Modular Multilevel Converters: Recent Applications [History]

By Gen Li and Jun Liang

The story of the modular multilevel converter (MMC) started with the invention by Prof. Rainer Marquardt in 2001. Since then, this new concept has been recognized as a milestone achievement in power electronics. MMC has revolutionized the capabilities of power conversion technologies, particularly in the high-voltage direct-current (HVDC) transmission system.

MMC is now the most widely recognized type of voltage source converter (VSC) for HVDC because it provides an efficient and flexible alternative to traditional two-level and three-level VSCs. Also, featuring its low switching frequency and harmonic distortion, compact footprint, scalable system design and flexible control, the MMC has gained more traction in areas beyond HVDC, as shown in Figure 1.

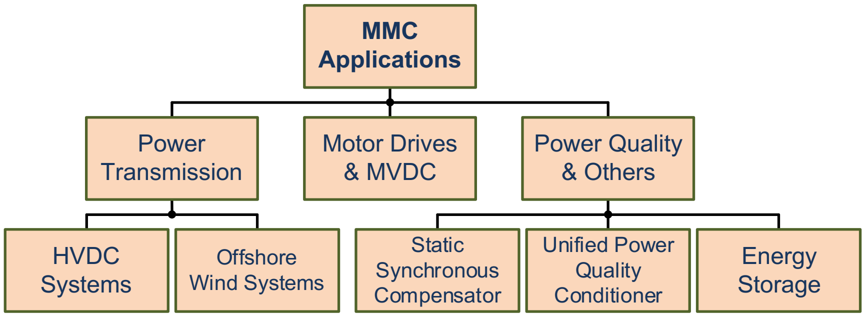


Figure 1 Applications of MMCs.

Power Transmission

Figure 2 shows a typical three-phase MMC. The nature of the MMC is the switching on and off different numbers of the cascaded submodules (SMs) in the arms to produce multilevel voltage waveforms at the AC terminal. In industrial MMC-HVDC, there will be several hundred SMs in each arm to generate a quasi-sinusoidal voltage waveform. Therefore, large AC passive filters are not required. Moreover, the embedded redundant SMs (e.g. 5%-10%) ensure the continuity of operation at full capacity in case of component failures.

Each SM within the MMC is a discrete voltage source with a capacitor holding its output voltage. This modular design realizes the converter's scalability in terms of voltage and current. The half-bridge (HB) and full-bridge (FB) SMs shown in Figure 2 are most commonly used in practical applications. The fully controllable insulated-gate bipolar transistors (IGBTs) are at the heart of the SMs, which enables the MMC to regulate the active and reactive power independently and flexibly.

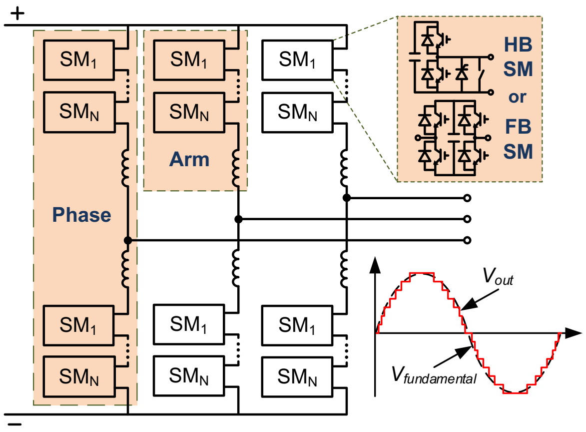


Figure 2 A typical MMC topology.

The HB-MMC has proven its high efficiency and reliability in many MMC-HVDC projects worldwide. The world's first HVDC link using the HB-MMC is the Trans Bay Cable project (± 200 kV / 400 MW) connecting the San Francisco and Pittsburg in California, U.S. It was commissioned in November 2010 and then upgraded to have the black-start capability in 2016. The HB-MMC technology has become more mature in point-to-point, multi-terminal and back-to-back HVDC systems.

The Nan'ao project is the world's first three-terminal MMC-HVDC network (± 160 kV / 240, 120, 63 MW) commissioned in China in December 2013. The first multi-terminal MMC-HVDC network in Europe will be the three-terminal system (± 320 kV / 1200, 800, 600 MW) interconnecting the Shetland Islands and the Scottish mainland by 2024. This network is designed as a five-terminal system for future HVDC extensions. Europe's first back-to-back MMC (± 140 kV / 410 MW) is in the Kriegers Flak Combined Grid Solutions project to integrate the three offshore wind farms called Baltic 1, Baltic 2 and Kriegers Flak and interconnect the asynchronous grids of Denmark and Germany. The project became operational in December 2020.

