Modular Multilevel Converters an Overview : Basic Concepts, Design and Control along with Applications

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Abstract : ***With the recent upgradation in technology, semiconductors have brought revolution into their usage as dc-dc converters. Tons of research has been carried out for HVDC transmission. Out of all dc-dc converters, Modular Multilevel Converters (MMC) has emerged as an attractive area for research and design in industry due to their modular & easy scalable features, compact space requirement, and control of power flow along with regulation of voltage. The paper here presents an overview of the various fundamental concepts in Modular Multilevel Converters, their control and modulation techniques and applications along with the challenges that are faced during designing.***

Index Terms - Modular Multilevel Converters (MMC), Sub-module (SM), HVDC, Capacitor Voltage Balancing, Circulating Current Control, PWM, SHE.

I. INTRODUCTION

Inclination of technocrats these days indicate Modular Multilevel Converters (MMC) to be a leader and most competing solution for dc-dc converter usage in the area operating at high power and high-voltage levels [1][2]. It is their boosting capability has been attractive and widely used in power conversion applications[3]. The credit to invent MMC goes to Prof. R. Marquardt in 2001. On comparison with the two-level converters, one can observe redundancy of circuits, lesser filter expenses and decrement in semiconductor losses[4]. An important application of this converter topology can be seen in power transmission via HVDC [5]. The summary of characteristics of MMC is discussed in publications such as scalability or modularity and its transformer-less operation in[6][7][8]. These reasons prove an MMC as flexible and most suited converter design that can be very well adopted for different range of voltage and power. Works from the past show various models, adopted topologies and modulation techniques and control schemes, proposed for this converter[9]. This paper aims in providing a thorough review on these converters by discussing appropriately their basic modulation, balancing of capacitor voltage and control techniques, underlying sub-module concepts used, and allowable converter losses which to understand this technology are mandatory. The paper here briefly explains the concepts and key points regarding Modular Multilevel Converters along with additional details present in the references.

II. MODULAR MULTILEVEL CONVERTER (MMC)

Most of the fundamental dc-dc converters transfer unidirectional power, i.e. the input source either supplies the load in generation or absorbs energy during regeneration. The application of this lies in on board loads such as sensors, utilities, and safety equipment. For medium/high power application the converter topology ,i.e. the Voltage- Sourced Converter High-Voltage Direct Current (VSC-HVDC) transmission systems [10]–[12] has made MMC as the most attractive multilevel topology. In an MMC, the determination of sub-modules determines the number of voltage levels. Each sub-module being identical in nature makes it very easy for cascading of more number of SMs incase of higher voltages; also a low THD can be obtained when number of modules used are large.

On the DC line, the requirement of big capacitance is eliminated as each module owns its capacitor bearing rated voltage for its module. The salient features and issues in the MMC are present in Table 1 .

Table 1 – Characteristics of Modular Multilevel Converter

Features	Issues
Modularity and scalability	Large size and large volume
High efficiency	Voltage ripples
Superior harmonic performance	Capacitor voltage balancing
Reduced filter size due to low voltage rating of identical SMs being stacked up.	High inrush currents during charging of a capacitor at converter start or after fault.

III. TOPOLOGY AND MODELING

Figure. 1 shows a schematic representation of a three-phase Modular Multilevel Converter consisting of a series inductor La, two arms in each phase-leg comprising 'x' number of series connected identical sub-modules(SMs). This type of multilevel converter consisting of several sub-modules is therefore named as multilevel modular dc–dc converter(MMC). A PWM converter is generally employed as the basic level of a multilevel converter. The sub-module here is a half-bridge circuit containing a capacitor and two switching devices (generally used is a unidirectional IGBT with an antiparallel diode) that has complementary signals. The upper end arm and lower end arm of three phase-legs of MMC are subscripted as "P" and "N". This sub-module allows for namely two possible voltage levels; (+Vc) or (zero voltage). (+Vc) is the voltage across capacitor and (zero voltage) means capacitor voltage is bypassed; which are both dependent on status of switching. To limit fault and parasitic currents an inductance in arm is required. Based upon sub-module voltage and dc-link voltage, adjustment is made in arm for the number of sub-modules.

