the DC transmission network [31]. MTDC systems can be classified into three types: radial connected MTDC system, meshed or ring MTDC system, and series-connected MTDC system [6]. The converter station is connected to a single DC line in radial MTDC grids. Each converter station is connected to more than one DC line in meshed MTDC system, whereas all the converter stations are connected in series for the series-connected MTDC system. The proliferation of HVDC systems has opened the opportunity for interconnecting different HVDC systems forming HVDC Supergrids [32]. Plains and Eastern Clean Line project proposes North American Supergrid (NAS) concept, integrating 52-node HVDC connection throughout the 48 states [33, 34]. The future of this technology is expected to be possible developments of continental and intercontinental Supergrids. Continental Supergrids can be considered futuristic and are expected to happen in 15 years from today. Continental Euro-African Supergrid is under consideration, which can benefit the European grid by taking advantage of solar potential in North Africa. The future transformation of HVDC systems is reviewed in detail by [7]. Table 1 provides details of a few of the projects installed worldwide.

### 3. Developments of MMC Circuit Topologies

MMC is the basic building block of MTDC grids. New enhanced MMC topologies need to be explored to develop

MMC-based MTDC systems. MMC characteristics such as control flexibility, DC fault blocking capacity, and power switching losses are decided by the type of SM configuration.

The cell is the basic building block of any MMC topology. Generally, MMC can be implemented using unipolar cells (half bridge), symmetrical bipolar cells (full bridge), and asymmetrical bipolar cells (hybrid cells) [35–39]. The unipolar cell can generate two-level output voltages such as HB and can generate multilevel output voltage such as neutral-point-clamped (NPC) cells [1, 4]. Unipolar cells such as HB have a simpler structure, fewer switches, reduced switching losses, higher efficiency, and lower cost, as shown in Figure 5(a).

However, unipolar cells have characteristics and limitations similar to those of HB, such that they cannot block fault currents during short-circuit DC pole to pole fault [4]. The equivalent circuit of the HBMMC during a DC short-circuit fault is shown in Figure 6. Therefore, MMC based on unipolar cells must have additional protections against such faults.

The variant of HBSM topology referred to as self-balancing submodule (SBSM) is presented in [40, 41]. It can automatically balance the capacitor voltage without any need for a voltage balance algorithm. This topology consists of HBSM with an inductor and a diode, as shown in Figure 5(b). Another variant of HBSM known as a clamp-single submodule (CSSM) is proposed in [42]. This topology

TABLE 1: MMC-based HVDC/MTDC projects installed worldwide.

S. no.	Project name and country	Rated capacity (MW)	Rated DC voltage (kV)	No. of terminals	Commissioning year
1	Zhoushan, China [1]	1000	$\pm 200$	5	2014
2	Nanao, China [1]	200	$\pm 160$	3	2015
3	Zhangbei, China [1]	3000	$\pm 500$	4	2020 (under construction)
4	Trans Bay Cable, USA [1]	400	$\pm 200$	2	2010
5	Nanhui, China [1]	18	$\pm 30$	2	2011
6	BorWin3, Germany [1]	900	$\pm 320$	2	2019
7	Chongqing-Hubei, China [1]	2500	$\pm 420$	2	2016
8	Luxi, China [1]	1000	$\pm 350$	2	2016
9	HelWin2, Germany [1]	690	$\pm 320$	2	2015
10	Xiamen China [1]	1000	$\pm 320$	2	2015
11	COBRACable, between Denmark (Endrup) and Netherlands (Eemshaven) [16]	700	$\pm 320$	2	2019
12	North Sea Link [16] (between Norway and the United Kingdom)	1400	$\pm 525$	2	2021
13	Caithness, Scotland [124]	1200	$\pm 320$	3	2018
14	BorWin1, Germany [16]	400	$\pm 150$	2	2011
15	BorWin2, Germany [16]	800	$\pm 300$	2	2015
16	DolWin1, Germany [16]	800	$\pm 320$	2	2015
17	DolWin2, Germany [16]	916	$\pm 320$	2	2016
18	DolWin3, Germany [16]	900	$\pm 320$	2	2017
19	HelWin1, Germany [16]	576	$\pm 250$	2	2015
20	HelWin2, Germany [16]	690	$\pm 320$	2	2015
21	SylWin, Germany [16]	864	$\pm 320$	2	2015
22	INELFE, Santa Llogaia (Spain) and Baixas (France) [16]	2000	$\pm 320$	2	2015
23	Skagerrak Pole 4, Tjele (Denmark) and Kristiansand (Norway) [16]	700	$\pm 500$	2	2014
24	Sydvestlanken [5], Sweden and Norway	1440	$\pm 300$	2	Expected to complete in 2021
25	Dalian City, China [122]	1000	$\pm 320$	2	Under construction
26	AWC, USA [125]	700	$\pm 320$	3	Expected to complete in 2021
27	ULTRANET, Germany [125]	2000	$\pm 380$	3	2019

improves resilience to DC fault and suppresses the fault current. CSSM has two kinds of configuration, as shown in Figures 5(c) and 5(d), and is made up of HBSM incorporated with a transistor and a diode. In case of a DC short-circuit fault, all transistors are turned off to avoid fault current. Otherwise, during normal operation, S3 is turned on. Another approach to improve DC fault blocking capacity is to use thyristors with the HBSM as proposed in [43]. A single thyristor or double thyristor may be used with HBSM, as shown in Figures 5(e) and 5(f). The fault current flows through thyristors in DC pole to pole fault. However, during normal operations, thyristors are turned off. The proposed variants of HBSM may be preferred over FBSM due to their lower cost and less switching losses. Storage capacitor has a large impact on the overall footprint and weight of the MMC converter. Therefore stacked switch capacitor, as shown in Figure 7(a), having three capacitors C1, C2, and C3 used as an energy buffers, is proposed in [44]. This topology has a 40% reduced volume as compared to HBSM. A clamp-double submodule (CDSM) contains two similar HBSMs connected by two extra diodes and an IGBT, as shown in Figure 7(b) [45]. It can produce three-level voltage:

