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A Review on Designand Control Methods of Modular Multilevel Converter

Ramya G, Ramaprabha R
Department of Electrical and Electronics Engineering, SSN College of Engineering, Kalavakkam, India

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ABSTRACT

Modular multilevel converters (MMC) are an emerging voltage source converter topology suitable for many applications. Due to abundant utilization of HVDC power transmission, the modular multilevel converter has become popular converter type to be used in high voltage applications. Other applications include interfacing renewable energy power sources to the grid and motor drives. Modular multilevel converters are beneficial for high voltage and high power motor drives because of the properties of this converter topology, such as, low distortion, high efficiency, etc. For the past few years significant research has been carried out to address the technical challenges associated with operation and voltage balancing of MMC. In this paper, a detailed technical review on the control strategies is presented for ready reference.

Corresponding Author:

G. Ramya,
Department of Eletrical and Electronics Engineering,
SSN College of Engineering, Rajiv Gandhi Salai, Kalavakkam, Chennai 603110, India.
Email: ramyamrose@gmail.com

1. INTRODUCTION

The modular multilevel converter has become the most attractive multilevel converter topology for medium/high-power applications. These converters can be used for medium and high voltage applications with low voltage IGBT switches [1]. There are several types of multilevel converter topologies. Even thoughthe fundamental concepts are similar, there are differences in the control requirements across these various topologies. MMC has several advantages compared with other multilevel topologies such as its modular structure and scalability, high efficiency, low harmonic distortion [2]. In recent years, addressing the issues based on operation and control of MMC has become significant. There has been substantial progress in the development of pulse-width modulation techniques, voltage balancing algorithms and conventional control approaches applicable to modular multilevel converters.

The main objective of this paper is to provide better understanding of MMC considering the issues. This paper deals with complete technical review on the operational issues, control and modulation techniques. The paper is organised as follows: Section II briefs about the operation of MMC. Section III describes various modulation techniques and various operational issues such as capacitor voltage balancing and circulating current control and also the reduction of ripple in capacitor voltage by various techniques are also explained. The concluding remarks are presentedin Section IV.

2. MODULAR MULTILEVEL CONVERTER-ANOVERVIEW

The schematic of three phase modular multilevel converter is shown in Figure 1. MMC consists of a sequence of sub-module connected in series for each phase of the converter. Each sub-module consists of two switches connected in half-bridge topology with capacitor across the device which is used as the energy storage and supply device. The output terminals are connected to the converter across the lower switching device. This shows that the capacitor across two devices is either directly connected to the converter or shorted out depending on the gating signals [3]. The sequence of sub-modules along with an arm inductor makes an arm of the converter. The single phase of the converter consists of two arms such as upper arm and lower arm. Each phase is connected to the supply by the end of the sub-module. The arm inductor present in each arm is used to limit the circulating current and to filter the harmonics. The number of levels in MMC depends on the number of sub-modules present in each arm. The number of levels is determined by N=2S+1, where S is the number of sub-module present in each arm [4].

The conduction path of the sub-module depends on switching of the switching devices. Each sub-module will be in one of the two states (i.e. one switch in ON state and other at OFF state) [5]. The conduction path is explained when the current polarity is positive and negative which is shown in Figure 2.

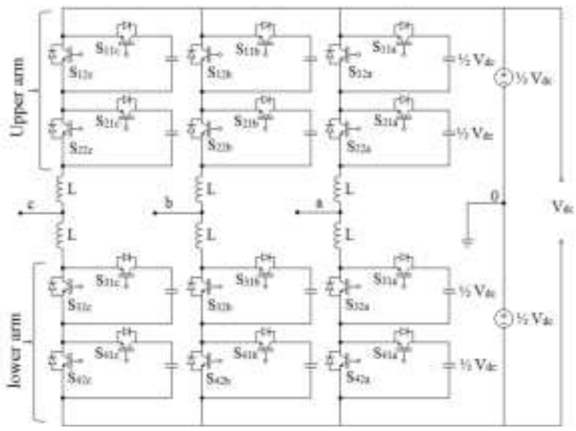

Figure 1. Schematic of three phase MMC

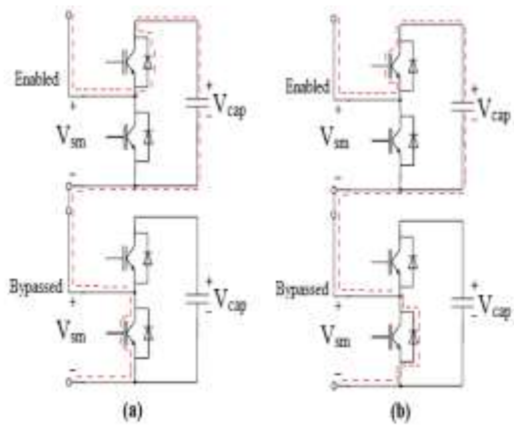

Figure 2. MMC Conduction path (a) Positive current (b) Negative current

3. REVIEW ON DESIGN, MODULATION AND CONTROL TECHNIQUES OF MMC

In this section, the mathematical modelling of MMC, modulation techniques, voltage balancing control, circulating curremt control and Sub module capacitor voltage ripple reduction control methods are explained briefly.