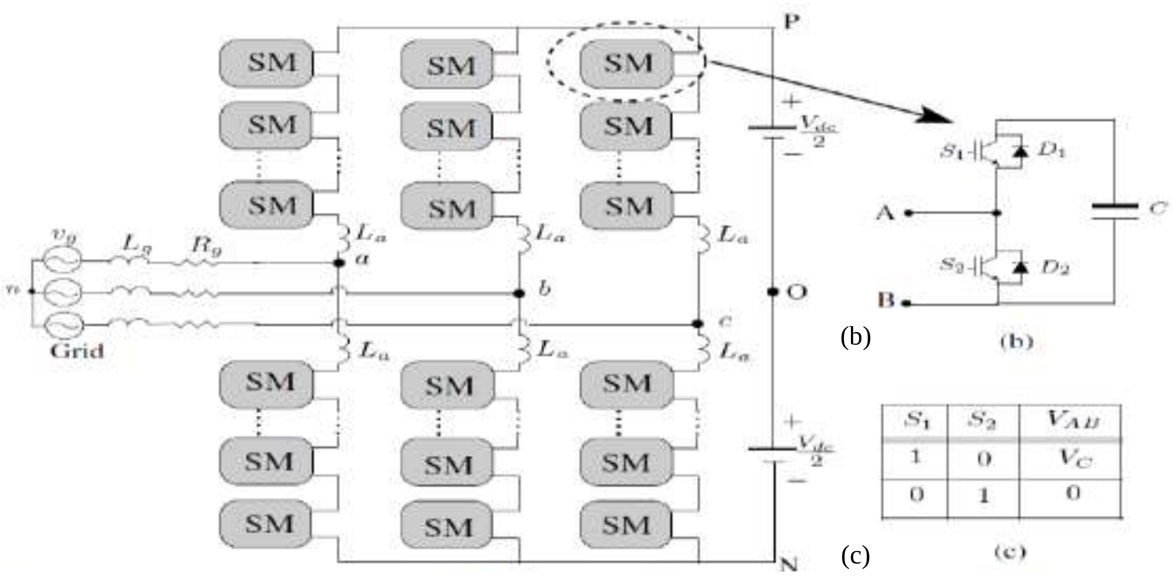
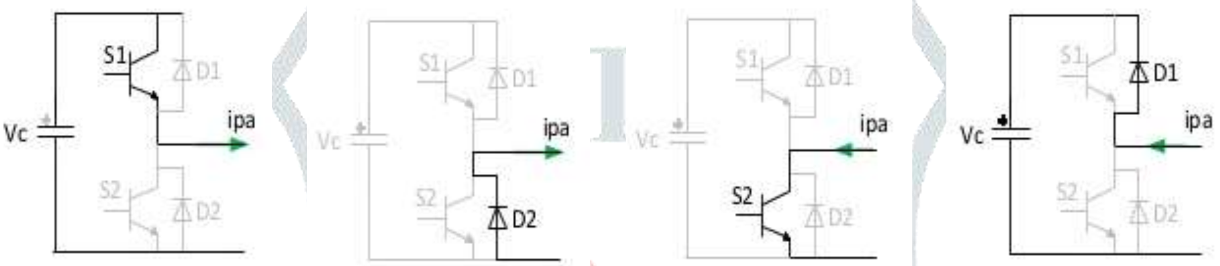


Fig. 1- Schematic representation of MMC: (a) Topology, (b) Sub-module, (c) Switching states



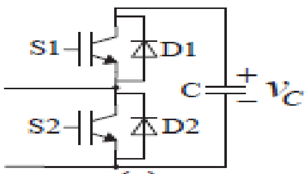
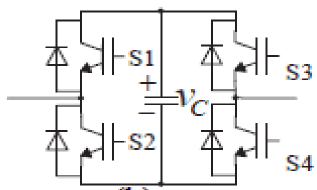
Sub-module inserted Capacitor in discharge mode | Sub-module bypassed | Sub-module bypassed | Sub-module inserted Capacitor in charge mode