Due to the attractive features of HB-MMC's low losses, compact design and small footprint, it has been used in many offshore wind HVDC projects. A recent one is the ± 400 kV / 1100 MW Rudong offshore wind MMC-HVDC link commissioned in China in December 2021. The 100 km HVDC link connects three offshore wind farms to the onshore station. It is now the largest offshore wind project in Asia.

As the HB-MMC cannot block the infeeding fault currents from the AC source during a DC fault, an HB-MMC based DC network needs to interrupt DC fault currents by means of DC circuit breakers (DCCBs) or AC side switchgears. The ± 500 kV Zhangbei four-terminal HB-MMC HVDC grid in China is the world's first project that uses DCCBs for overhead DC transmission line fault clearance. The Zhangbei project is in bipolar configuration, in which the largest converter station is of 3000 MW. It was commissioned in June 2020. The 720 km North Sea Link (connecting Norway and UK) commissioned in October 2021 is currently world's longest HB-MMC HVDC (± 515 kV / 1400 MW, bipolar) link using undersea power cable.

In the FB-MMC, the SM capacitors can be inserted into the circuit in either voltage polarity. This gives higher control freedom compared with the HB-MMC. For example, FB-MMC can reduce its DC voltage to zero and even reverse it to negative polarity. In this way, the current control on the AC and DC sides can be maintained even under faults, which makes the FB-MMC suitable for HVDC with overhead DC transmission lines. A DC fault in an FB-MMC HVDC link can be cleared by reverting the DC voltage temporarily for current extinction and electric arc deionization. However, the FB-MMC has some disadvantages limiting its wide applications: its power losses, cost and weight are much higher than the HB-MMC.

The world's first HVDC link that uses the FB-MMC technology is the ULTRANET project in Germany. It's a bipolar FB-MMC link (± 380 kV / 2000 MW) with 340 km DC overhead lines placed on existing AC pylons which are retrofitted to transmit AC and DC power together. The ULTRANET link will be commissioned in 2023, then it will be extended with another 300 km DC cable based FB-MMC HVDC link called A-Nord, which will form Germany's first multi-terminal HVDC system by 2028.

In fact, to achieve the fault blocking capability and at the same time reduce the power losses and cost, many MMC topologies have been proposed in the literature, such as the alternate arm converter (AAC) and clamp-double-submodule (CDSM) based MMC, as shown in Figure 3. Instead of using IGBTs, an MMC based on the integrated-gate commutated thyristors (IGCTs) has been proposed for HVDC applications to improve the efficiency, reliability, voltage rating and largely reduce cost. The hybrid MMC using mixed HB- and FB-SMs can be an alternative for overhead line based HVDC systems. With at least 50% of FB-SMs, it can achieve the DC fault regulating capability with reduced cost and power losses compared to the traditional FB-MMC. However, due to the high cost, complexity and immaturity of those topologies, they are not widely deployed in practical HVDC projects. The HB-MMC is still now dominating the MMC-HVDC market.

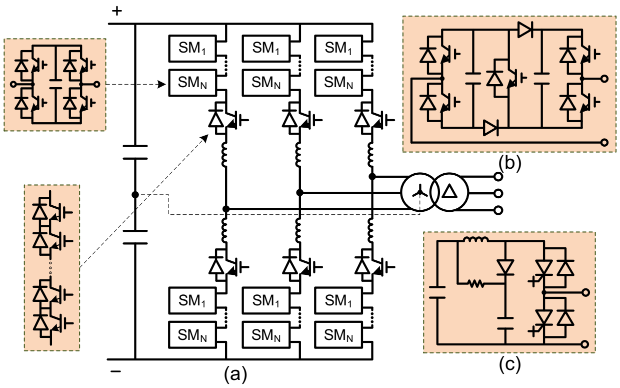


Figure 3 MMCs with alternative topologies. (a) AAC; (b) CDSM; (c) IGCT SM.