$V_{C1} + V_{C2}$ ,  $V_{C1}/V_{C2}$ , and zero. All the switches are turned off during DC short-circuit fault. However, CDSM may not be preferred due to increased losses as all the switches are turned on during normal operation. FB and five-level cross-connected cells are referred to as symmetrical bipolar cells, as shown in Figures 7(c) and 7(d), respectively. They produce an equal number of positive and negative voltages such that FB produces three levels ( $V_C$ , 0,  $-V_C$ ) and five-level cross-connected submodule (CCSM) produces five levels ( $2V_C$ ,  $V_C$ , 0,  $-2V_C$ ,  $-V_C$ ). Five-level cross-connected SM consists of two HBSMs connected back to back via two IGBTs with antiparallel diodes [46]. It can generate five levels:  $\pm(V_{C1} + V_{C2})$ ,  $\pm V_{C1}/\pm V_{C2}$ , and zero. The DC fault current may be avoided by turning off crossed transistors S5 and S6 at the cost of increased power losses. MMCs realised with symmetrical bipolar cells offer similar attributes and advantages to those of FB such as greater control flexibility and DC fault ride-through at the cost of higher switching losses than unipolar and asymmetrical bipolar cells. Moreover, they offer bipolar DC voltage operation; hence, power reversal is possible either by the DC voltage or by the current [47].

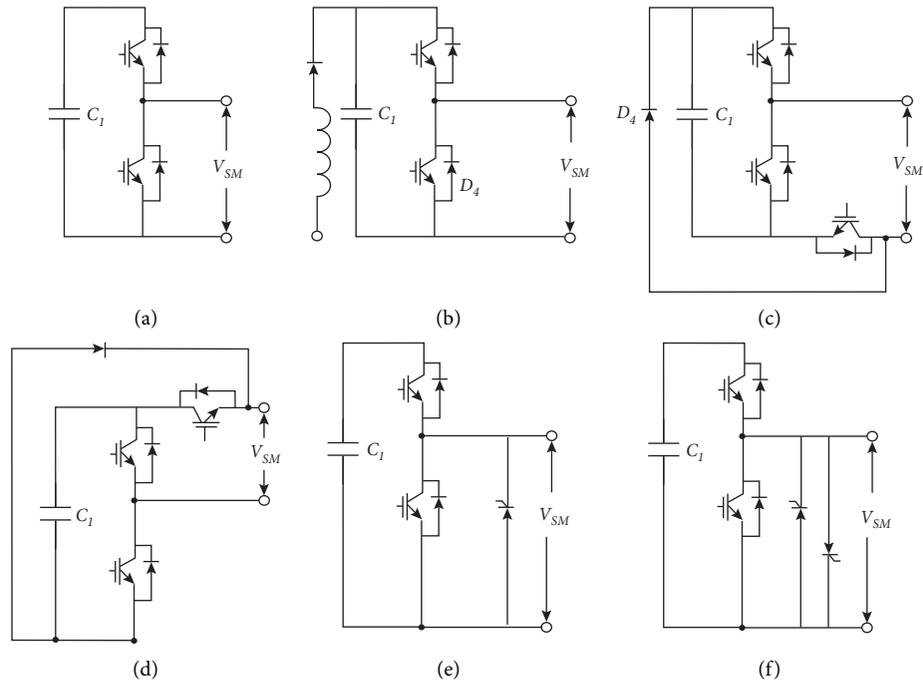


FIGURE 5: Two-level submodule topologies: (a) half-bridge submodule (HBSM); (b) self-balancing submodule (SBSM); (c) clamp-single submodule (CSSM) type I; (d) CSSM type II; (e) single-thyristor HBSM; (f) double thyristor.

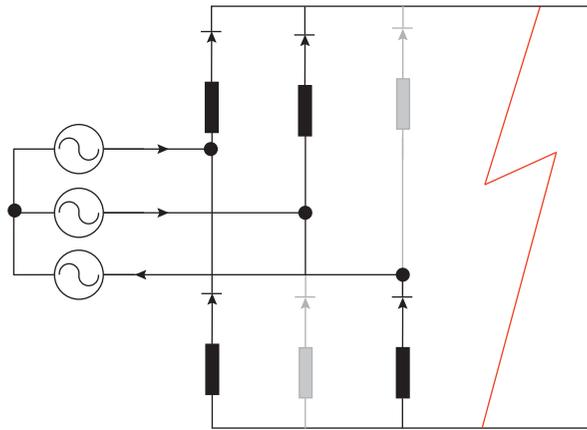


FIGURE 6: The equivalent circuit of the MMC during a DC side short-circuit fault.

Therefore, the main motivation is to use MMC with bipolar symmetrical cells along with the LCC in futuristic MTDC grids. Asymmetrical bipolar cells, also known as hybrid cells, are a mixed combination of FB and HB cells [48]. They generate an unequal number of positive and negative voltage levels and combine the inherent benefits and features of both unipolar and bipolar cells [49, 50]. Therefore, they offer resilience to DC short-circuit fault and improved efficiency. Mixed cell MMC (MC-MMC) uses asymmetrical bipolar cells [39]. Comparison of different cell configurations in terms of voltage levels, switching losses, and DC fault blocking capacity is provided in Table 2.