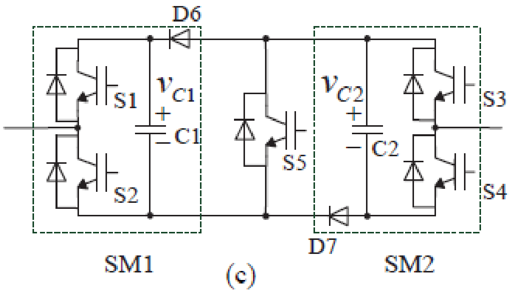
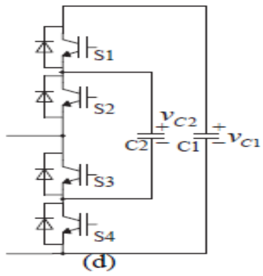
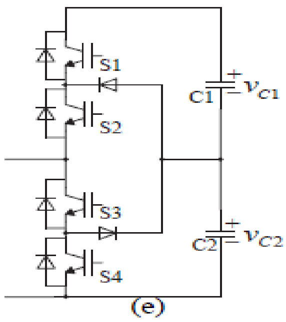
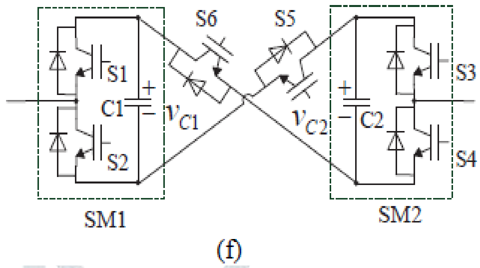
Fig. 2 -MMC Sub-Module Operation

The operating stages of a half-bridge sub-module is shown in fig. 2. Figure. 1 shown sub-module in MMC may further changed to the below listed circuits[13][14][15]:

1. The half-bridge circuit or chopper-cell : Depending upon the switching states of the complementary switch pairs, S1 and S2, the output voltage of a half-bridge SM is either equal to its capacitor voltage VC (switched on/ inserted state) or zero (switched-off/bypassed state) as shown in Table 2(a).
2. The full-bridge circuit or bridge-cell : It consists of two half bridge or say four switches i.e. S1-S4 as shown in Table 2 (b). Depending on the status of switching of the four switches S1-S4, the output voltage of a full-bridge SM is either equal to VC or zero. As the switches are twice as half bridge SM, the semiconductor losses and cost incurred are significantly more than in half bridge SM MMC.

Table 2 – Various Sub-Module Topology

 (a) **Half Bridge** Voltage Level – [0, Vc] DC Fault Handling - No Losses - Low	 (b) **Full Bridge** Voltage Level – [0, +Vc] DC Fault Handling - Yes Losses - High

 **Clamp Double** Voltage Level – [0, Vc1,Vc2,(Vc1+ Vc2)] DC Fault Handling - Yes Losses - Moderate	 **3 Level FC** Voltage Level – [0, Vc1, Vc2,(Vc1- Vc2)] DC Fault Handling - No Losses - Low
 **3 Level NPC** Voltage Level – [0, Vc2,(Vc1+ Vc2)] DC Fault Handling - No Losses - Moderate	 **5 Level cross connected** Voltage Level – [0, Vc1, Vc2,±(Vc1+ Vc2)] DC Fault Handling - Yes Losses - Moderate

3. The clamp-double circuit: Table 2 (c) shows a clamp-double SM that has five switches and two diodes. It is basically two half-bridge SMs, one spare Integrated Gate Bipolar Transistor (IGBT) with its anti-parallel diode and two added diodes. The switch S5 being switched on always during normal operation, and this SM acts equivalent of two half-bridge SMs in series connection. Keeping the voltage levels number as same, the clamp-double MMC semiconductor losses lies in between the above two SMs .
4. The 3-level converter circuit: A converter of three-level SM consists of namely three-level neutral-point-clamped (NPC) circuit or a three-level flying capacitor (FC) converter shown in Table 2 (d) and (e),. There is similarity in semiconductor losses of three-level FC MMC with the half-bridge configured MMC. Howsoever, from manufacturing and control point of view, the three-level NPC MMC has losses higher than half-bridge MMC and lower as compared to the full-bridge MMC.
5. The 5-level cross-connected circuit: Table 2 (f) shows a five-level cross-connected SM. It comprises 2 extra IGBTs with their anti-parallel diodes connected to SMs with two half-bridges one after the other. The nature of losses remain same as in clamp-double SM.

IV. Modulation Techniques

4.1Pulse-width modulation (PWM)

In the MMC, various pulse-width modulation techniques are used that are carrier based multilevel PWM methods. With high sub-module numbers, nearest-level modulation (NLM) sometimes fit to MMC, because of low harmonics and low amplitudes of voltage[16].