Thanks to the intensive research, development and field application of the MMC-HVDC technology, its voltage and capacity have reached the same level as its counterpart the line commutated converter (LCC) based HVDC. Table 1 shows the products of HVDC converter manufacturers worldwide. It can be seen that some suppliers are now able to produce MMCs for ± 800 kV ultra-high-voltage DC (UHVDC) applications. This makes the hybrid LCC/MMC HVDC a promising solution integrating the advantages of the two technologies in terms of capital cost, power losses, control flexibility, fault blocking, etc.

Table 1 HVDC converter manufacturers (Non-Exhaustive)

Manufacturers	LCC	MMC
Hitachi Energy	± 1100 kV, 12 GW	± 640 kV, 3 GW
Siemens Energy	± 800 kV, 10 GW	± 525 kV, 2 GW
GE Grid Solutions	± 800 kV, 6.4 GW	± 525 kV, 2.1 GW

Toshiba	± 500 kV, 1.2 GW	250 kV, 300 MW
Mitsubishi	--	± 500 kV, 1 GW
NR ELECTRIC	± 1100 kV, 12 GW	± 800 kV, 5 GW
RXHK	--	± 800 kV, 5 GW
XUJI Group	± 1100 kV, 12 GW	± 500 kV, 1.5 GW
XD Group	± 1100 kV, 12 GW	± 800 kV, 5 GW
TBEA	± 1100 kV, 12 GW	± 800 kV, 5 GW
NARI Group	± 1100 kV, 12 GW	± 535 kV, 3 GW

The world's first hybrid LCC/MMC HVDC project is the Skagerrak 4 link (500 kV / 700 MW) commissioned in 2015. In this project, the newly built MMC-HVDC link was tied together with the existing Skagerrak 3 LCC-HVDC link to form a bipolar configuration. The MMC link not only boosts the transmission capacity but also mitigates the risk of commutation failures on the nearby LCC through MMC's fast reactive power support. MMC's black-start capability also helps achieve a fast system restoration. Similar technology has been used in the Hokkaido-Honshu HVDC link (250 kV / 300 MW) in Japan, which was commissioned in 2019.

China's Kun-Liu-Long project commissioned in December 2020 is the world's first ± 800 kV hybrid LCC/MMC UHVDC transmission network. It is a three-terminal system in a bipolar configuration, wherein the power sending end is an LCC station with 8000 MW and the two receiving ends are MMCs with 3000 MW and 5000 MW. The MMCs use cascaded low-voltage (LV) and high-voltage (HV) bridges to build up the DC voltage to 800 kV, as shown in Figure 4. Moreover, in each bridge, the hybrid MMC with mixed HB-SMs (30%) and FB-SMs (70%) is used to achieve the DC overhead line fault clearance. The total length of the overhead transmission line is over 1489 km.