There are two established realisations of MMC in literature. The first approach prefers a larger number of submodules per arm, where the rating of switches and

capacitors is relatively small (1.5 KV–3 KV) [51]. This approach is adopted in many MMC-based HVDC projects worldwide and offers better AC and DC power quality. Moreover, filter requirements are eliminated, and reliable operation is ensured by bypassing faulty cells. Fundamental switching frequency techniques such as nearest voltage level modulation (NLM) are recommended for this approach, hence having lower switching losses. However, such an approach increases the overall complexity of the system, and implementation of the PWM controller becomes difficult. The second approach requires a reduced number of submodules per arm, with each cell rating ranging between 16 KV and 20 KV [52]. The second approach looks attractive as it reduces the overall complexity and size of the converter but at the cost of compromised AC and DC power quality

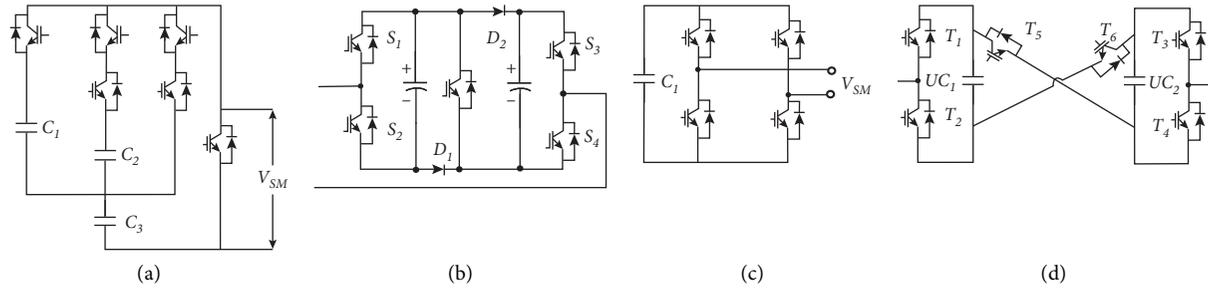


FIGURE 7: Multilevel submodule topologies: (a) stacked switched capacitor submodule (SSCSM); (b) clamp-double submodule (CDSM); (c) full-bridge structure (FBSM); (d) five-level cross-connected submodule (CCSM).

TABLE 2: Comparison of various SM circuits.

SM circuit	Voltage levels	DC short-circuit fault ride-through capability	Power losses
Half-bridge SM	$0, V_C$	No	Low
Full-bridge SM	$0, \pm V_C$	Yes	High
Five-level cross-connected SM	$0, V_{C1}, V_{C2}, \pm(V_{C1} + V_{C2})$	Yes	Moderate
Clamp-double SM	$0, V_{C1}, V_{C2}, (V_{C1} + V_{C2})$	Yes	Moderate
Three-level neutral-point-clamped cells	$0, V_{C2}, (V_{C1} + V_{C2})$	No	Moderate
Three-level flying capacitor	$0, V_{C1}, V_{C2}, (V_{C1} - V_{C2})$	No	Low

[53]. Moreover, the second approach causes significant errors in common-mode voltages, resulting in high-frequency ripples in DC side voltage and current, and hence requires DC filters [54]. Furthermore, it introduces poor output AC power quality and relatively high-frequency circulating components in arm currents. Hence, an AC side filter and relatively large arm inductors are required to enhance power quality and suppress circulating currents. Another limitation of the second approach is that most manufacturers lack the expertise of driving medium-voltage cells.

Besides, MMC is being implemented using either symmetrical or asymmetrical cells. Further optimisation can also be done by mixing different types of cells, resulting in hybrid multilevel converters [55]. Industry and academia have proposed hybrid converter topologies in the last two decades to improve specific aspects of MMC performance such as DC fault blocking capability, footprint, and efficiency [56–61]. Hybrid converters are classified into two groups. The first group, called MC-MMC, is the most invincible topology [62]. It holds salient features of conventional MMC, such as modularity and bypassed operation of faulty cells, to ensure continuous operation. Besides these benefits, it also offers custom-made features such as bespoke control flexibility and DC fault ride-through capability at the cost of increased switching losses. The second group, referred to as alternate arm converter and hybrid cascaded two-level converter, use symmetrical cells (FB cells) and integrate director switches operating at very low frequency [63–65]. They offer fault blocking capacity, bipolar DC voltage operation, and switching losses similar to HBMMC. However, the second group lack modularity and reduced power quality. Therefore, a filter may be required.

Some researchers have proposed hybrid VSC, as shown in Figure 8, where both two-level converter and MMC have

been combined [64, 65]. Hybrid VSC combines soft switched H-bridge converters, MMC cells, and H-bridge converters consisting of series IGBTs to meet voltage rating requirements at the fundamental frequency.

MMC cells used in hybrid VSC are mainly used for wave-shaping function and can only handle a part of the main line current. Therefore, the limitation of hybrid VSC is a lower rating. The motivation for this combination of converters is to reduce power losses and reduce harmonics while ensuring compact design. Due to MMC cells' presence, the need for a filter at the AC side may be eliminated. Moreover, MMC cells (FB) may not produce enough negative voltages to block fault current in the case of DC pole to pole fault. In the last year, 2020, enhanced MMC (EMMC) having reduced number of submodules and THD was proposed as shown in Figure 9 [66–68]. The proposed hybrid topology utilises both HB cells of medium-voltage and FB cells of low voltage. The conventional MMC generates  $N+1$  levels for  $N$  submodules per arm, whereas recently modified NLM control has been proposed for HBMMC to achieve  $2N+1$  levels [69–72]. The modified NLM control method has been further extended in an article to achieve  $4N+1$  levels for HBMMC [71]. Modified NLM may be further investigated and applied to FBMMC and other cell arrangements to generate  $4N+1$  levels. It should be noted that EMMC is the most attractive topology and produces  $2N_{HB} - N_{FB} + 1$  levels [66–68].