- Phase-shifted PWM- The benefit of this modulation is that all the modules are equally used and low harmonics is produced even though number of sub-modules is not high. The level of carriers is same but are level shifted in such a way that they in one cycle are equally spaced (n- number of identical triangular carriers are present with one carrier for each sub-module displaced at an angle of 360°/N.) A carrier set is owned by each arm . In fact, by adjustment in phase of carrier sets between upper and lower arms, n+1 or 2n+1 voltage level is possible to obtain at the phase terminal.
- Level-Shifted PWM Methods- This scheme also needs n-number of identical triangular carriers. In this scheme carrier waves are stacked one over the other. Each one of the carrier is assigned its own sub-module. The module has to be either applied or bypassed when compared to a reference signal.. A relatively low switching frequency with low harmonic output is produced when the modules are large enough in number.
- Selective harmonics elimination (SHE) – Presence of high number of output levels preferably allow low-frequency modulation in MMC. Selective harmonics elimination (SHE) used in MMCs [17], but the process to determine switching angles is complex as the number of modules rises.

4.2Nearest-level Modulation/ Staircase Modulation

The amplitude of the reference modulating signal decides the number of insertion of sub-modules In the nearest-level modulation (NLM). The comparison of magnitudes is done between reference signal and the discrete voltages that the converter may generate. Thus, complete no to the pulse-width modulation or carriers. This modulation technique is good for modular multilevel converter system which contains high numbers of sub-modules because the possibility of deterioration of output voltage quality is less with small voltage steps. In addition, for large modular multilevel converter systems, nearest-level modulation is simple to implement.

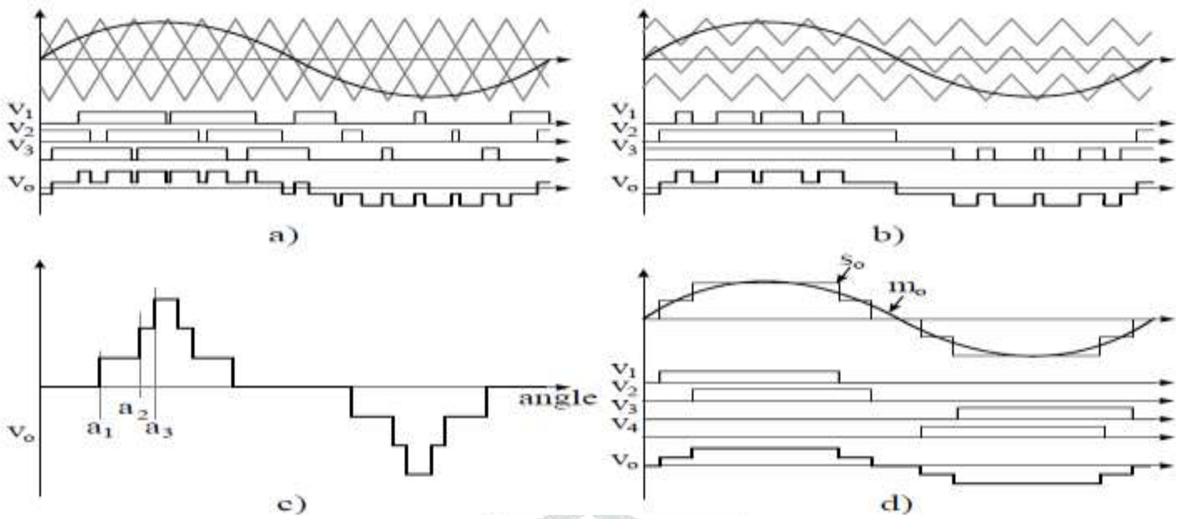


Fig 2- Various techniques for Modulation. a) Phase shifted PWM. b) Level shifted PWM. c) Multilevel SHE. d) Staircase modulation.

V. Control Parameters In MMC

It is very important to control voltage or current through the MMC terminals. In order to get steady-state-stable operation, the control on average capacitor voltage must be done , stress on sub-module cells must be equalized, influence of circulating currents must be taken into account. The capacitor present in the sub-module cell stores energy and acts as energy interface between input and output. As per desired applications, these parameters are varied and controlled. In this section controls to be taken care of are as described[18]. Figure 3 shows the primary parameters that are a must to be controlled for Modular Multilevel Converter proper functioning .