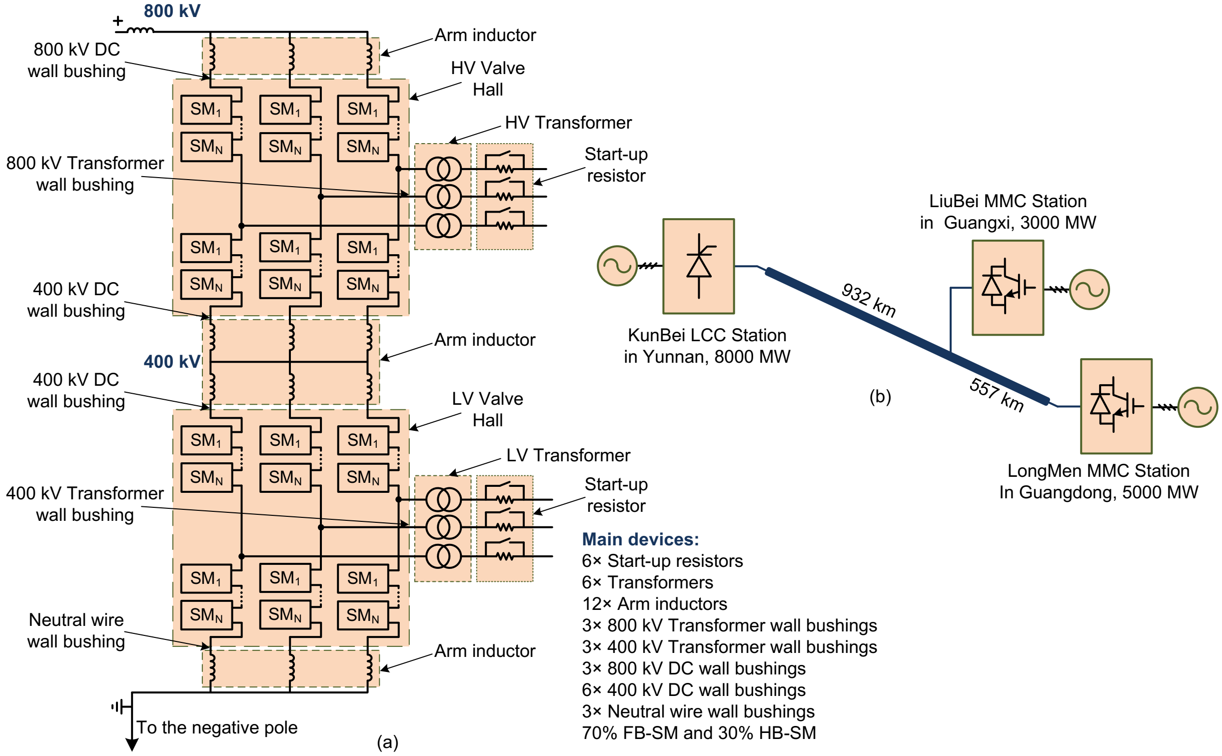


Figure 4 The Kun-Liu-Long hybrid LCC/MMC UHVDC project. (a) Setting of the HV and LV MMC bridges (positive pole); (b) System topology.

The Baihetan-Jiangsu ± 800 kV UHVDC transmission project is another hybrid LCC/MMC UHVDC project under construction in China. The hydropower from the Baihetan station, the world's second-largest hydropower station, will be transmitted over 2100 km to the load center in Jiangsu province. The configuration of this project is depicted in Figure 5. The power sending end is an LCC station with 8000 MW and the receiving end station contains cascaded LCC (4000 MW) and MMCs (3 × 1333 MW). A 12-pulse LCC is used for the HV inverter bridge. The DC terminal voltage of this LCC is 400 kV. There is a common DC bus of 400 kV at LCC's LV terminal which the three parallel-connected HB-MMCs connect to. The LCC and MMCs will be integrated into the 500 kV Jiangsu power grid at different locations. This UHVDC project is planned to be fully commissioned in late 2022.