It is concluded that conventional MMC requires 400 HB cells to produce 401 levels, whereas EMMC uses 40 HB medium-voltage cells and 5 FB low-voltage cells to generate 401 levels. Therefore, EMMC improves power quality at the AC and DC sides and reduces power circuit and control complexity compared to conventional MMC. It should be noted that the proposed EMMC does not have DC fault blocking capacity as negative voltage produced by FB cells is not sufficient for blocking DC fault currents [68]. DC fault

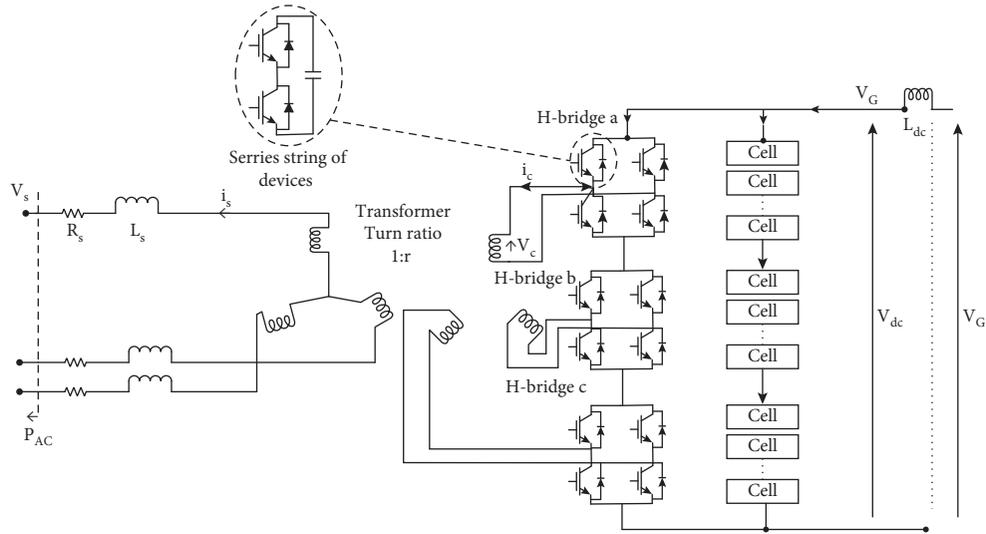


FIGURE 8: Short-term measures of resilience.

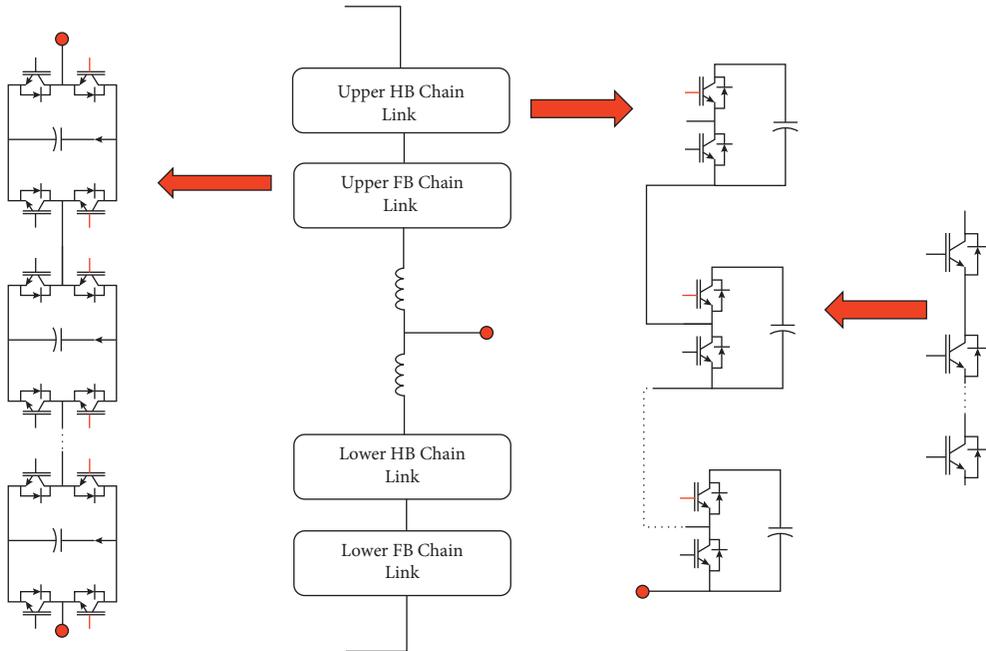


FIGURE 9: EMMC topology.

ride-through capability and control flexibility are decided by the ratio of FB cells to HB cells. Considering this ratio as an important factor, an extension of EMMC referred to as EMMC0 has been proposed in [66]. EMMC0 produces 401 levels, consisting of 30 high-voltage chain links (HB) and 100 low-voltage chain links (FB). EMMC0 can be a viable alternative to EMMC and possesses DC fault ride-through capability. High-level summary is presented in Table 3. In future, there is room to explore enhanced and new MMC topologies for MTDC grids.

#### 4. Modelling Issues and Challenges of MMC for MTDC Grids

MMC-based MTDC projects are growing faster worldwide [6]. It must be noted that the dynamics of the HVDC system are totally different due to the presence of DC circuit breakers and converters compared to HVAC. Power converters in MTDC have a time response that can be several orders of magnitude faster than that of its counterpart synchronous generator in HVAC due to lack of mechanical

TABLE 3: Comparison of HBMMC, EMMC, MC-MMC, and EMMC0.