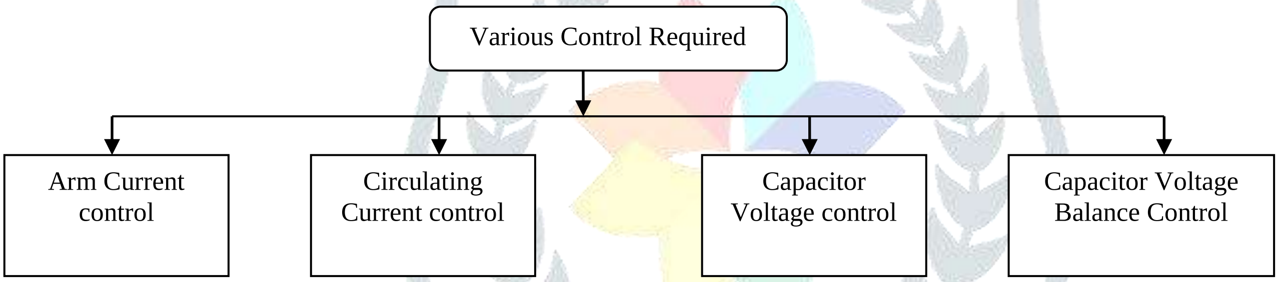


Fig. 3 – Various control required

- [illegible] voltages is decide. This arm voltage combination in turn controls the arm currents. This controlling of arm currents thus results into the controlled input and output voltages and flow of currents.
- Control Circulating Current - There are some currents that internally flow through the arms of converter but not allowed to flow outside the body of converter. These currents are termed as circulating currents. MMCs produce circulating currents. The presence of capacitor voltage ripples is prime source for production of circulating currents, the frequency of which is twice the output frequency. Also, during the multilevel modulation, when the voltage levels change instantaneously, the circulating currents are generated at switching frequency. Although this kind of circulating currents can be minimized by modulation techniques in the modulation stage.
- Control of Capacitor Voltage – For proper MMC operation, at a specific level of reference voltage it is to control capacitor voltage. The average voltage and voltage balance being the two divisions that need control. The voltage balance is further categorized into: the control of the voltage balance within arm and the imbalance among arms.
- Capacitor Voltage Balance Control- An optimum method for capacitor voltage balance is to measure and adjust voltage across the capacitor of the sub-module before sorting. The SMs whose voltage limits in capacitor has exceeded is pointed out, and other SMs states of switching is remain same. To function either insertion or bypass in the following cycle of switching, a factor of maintenance is thereby brought into picture and multiplied to the off-state SMs capacitor voltages , i.e. whose capacitor voltages surpass voltage limits.

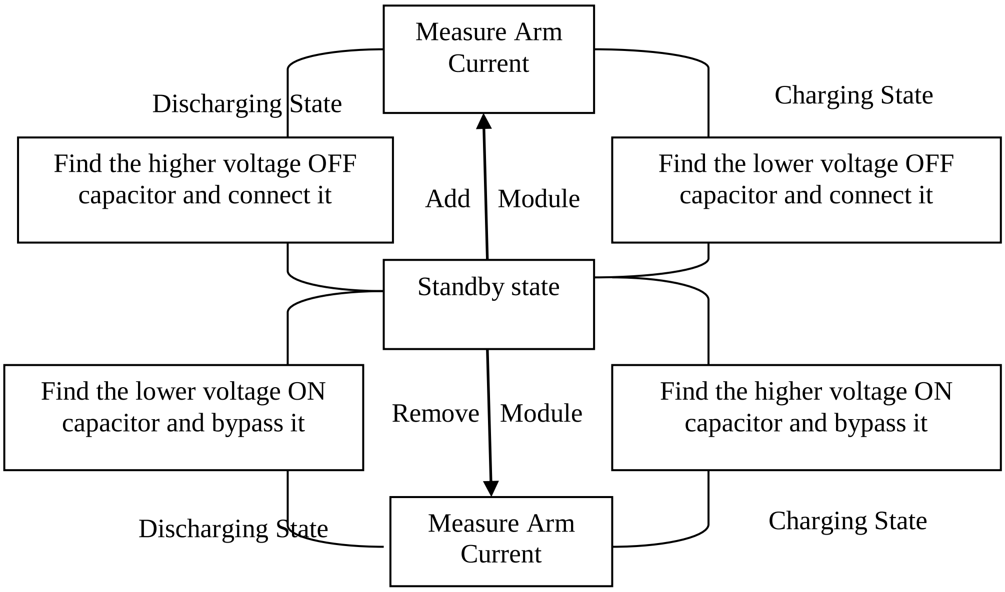


Fig. 4- Voltage Balance algorithm for MMC

VI. Design Constraints in MMC

The designing of MMC, includes deciding the size of the inductor and capacitor , the sub-modules number , arm current, reliability, current and voltage ripple, losses and short circuit current. Keeping this in mind certain issues of MMC are discussed in the following sections which are namely alternate converter topologies, design of components, analysis of semiconductor losses, fault operation, and capacitor precharging.