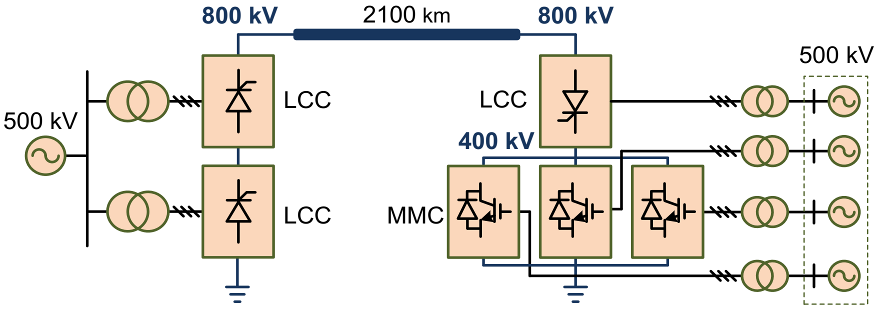


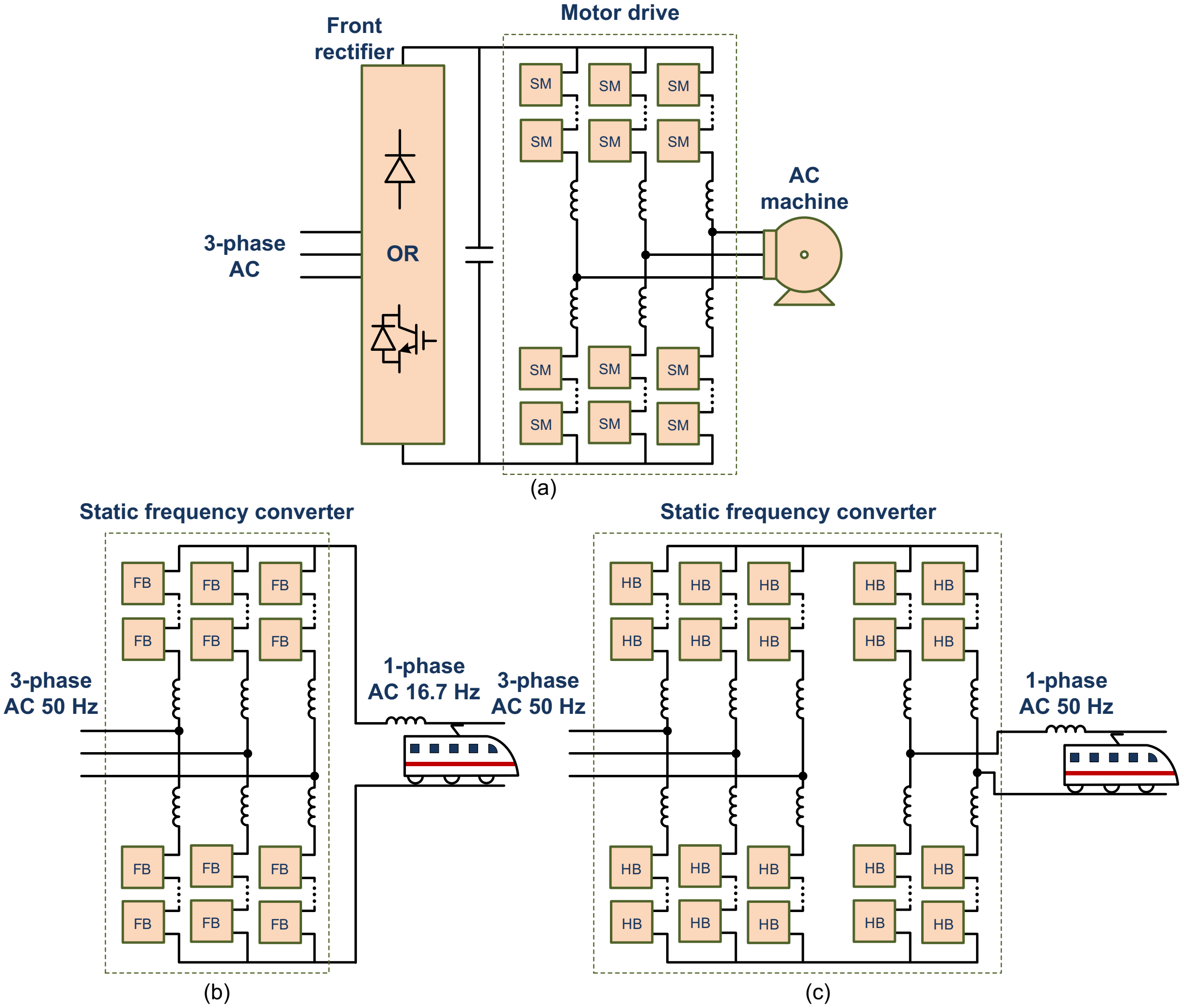
Figure 5 The Baihetan-Jiangsu hybrid LCC/MMC UHVDC project (positive pole).

There are specific concerns about this cascaded LCC/MMC design. One of the most challenging issues is the low multi-infeed effective short-circuit-ratio (MIESCR) caused by the existing multiple LCC-HVDC links located in the Jiangsu power grid. Additionally, several LCC-HVDC links infeeding to the same power region are under construction, which may further exacerbate the MIESCR and therefore may increase the risk of suffering concurrent commutation failure and voltage instability. This is the same concern as the Kun-Liu-Long project. The cascaded LCC/MMC architecture is therefore proposed to relieve the above challenges. The utilization of the LCC in the HV bridge can also reduce the risk of the failure of MMCs which lack operating experience in UHVDC applications. Moreover, due to the DC fault handling capability of the LCC, the proposed system can protect the overhead line from DC faults through proper LCC control. This avoids the use of DCCBs or FB-MMC in UHVDC. Therefore, the HB-MMC is used. The compact design and small station footprint of MMCs allow their deployment in urban areas (load centers).

Motor Drives and MVDC Systems

Due to the salient performance in efficiency and controllability, the MMC has also gained wide interest for medium-voltage (MV) applications, such as the MV motor drives and MVDC systems.

Compared to traditional MV converters for the drive systems, MMC's excellent output voltage control allows it to run with almost any motor. It also does not necessarily need a transformer and output harmonic filters. The modular and redundant configuration of the MMC improves the system's reliability and availability. Therefore, the MMC is suitable for achieving the electrification of the shipboard and aircraft drive systems wherein reliability is a critical concern. Figure 6 shows a typical MMC based motor drive system. The MMC drives the AC machine without using a transformer. The front rectifier can be a diode-based multi-pulse rectifier or a VSC.