Performance index	HBMMC 40 cells	HBMMC 400 cells	EMMC $N_{HVCL} = 30$ $N_{LVCL} = 5$	MC-MMC $N_{HVCL} = 30$ $N_{LVCL} = 10$	MC-MMC $N_{HVCL} = 300$ $N_{LVCL} = 100$	EMMC0 $N_{HVCL} = 30$ $N_{LVCL} = 100$
Number of voltage levels per arm	41	401	401	41	401	401
Power circuit and control complexity	Low	High	Moderate	Medium	Medium	Moderate
DC voltage and current ripples	Low	High	Moderate	Medium	Medium	Moderate
AC fault ride-through	Yes	Yes	Yes	Yes	Yes	Yes
DC fault ride-through	No	No	No	Yes	Yes	Yes

inertia and customised control abilities. Power converters are operating at a high switching frequency, and therefore they are characterised by discontinuous dynamic equations, which are difficult to analyse and model. Therefore, MMC-based MTDC systems' modelling needs to be reevaluated to accurately replicate the actual system behaviour. It should be noted that modelling issues and challenges will vary for different topologies of MMC discussed in Section 2. The dynamic behaviour of the MTDC system is discussed in [5, 6, 73].

Power system software has been classified into three types: electromagnetic transient (EMT) simulation techniques, electromechanical stability programs, and steady-state power flow programs. Switching is the fundamental operation of power converters and causes transients in the system. Therefore, EMT type solvers are recommended for simulations of power converters such as MMC [24, 74]. Steady-state power flow programs are preferred to study systems after all transients have damped out. Electromechanical stability programs are used to simulate very complex power systems, in which phasors represent AC power systems.

Despite several proposed MMC modelling techniques, the literature lacks an in-depth comparison of these models. Therefore, adequate MMC modelling techniques should be selected based on specific simulation objectives. Modelling of large scale MTDC system using unipolar, bipolar, and asymmetrical cells as SMs in MMC, with hundreds of cells, hundreds of levels, and thousands of IGBTs, is referred to as detailed switch modelling [75–77]. Detailed switch models (DSMs) represent actual converter behaviour, switching dynamics, and electromagnetic transients [78]. Therefore, they are the most accurate and used as reference models for comparison with other models. However, thousands of IGBTs in MMC–MTDC models increase the computational burden and require small integration steps to replicate fast switching operations accurately. DSMs best fit the targeted applications and studies at the component levels, such as component (switches) optimisation, electromagnetic compatibility (EMC) validation, switching and conduction losses calculation, blocked states, power MMC start-up procedures, and internal converter faults. Due to increased simulation times and high computation burden for EMT solver, these models are not applicable for large power system studies such as MMC-based MTDC networks.

Moreover, another limitation of DSMs is that intensive knowledge about MMC topology (down to component level) is needed, and such information can only be provided by the converter manufacturer [73]. To overcome these limitations of DSMs, simplified and more efficient yet reasonably accurate models are proposed by researchers to accelerate EMT simulation.

As per CIGRE technical report, modelling approaches are classified into seven types [79, 80]. Type 1 is called full physics-based models, where both switches and diodes are represented by either differential equations or an equivalent circuit, as shown in Figure 10(a) [81]. The full physics-based model for MMC is infeasible for grid studies due to the increased computational burden and simulation times. Type 2 is referred to as the full detailed model. These models are based on simplified nonlinear IGBT models [80, 82, 83]. IGBTs are replicated using an ideal controlled switch, and two nonideal diodes are represented using nonlinear resistance, as shown in Figure 10(b) [81].

Type 2 can represent every possible state of HBSMs and FBSMs but cannot calculate switching losses. Only type 1 can be used for estimating converter losses. Type 3 model is based on simplified switchable resistances. The only difference between type 2 and type 3 models is how power semiconductor devices are replicated. In type 3, two resistors represent IGBTs and diodes: a tiny resistor ( $m\Omega$ ) for turn-on state and one large value resistor ( $M\Omega$ ) for turn-off state. Type 3 considers only the turn-on and turn-off state but not the transient state [80, 81]. Therefore, simulation times are reduced compared to type 2, yet a large number of electrical nodes complicate the EMT solver. EMT equivalent representation for lumped elements of type 3 is represented as shown in Figure 10(c) and is known as detailed ideal model (DIM) [81]. These three types of models use the nodal admittance method on the EMT simulation tool. Types 2 and 3 are primarily used for targeted applications and studies such as a reference model to validate simplified models and analyse faults in SMs in MMC.

Few researchers have proposed an isolated submodule (ISM) model that uses a modified nodal admittance method [84–86]. This approach models each SM as a separate subsystem and thus requires an individual system matrix, as shown in Figure 10(d) [81]. Therefore, computational efficiency is improved and enables parallel processing of sub-modules (SMs) instead of solving one large matrix as in the