1 Alternate Configuration- With advanced technologies, certain designs have become outdated and need to be replaced. Talking of which a hybrid MMC is shown in Fig. 5 a) consisting of 2 three-phase power units connected in top and bottom. These units are responsible to control interchange of power among the arms [19]. This topologies although imparts improvement of the MMC, but in exchange they are likely to lose features such as, reducing reliability and modularity of converter.

One can interconnect two AC networks directly or back-to-back by a matrix MMC as represented in Fig. 5 b). The interconnection requires reduced number of arms which indicates as main advantage; although the controlling becomes rather complex due to arm currents existing in the two AC components[20].

Alternately an interesting design is the hexagonal shaped MMC, in Fig. 5 c). Using only six arms, this configuration connects two three-phase AC systems, but the control actions being restricted when compared with matrix MMC by combination of only two input phases each output phase is generated particularly for unbalanced grids [21].

(a) (b) (c)

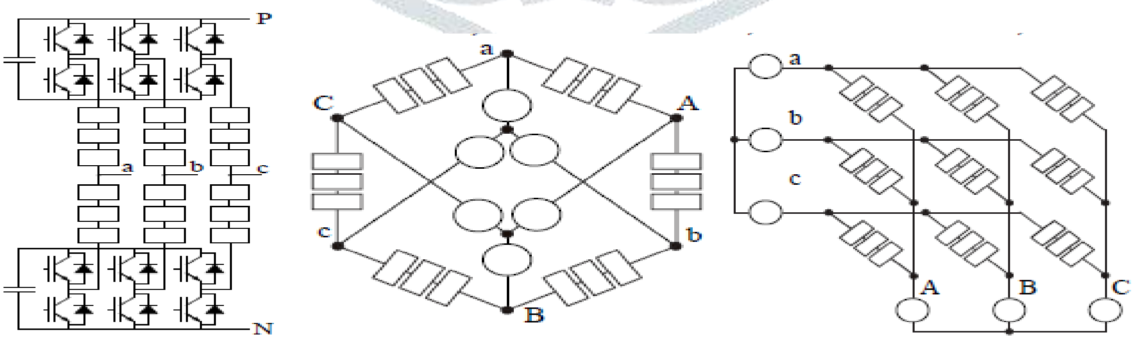


Fig. 5- Technically advanced topologies of MMC (Each box represents one power cell).a) Hybrid MMC. b) Matrix MMC. c) Hexagonal MMC

2 Design and Implementation- For reducing the size of the MMC, it is required to restrain circulating current, alleviate switching ripple and in each phase-leg limit the fault currents [22]. On the basis of trade-off between voltage ripple, size, cost, the SM capacitor is sized [23]. References [24] carry out an analysis under wide range of operating conditions for the sub-module capacitor voltage ripple.

3 Calculation of losses- The semiconductor losses include both switching as well as conduction losses. The determination of conduction losses is based totally on data-sheets of semiconductor device from the manufacturer and the SM current flows. Switching losses have dependency on transitions like the insertion and bypassing in SMs because of (i) the generation of required levels of voltage, switching transitions based on the waveforms in reference ,(ii) capacitor voltage balancing and selected

modulation strategies. We have two methods for semiconductor loss evaluation, first relys on the real-time simulation data and simulation model [25]–[27], providing results accurately whatsoever voltage level be , strategy for modulation or control be, and any SM circuit topology. Although this method has a heavy computational load. The other method, reduces the time for calculation and its basis being analytical analysis [28].

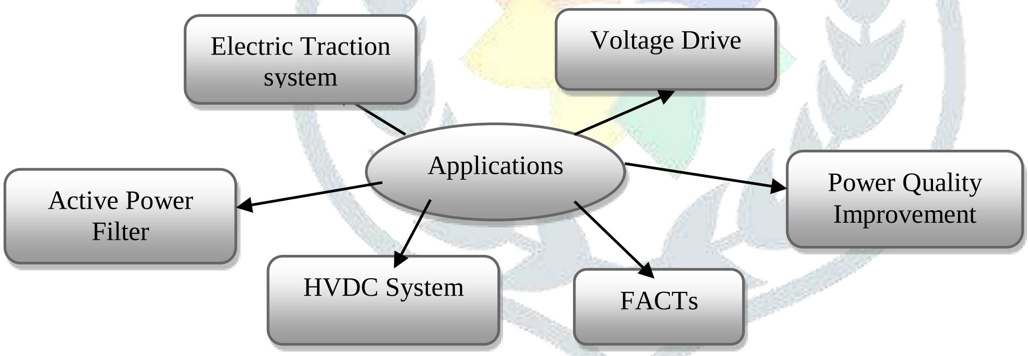
4 Fault Operation of MMC- Existence of high number of redundancies there is a fault tolerance in MMC. At times its very challenging to identify which sub-module experiences fault when identical sub-modules are present. This can be eliminated if sensors are installed with each sub-module. However, this may lead to increase in the cost and system complexity. To avoid this an additional control system can be placed that can locate the device failures and provide modification in the converter structure , and hence lessen the influence of failure on operation of converter as a whole [29]. Study of the high current dynamics show limitation strategy for short circuit currents that the converter on its own exhibits to take care of the DC faults [30] [31].