(a)

(b)

(c)

Figure 6 MMC machine drives applications. (a) Three-phase motor drive; (b) Direct AC/AC FB-MMC; (c) Indirect AC/DC/AC HB-MMC.

The MMC can also be used as static frequency converters (SFCs) for traction power supply in the electrified railway systems. Figure 6 shows two MMC based SFCs. The three-phase FB-MMC can perform AC/AC conversion for railway power supply systems in a low-frequency e.g. 16.7 Hz. Compared with other VSC based railway power supply systems, the direct AC/AC FB-MMC does not need the expensive and bulky 16.7 Hz transformer and 33 Hz filter. However, this topology needs a frequency separation accompanied by a complex control. The indirect AC/DC/AC MMC consists of a three-phase AC/DC HB-MMC and a single-phase DC/AC HB-MMC. This topology is suitable for 50 Hz railway systems because it will need larger SM capacitors and higher current rating devices on the single-phase part compared to the direct MMC if it is used for 16.7 Hz systems.

Due to the application of the MMC in HVDC, the technology readiness level of MMCs for MVDC systems is in place. The MVDC systems can be viewed as acting in the same way as HVDC, just on a smaller scale and over comparatively shorter distances or at a specific site. The MVDC system can also be a layer connecting the HV and LV systems. Such MVDC systems allow much more flexible ways of grid operation beyond the scope of conventional AC systems by flexible power flow control and hence a more efficient use of renewable energy resources.

Unlike the MMC in VSC-HVDC applications, consensus on using MMC in MVDC hasn't been built. Some initial work has been carried out to select the optimal converters for MVDC systems, considering different converters' reliability, capital cost, power losses, etc. The two-level and three-level VSCs are competitive at a low voltage range, e.g. less than 10 kV. MMCs start to show benefits for the voltage range higher than 10 kV. There have been some pilot projects in field to test the feasibility of MMCs for MVDC distribution networks, as shown in Table 2. However, the selection of MVDC converters still needs to be case-by-case based on the requirements on size, weight, capacity, voltage level, fault protection, etc. There are also other alternative converters for MVDC applications. For example, the cascaded three-level VSC used in the ANGLE-DC project (±27 kV / 33 MW, bipolar) in the UK.

Table 2 Applications of MMCs in MVDC systems

Projects	Year	DC Voltage / kV	Converters
Baolong industrial district, China	2018	± 10, ± 0.375	HB-MMCs and two-level VSC
Guizhou University, China	2018	± 10, ± 0.375	Hybrid MMCs with HB-SM (50%) and FB-SM (50%)
Tangjia Bay, China	2018	± 10, ± 0.375, ± 0.11	HB-MMCs and HB-MMC with IGCT clamp modules
Zhangbei Flexible Substation and AC/DC Distribution Network, China	2018	±10 kV, 0.75	MMCs with CDSM in the power electronic transformers
Suzhou Industrial Park, China	2018	± 20 kV	HB-MMCs

Taking the Tangjia Bay project as an example, as shown in Figure 7, the network consists of three MMCs with capacities of 10 MW, 10 MW and 20 MW. The DC voltage is ±10 kV. The converters in Stations 2&3 are the widely used HB-MMCs. The converter in Station 3 uses an HB-MMC with IGCT based cross-clamped SMs (ICM). The connection between the HB-SM and ICM is shown in Figure 7. The ICMs will be always on during normal operations. They will be blocked if a DC fault is detected to block the AC side infeeding current. Therefore, no DCCB is installed in the DC terminal of MMC1. A dual-active-bridge based DC-DC converters are used in this network to supply DC loads in different DC voltage levels. The project is in Zhuhai China and was commissioned in 2018.