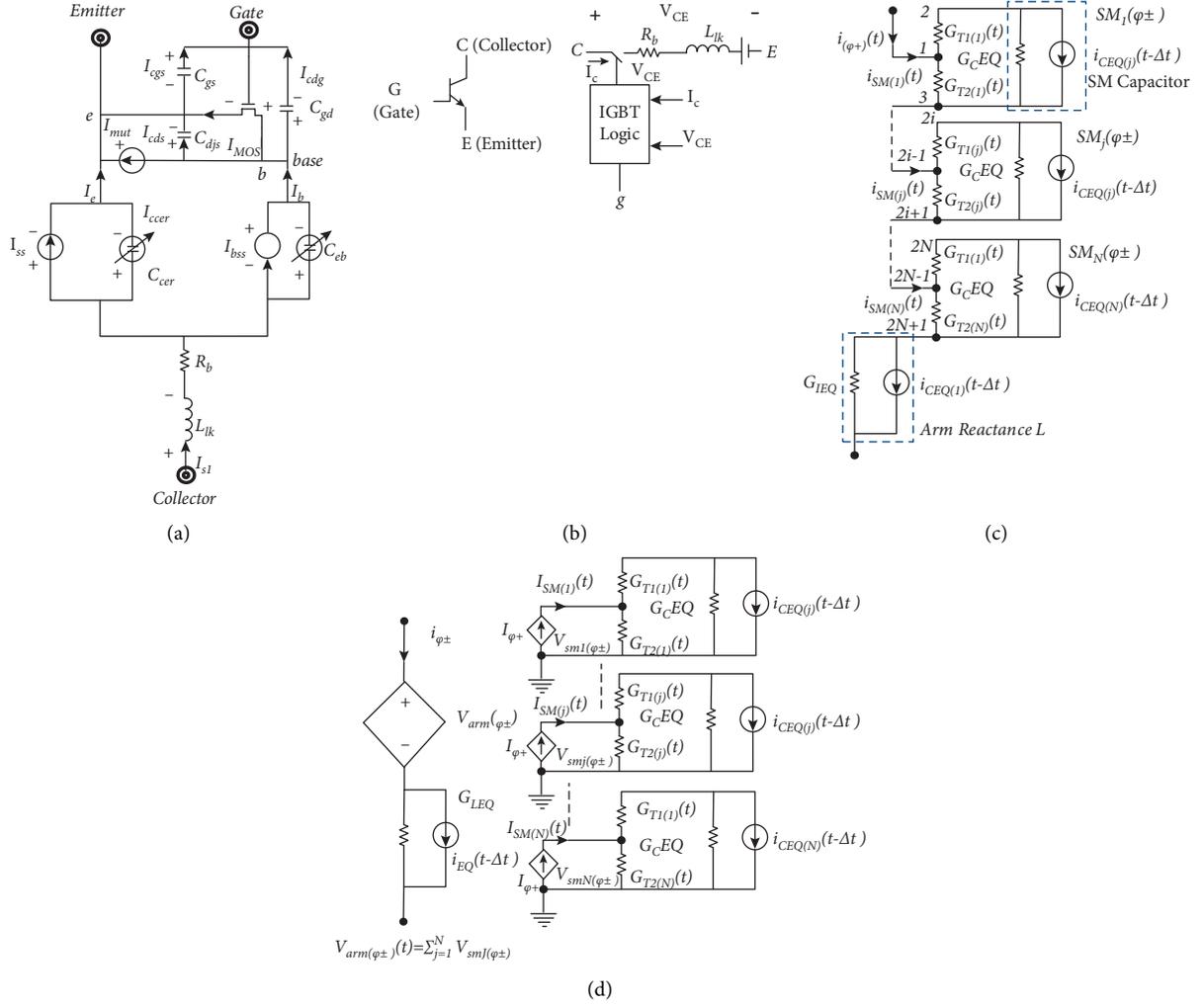


FIGURE 10: CIGRE modelling approaches: (a) physics-based model for IGBT; (b) full detailed model; (c) detailed ideal model; (d) ISM-equivalent representation of an arm.

previous three types. However, due to the large number of SMs used and fast switching frequency, the aforementioned model is unsuitable for real-time simulations. Individual SMs can be accessed in this modelling approach, and therefore it is feasible to analyse internal faults.

Type 4, known as detailed equivalent circuit models (ECM), is used further to reduce the computational burden and number of electrical nodes, thereby increasing simulation speed [87, 88]. Based on this approach, the arm Thevenin equivalent model (EIM) is proposed in [87, 88]. It offers a fast simulation method by modelling all SMs in an arm by its equivalent, Thevenin or Norton. This modelling approach uses algebraic relations to represent the internal dynamics of an arm instead of the computationally intensive nodal admittance method. Based on this approach, equivalent representations of  $N$  SMs of MMC arm are shown in Figure 11(a). Inserted and bypassed states of all SMs is simulated using equivalent Thevenin or Norton subsystem, whereas blocked states are represented using extra diodes and switches. It should be noted that the proposed model has a reduced number of nodes and a reduced computational

burden. Therefore, this modelling approach is the perfect choice for accurate time simulation (hardware in the loop simulation) [89, 90]. However, the accuracy of this model may be a little compromised compared to detailed models, but errors are insignificant for most dynamic studies. Type 4 modelling is recommended for targeted applications such as dynamic and steady-state analysis on the AC and DC side, modelling and tuning low-level controllers such as capacitor balancing algorithms (CBA), and validating average models.

Some of the researchers have proposed switching function model (SFM) [91–94]. SFM replicates the switching behaviour using binary functions. The research work in [91–93] has more computational burden as it uses state-space formulation and is infeasible for fault analysis in the HVDC system. In [94], binary functions are proposed to simulate the individual operation of SMs with better simulation speed and efficiency. The work in [95–97] has improved the SFM by including blocked states of the converter. [81, 97] have realised SFM using generalised blocks from simulation software, as shown in Figure 11(b). SFM allows easier implementation as compared to Thevenin equivalent

representation. Moreover, similar to type 4, SFM enables parallel computation and is feasible for real-time simulations.

Type 4 model, isolated SM model, and SFM are suitable for system-level studies, for analysis of large-signal behaviour of the MMC, SM level control, and PWM schemes. However, type 5 and type 6, referred to as average value model (AVM) and simplified AVM, respectively, may be recommended for targeted applications such as network-level studies, load flow analysis, design of protection relays, stability studies, large-signal analysis of MMC, dynamic analysis such as external faults, and designing and tuning high-level controllers such as DC voltage control. AVM (types 5 and 6) further simplifies MMC representation as converter dynamics are replicated by neglecting switching effects in individual SMs, as shown in Figure 12 [98]. In AVM, the average response of IGBTs, converters, and control is simulated by simplified functions and controlled voltage and current sources [14]. It should be noted that AVM has comparatively better simulation efficiency and reduced computational burden and uses larger integration time steps than all aforementioned models. The distributed arm capacitors of MMC are represented by a lumped capacitor such that the dynamics of all SMs are the same and all the capacitor voltages are equal [81]. Therefore, they are not suitable for studying the internal dynamics of a converter like SMs faults, switching, and conduction losses. The research work presented in [99–110] uses the AVM of MMC.