5 Capacitor Pre-charge[32][33] - While operating normally, the capacitors are charged to a nominal value. Also, there is a possibility of high inrush currents during the process of charging at start-up of the converter or after a fault; because the equivalent capacitance is high. One way to escape is to make a temporary series connection of resistor to the converter. But, this isn't an efficient method in terms of energy, and can lead to bulky and big resistances operating at high voltages . Another way is to charge capacitors, one capacitor at a time in a staggered sequence by providing a delay in the charging of each capacitors. There is no any requirement of external hardware but more complexity in system control, that must operate even if complete discharging of modules occur. A blend of both can be implemented to reduce the pre-charge resistor and the complexity in control.

6 Voltage Ripple[34]- The ripples in the capacitor voltage are caused due to interaction between modulation signals and arm currents. A limited operating range for minimization of ripples is because of the maximum amount of allowable circulating currents.. The power losses of the components and current rating is seen as increasing as most of the proposed reduction techniques of ripple leads to increased RMS peak and values of arm currents . By limiting arm currents and power losses in converter, it is possible to reduce voltage ripples. In addition to reduction of voltage ripples, maximization of the operating region is done by shaping of the capacitor voltage ripple using second harmonic circulating current[35] or by use of circulating current consisting second harmonic and a common-mode third harmonic phase voltage etc.

VII. APPLICATIONS

MMCs provide high voltage capability with good power quality, in HVDC transmission systems shown by figure(6). Other areas of applications includes active filters and medium voltage drives is proposed in the writing. MMC-based STATCOM used as FACTS controller is discussed in [36] which consists half-bridge SMs for active filtering. Reference [37] provides for a unified power-flow controller (UPFC)based on concepts of MMC.



. An MMC based shunt active power filter is proposed and discussed in [38].Another potential applications is in railway electric traction systems where as transformer-less converter of medium-voltage supplies the traction motors [39][40].

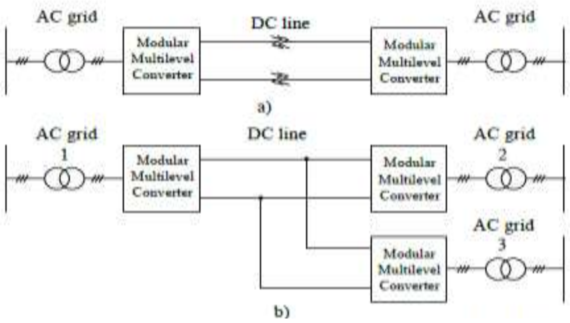
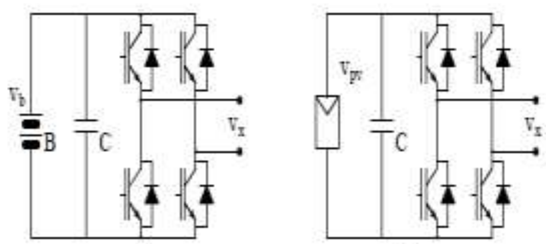


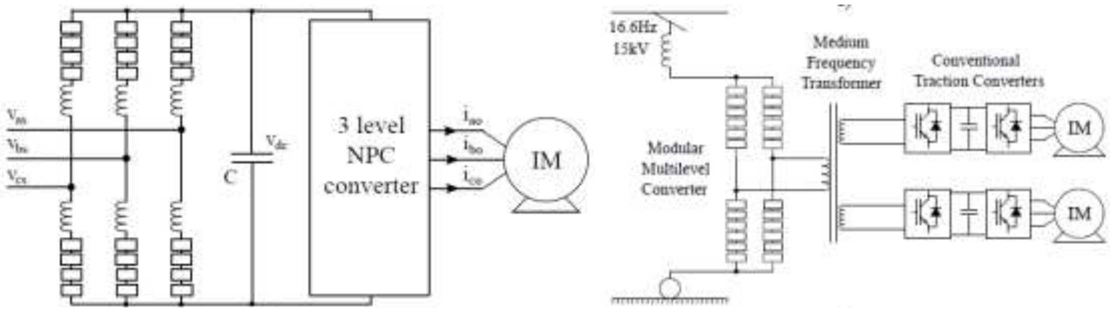
Fig. 6. MMC in HVDC applications.
a) Overhead line Long distance HVDC.
b) Multi-terminal HVDC