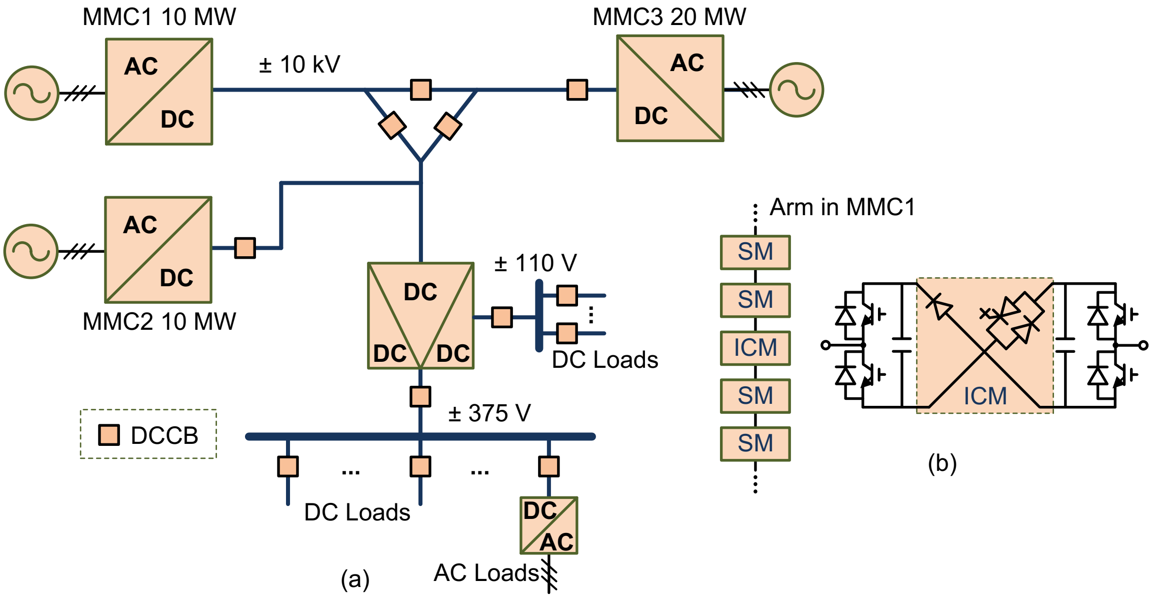


Figure 7 Tangjia Bay MVDC distribution network. (a) System topology; (b) Connection of the ICM.

Power quality and other applications

Another application of MMCs is to build the static synchronous compensator (STATCOM) and unified power quality conditioner (UPQC) to provide reactive power compensation during faults and transient conditions and address the power quality issues (harmonics, distorted and unbalanced voltages).

The ± 75 MVar STATCOM deployed at the East Claydon substation in the UK in 2001 can be considered as the first commercial STATCOM using the MMC configuration (a chain-link topology). The gate turn-off thyristor is used in the H-bridge blocks in the STATCOM. Nowadays, the IGBT based MMC-STATCOM performs much better in efficiency, dynamic responses, modularity and flexibility. They can be installed at distribution and transmission levels. Both HB- and FB-SMs can be used in different converter configurations, as shown in Figure 8. A FB-MMC based STATCOM station built in South Korea in 2018 has reached to ± 400 (3 × ±134) Mvar. The MMC-STATCOM can also be installed with thyristor switched capacitors and thyristor switched reactors to further increase the dynamic reactive power range.

The MMC-UPQC can achieve excellent active filtering functions for distribution networks. The series-connected MMC will be regulated in the AC voltage control mode to support the grid voltage and therefore can address the voltage sag and swell problems. The parallel-connected MMC will be regulated in the current control mode which can provide reactive power compensation, absorb harmonics and control negative-sequence components. Due to the high-quality output voltage waveform of the MMC, the use of the transformer at the parallel MMC can be avoided, which is an advantage for its application in distribution networks.

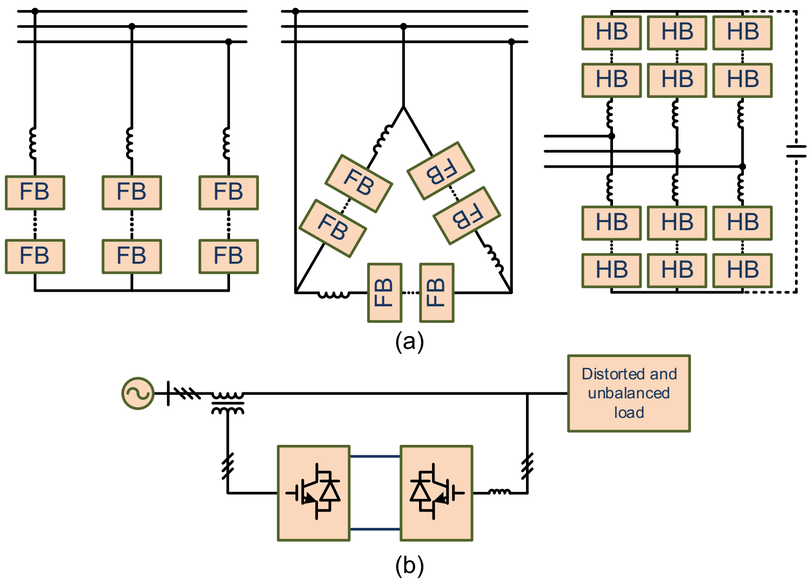


Figure 8 MMC based STATCOM and UPQC. (a) STATCOM configurations; (b) UPQC.