In [98], 21-level HBMMC-based HVDC system is used to compare three modelling techniques: DSM, detailed ECM, and reduced-order ECM using PSCAD. It has been observed that reduced-order ECM is more efficient and faster. A novel AVM for 401-level MMC-HVDC has been proposed in [14]; it is at least 371 times more efficient and faster than a detailed model without compromising the accuracy. The performance of both models is validated when integrated into a 400 kV transmission system in Europe between France and Spain under different scenarios such as active power flow reversal and AC and DC faults. [24] compares four models for MMC—namely, full detailed model (type 2), ECM (type 4), and SFM and AVM (type 5)—for different practical scenarios such as AC and DC faults, power reference change, and converter start-up. Full DM, ECM, and SFM provide identical results in the case of converter start-up, but the AVM is infeasible for converter start-up study. Finally, it has been concluded that full DM is the most accurate reference model but suffers from the highest computational burden. ECM and SFM offer identical results to those of full DM in all scenarios and has less computational burden as detailed modelling of IGBTs can be avoided. AVM has a good trade-off between accuracy and efficiency. AVM offers almost identical results in all scenarios with a reduced computational burden, but it is infeasible for converter start-up studies. In [111], simplified arm Thevenin equivalent model for hybrid MMCs has been proposed and validated against DM for steady-state and transient conditions (AC and DC faults). It has been observed that the simplified model of hybrid HBMMC and FBMCC offers accurate and 50 times faster simulation time.

DIM is compared with hardware setup in [24, 51, 121]. As a result, it has been found that hardware setup validates the DIM and has reasonable accuracy. Therefore, the DIM has been used as a reference to validate other models in [112–114]. The isolated SM model has been compared in [115]. The detailed model and EIM have been compared against different transient scenarios in [116–118]. The variant of EIM has been compared against the hardware setup in [54]. SFM and AVM have been validated against DM or EIM in the research work by [99, 119]. EIM, SFM, and AVM are validated against DIM in [81] against different cases such as active and reactive power reversal, AC side faults, and DC side faults. As a result, it is concluded that with 14 SMs per arm of MMC, SFM and EIM offer 20 times faster simulation speed than DIM. In contrast, AVM has reduced computational burden comparatively, and the computational burden does not increase with increasing the number of SMs. Moreover, all three models offer good accuracy as compared to DIM. However, AVM is found infeasible for internal dynamic studies of the converter. AVM has compromised accuracy compared to detailed ECM, especially under blocked mode. Therefore, a fast, efficient model referred to as the arm equivalence model (AEM) is proposed [120]. AEM gives identical results compared to detailed ECM in both deblocked and blocked mode for dynamic studies. Similar to AVM, simulation speed does not depend on the number of SMs in AEM. However, AEM is 45% slower than AVM [120]. Hybrid cascaded multilevel converters (HCMCs) are emerging converter technologies for HVDC/MTDC systems. Several fast and efficient AVMs have been proposed recently for HCMCs and validated against detailed equivalent models for dynamic transients in [121]. Moreover, a combined model that allows users to select between the AVMs and detailed equivalent models depending on simulation objectives is suggested. Table 4 presents high-level summary of all aforementioned models. MMC model evaluation in decreasing complexity is shown in Figure 13 [24].

## 5. Future Trends and Challenges

Several enhanced and attractive MMC circuit configurations have been suggested. However, there is room for the development of novel MMC topologies that allow better efficiency, better power quality, bespoke control range, reduced volume, and DC fault resilience. Additionally, it will be essential to ensure that the proposed MMC topologies are highly reliable and work according to installed requirements. Transformerless MMC topologies are desirable and are topics of future research. The transformerless MMC topologies significantly reduce overall cost, weight, volume, system complexity, and losses. Compact MMCs with reduced volume and weight are preferred in some applications such as offshore wind. Therefore, researchers explore advanced MMC configurations that should have reduced volume and weight.

Researchers are also exploring state of the art (advanced) materials for power semiconductor devices to improve converter efficiency and reduce switching losses. Mature

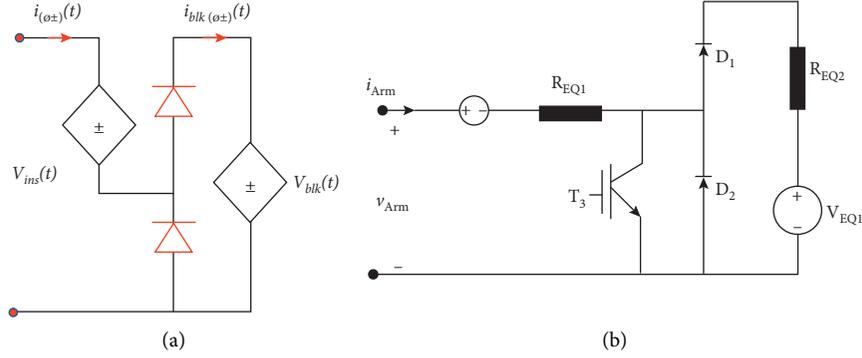


FIGURE 11: Modelling approaches: (a) arm Thevenin equivalent; (b) arm switching function model (SFM) using generic EMT blocks.