(a) (b)

Fig. 7. FACTS. a) For BESS systems, Cell with an integrated battery ; b) Provision of distributed energy generation for Cell with an integrated photovoltaic-panel

An integrated energy storage MMC system for interfacing batteries of low/medium-voltage to the grid is presented[41]. For transformer-less grid connections, reference [42] shows optimal design of MMC for high-power energy storage system as standalone. Action of MMC as an interface between the photovoltaic panels and grid is proposed in [43].



(a) (b)

Fig. 8. Applications of MMC in Machine drives. a) Front-end converter for a medium voltage drive. b) Interface converter for trains.

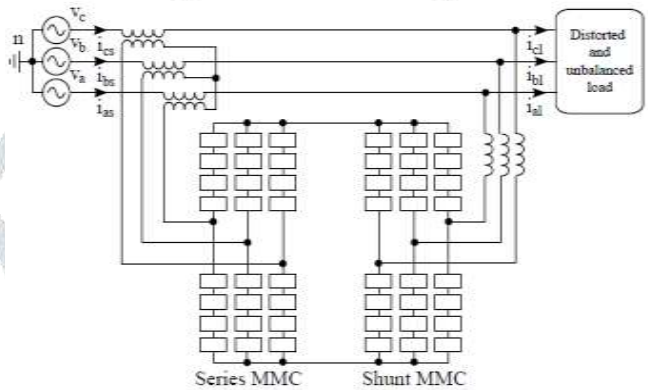


Fig. 9. Flexible AC transmission systems-Unified power quality compensator.

VIII. Future Trends

The low frequency of switching in IGBTs makes it the most dominating semiconductor technology used in modular multilevel converter topologies . On the latter, establishment of alternative power devices for example diamond , Gallium Nitride (GaN), and Silicon Carbide (SiC), would drastically reduce the losses during switching and minimize the requirement of system for cooling.

Modular multilevel converters those used for applications dealing high power are of increased size and weight due to presence of more number of capacitors , semiconductor devices, and inductors. A compact nature of converter is highly desirable for applications such as offshore wind. One likely solution is use of stacked phases which helps in reducing the volume of these converters. However, this is not sufficient and yet further development is insisted to minimize the structural volume.

A transformer-less topology in converter reduces complexity, cost, volume & losses which is highly desirable in matching voltage in grid connected to high power applications. Even with some faulty cells, converter must provide fault tolerant operation by exploiting its modularity. In order to manage DC faults a controller must be designed to enable faster current control thereby avoiding need for DC breakers which are by nature costly and bulky.

Considering productive benefits of MMC operations, it can be used in medium voltage, low voltage and in photovoltaic plants to increase the storage of energy in plant so as to utilize it during night. Machines can be connected directly to medium voltage grids as MMC has high voltage capability. In view of power quality low voltage applications can also be benefitted from MMC. There is a large scope for future development incase of medium voltage variable speed drives and to address the issues of operation and control during constant-torque-low speed operation.

IX. Conclusion

This paper has concisely reviewed various concepts in MMC. The exceptional qualities of MMC, i.e., its efficient performance, reduced components ratings, modular approach and scalable nature allow it to meet any required voltage level; has enormously dragged the attention of researchers , resulting into development of newer, control schemes and modulation strategies. Over the years, the MMC is successfully implemented in areas of HVDC transmission and installed in industrial applications such as in FACTS, dc-dc converters for medium/high voltage and variable-speed drives. One major difficulty is the occurrence of capacitor voltage ripple. At lower frequencies the converter SMs are required to minimize the magnitude of capacitor voltage ripple without losing the converter efficiency.

A new avenue for research and development has opened up by the introduction of a family of modular multilevel dc-dc converters for medium/high voltage. It is clear that these developments and demands for betterment will drive and restructure the future of modular multilevel converter technology.

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