There have been discussions to use the MMC in PV systems. The MMC can be employed as the centralized inverter for large-scale grid-connected PV plants. However, due to the intermittence of the photovoltaic power generation, MMC's DC side voltage needs to be controlled to achieve the maximum power point tracking (MPPT) and the dynamic balancing of the SM capacitors is challenging. Also, considering the high capital cost of the MMC, the traditional two-level and three-level VSCs are still dominating in the MV and LV PV integration. Instead, the PV modules can be connected to each SM directly or through an extra interface (e.g. a DC/DC converter), as shown in Figure 9. However, those kinds of topologies are still under investigation to address their limitations, for instance, the MPPT under partial shading, circulating current control, SM voltage balancing, etc.

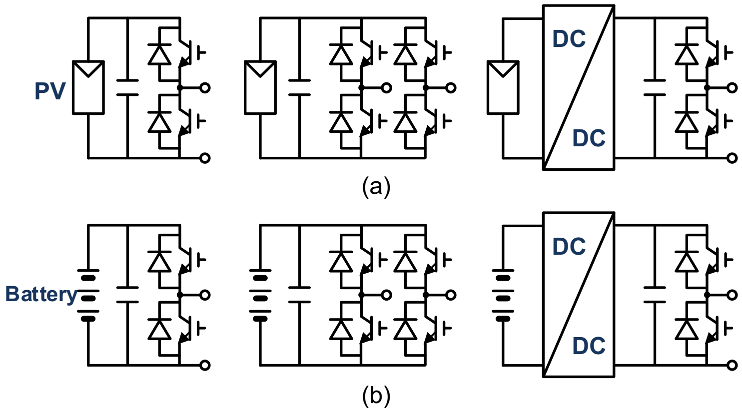


Figure 9 MMC SMs with PV panel and battery. (a) PV embedded SMs; (b) Battery embedded SMs.

The MMC is also an option for the energy storage system. For example, the supercapacitor can be installed in the DC side of an MMC-STATCOM to build the so-called energy storage STATCOM (E-STATCOM), as shown in Figure 8. This device combines the active power compensation capability in STATCOM. The energy stored in the supercapacitor can be released to support the grid during a disturbance. It can emulate system inertia and provide a fast frequency response. Therefore, it is also called a frequency stabilizer. One commercial product has been launched in 2018, which allows ± 50 MW active power for a few seconds and ± 70 MVar reactive power. Similar to the above SM with a PV panel, a battery can also be installed within a SM to form an MMC based battery energy storage system (BESS), as shown in Figure 9. As the SM can be independently regulated, the MMC-BESS features in excellent state-of-charge management of the batteries to avoid overcharge and overdischarge. Therefore, the retired batteries (e.g. from electrical vehicles) can be deployed in such topology. In the literature, some topologies connect the battery/superconductor and PV panel to the SM to mitigate PV's power fluctuation and even supply power at night. Although attempts have been made to realise these SM embedded topologies, more work should be done to increase their technology readiness level.

Conclusion

The MMC is now a very popular technique being used in power systems with a large amount of power electronic interfaces. The recent successful applications in the HVDC, offshore wind, motor drive and STATCOM make the MMC well-placed to expand its industrial applications and commercial products, especially in the medium-voltage levels. To achieve this, their cost, efficiency, reliability, control and fault management should be further investigated. Efforts should also be made to study the use of other devices except for IGBT, such as the wide-bandgap power devices (e.g. silicon carbide and gallium nitride) and IGCT, which may offer new breakthroughs.

For Further Reading

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Prof. Liang is a Fellow of the Institution of Engineering and Technology (IET). He is the Chair of IEEE UK and Ireland Power Electronics Chapter. He is an Editorial Board Member of CSEE JPES. He is an Editor of the IEEE Transactions on Sustainable Energy.