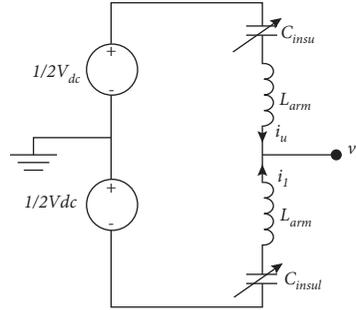


FIGURE 12: The averaged model of the MMC.

TABLE 4: CIGRE modelling approaches for MMC: summary.

Model type	Semiconductor representation	Solution method	Targeted applications
Detailed model (CIGRE types 1 and 2 [81])	Full physics or nonlinear diodes with parasitic elements	Nodal admittance method	Switching losses, component optimisation, and EMC studies
Detailed ideal model (DIM) (CIGRE type 3 [81])	Bi-value resistors	Nodal admittance method	Control and protection system design. Internal and external faults, simplified model validation
Isolated submodule (ISM) model [81]	Bi-value resistors	Nodal admittance method	Control and protection system design. Internal and external faults
Thevenin equivalent model (EIM) (CIGRE type 4) [81]	Bi-value resistors	Algebraic relations to model operation of all SMs individually	Control and protection system design. External faults only. Suitable for real-time simulations with parallel computation
Switching function model (SFM) [81]	Switching functions (0 and 1)	Algebraic relations to model operation of all SMs individually	Control and protection system design. External faults only. Suitable for real-time simulations with parallel computation
Average model (AVM) [81]	Switching harmonics incorporated through discrete value of insertion index	Algebraic relations with single average equivalent module	Load flow analyses, design of protection relays and stability studies. Simulation of terminal dynamics for external faults

wideband gap devices such as silicon carbide (SiC), gallium nitride (GaN), and diamond power devices may be used to enhance converter efficiency and reliability, thereby reducing switching losses and cooling system requirements.

Another critical challenge is the resilience to DC short-circuit fault in the MTDC grids. HBMMC is the dominant topology due to its simpler structure, higher efficiency, and lower cost but cannot block DC fault currents. FBMMC and other symmetrical bipolar cells have DC side fault blocking capacity. Still, these SMs are not considered cost-effective for commercial MTDC

systems due to increased cost and losses [122]. This problem encouraged researchers to research DC circuit breakers (CBs). However, using only DC CBs is also not a cost-effective solution for fault interruption because, in meshed MTDC networks, more DC CBs are required [123]. Therefore, coordination of MMCs with DC CBs seems the best approach for future protection systems of MMC-based MTDC systems. The literature review suggests that coordination strategies proposed need improvement due to higher switching losses and cost [6, 98]. Therefore, there is plenty of room for the development of

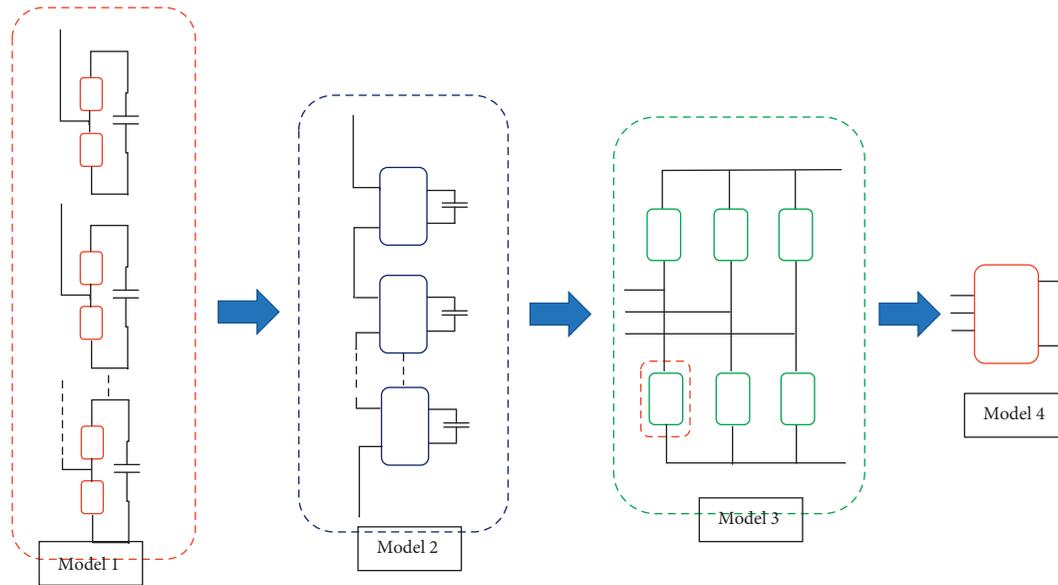


FIGURE 13: MMC model evaluation in decreasing complexity.

a cost-effective coordination method of MMC with DC CBs to address DC short-circuit faults.

Modelling issues and challenges will vary for different topologies of MMC. With the invention of new and enhanced MMC topologies, the need for efficient and accurate models will emerge. MMC-based MTDC systems would transform into the concept of Supergrids in the near future. Moreover, the future of this technology is expected to be possible developments of continental and intercontinental Supergrids. Hence, developing efficient and accurate models will be an important challenge and issue for such a highly hybridised system.

## 6. Conclusions

Modularity and fault blocking capacity features of MMC make it an attractive topology for MTDC applications. This paper presents a detailed review of the recent developments in MMC circuit topologies. Enhanced and novel MMC topologies are discussed with the reduced number of cells and harmonic content, having bespoke features such as DC fault blocking capacity. Moreover, a detailed systematic review of MMC modelling techniques is presented based on specific simulation objectives and studies. Simplified and more efficient yet reasonably accurate models to accelerate EMT simulation speed are discussed. The list of MMC-based MTDC projects installed worldwide is provided.

## Conflicts of Interest

The authors declare no conflicts of interest.

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