3.1. Mathematical Modelling of MMC

Three phase MMC based half-bridge sub-module is shown in Figure 1. The addition of arm resistance models the power loss within each arm of MMC. The detailed description on modelling of MMC is given in [6]. The upper and the lower arm current of each phase is given by,

$$i_{u,x} = \frac{i_{dc}}{3} + i_{circ,x} + \frac{i_x}{2} \tag{1}$$

$$i_{l,x} = \frac{i_{dc}}{3} + i_{circ,x} - \frac{i_x}{2} \tag{2}$$

where x= a, b, c (phase), $i_{u,x}$ and $i_{l,x}$ are the upper and lower arm current, $i_{circ,x}$ is the circulating current in each phase. The circulating current is given by,

$$i_{circ,x} = \frac{i_{u,x} + i_{l,x}}{2} - \frac{i_{dc}}{3} \tag{3}$$

The dynamic behaviour of MMC is described by,

$$\frac{V_{dc}}{2} - V_{u,x} = L_0 \frac{di_{u,x}}{dt} + R_0 i_{u,x} + V_x + V_{cm} \tag{4}$$

$$\frac{V_{dc}}{2} - V_{l,x} = L_0 \frac{di_{l,x}}{dt} + R_0 i_{l,x} - V_x - V_{cm} \tag{5}$$

where $V_{u,x}$ and $V_{l,x}$ are the upper and lower arm voltage, V_x is the fundamental component and V_{cm} is the common mode voltage. The MMC phase voltage is expressed as in (6) and MMC circulating current is given by (7).

$$V_x + V_{cm} = \frac{V_{u,x} - V_{l,x}}{2} - \frac{R_0}{2} i_x - \frac{L_0}{2} \frac{di_x}{dt} \tag{6}$$

$$L_0 \frac{di_{circ,x}}{dt} + R_0 i_{circ,x} = \frac{V_{dc}}{2} - \frac{V_{u,x} - V_{l,x}}{2} - R_0 \frac{i_{dc}}{3} \tag{7}$$

The upper and the lower arm voltages of MMC are given by the following equations.

$$V_{u,x} = n_{u,x} V_{cu,x} \tag{8}$$

$$V_{l,x} = n_{l,x} V_{cl,x} \tag{9}$$

where $V_{cu,x}$ and $V_{cl,x}$ are the individual sub module capacitor voltage of upper and the lower arm. Each sub module capacitor voltage of the MMC is modeled by the power processed by each arm. The power processed by each arm is given by

$$P_{u,x} = V_{u,x} i_{u,x} = n_{u,x} V_{cu,x} i_{u,x} \tag{10}$$

$$P_{l,x} = V_{l,x} i_{l,x} = n_{l,x} V_{cl,x} i_{l,x} \tag{11}$$

Each sub module capacitor voltage ripple can be defined as

$$\frac{dV_{cu,x}}{dt} = \frac{i_{u,x}}{NC_{SM}} n_{u,x} = \frac{1}{NC_{SM}} \left(\frac{i_{dc}}{3} + i_{circ,x} + \frac{i_x}{2} \right) n_{u,x} \tag{12}$$

$$\frac{dV_{cl,x}}{dt} = \frac{i_{l,x}}{NC_{SM}} n_{l,x} = \frac{1}{NC_{SM}} \left(\frac{i_{dc}}{3} + i_{circ,x} + \frac{i_x}{2} \right) n_{l,x} \tag{13}$$

The generalised dynamic model of MMC is given by above equations and is used in the control purpose. The dynamic modelling of MMC is proposed [7] by considering the summation of sub-module capacitor voltage in each arm instead using of individual sub-module capacitor voltage in generalized dynamic model. The direct and indirect modulation strategies to determine the MMC dynamic model is proposed [8] by using the $n_{u,x}$ and $n_{l,x}$expression. It results in the continuous dynamic model since low frequency components are considered. Many methods of continuous modelling of MMC and frequency domain modelling are proposed [9]. The main advantage of this modelling compared to general modelling of MMC is that faster computation of system states for increase in number of levels. Hence it is understood that the dynamic model can be opt selection while simulating MMC with grid interfacing applications.

3.2. Modulation Techniques

Many pulse width modulation techniques have been carried out in MMC that are discussed below. Carrier disposition pulse width modulation technique was proposed [10] which require N triangular carrier signal that are displaced proportionally with respect to zero axis. The desired output voltage is obtained by comparing the phase voltage reference with the carrier signal. Based on the shift in the triangular carrier signal this PWM technique is further classified into phase disposition (PD), phase opposition disposition (POD) and alternate phase opposition disposition (APOD). The carrier signals of above techniques are shown in Figure 3. The main drawback of these PWM techniques is that unequal voltage distribution among the sub module which results in the increase in the total harmonic distortion (THD). To report this issue the different modulation techniques such as simple carrier rotation, modified carrier rotation PWM techniques are used to equalize the voltage distribution among the sub module. However the THD is relatively high. Hence the modified PD-PWM technique with capacitor voltage balancing is proposed [11]. In this technique particular gating sequence is not assigned to a specified sub module. The comparison of reference signal with the carrier signal produce N+1 level in the output side which determines the number of sub module to be added in upper and lower arm. The PD-PWM with selective loop bias mapping method is proposed for voltage balancing in the module. The sub module capacitor voltage and direction of inductor current are the feedback signals used in this method. The other techniques are that the phase shift carrier modulation technique [12] in which each carrier is phase shifted by 360/(N-1). The number of carrier signals used in this technique depends on the number of level in MMC. In this technique each submodule of MMC is controlled independently and voltage balancing control is done by averaging control and balancing control. These control technique control the average sub module voltage in each phase and also individually balancing the capacitor voltage of each sub module. The switching signals are given to each sub module by comparing the reference voltage with from each phase with the triangular carrier signal. The main drawback of this modulation technique is that complexity with increase in the number of sub module and instability under certain condition. This issue is overcome by introducing the arm balance control in the reference signal based on the difference in the capacitor voltages of upper and the lower arm.The different PWM techniques are shown below in Figure 3. Comparison of above mentioned modulation techniques is summarized in Table 1.

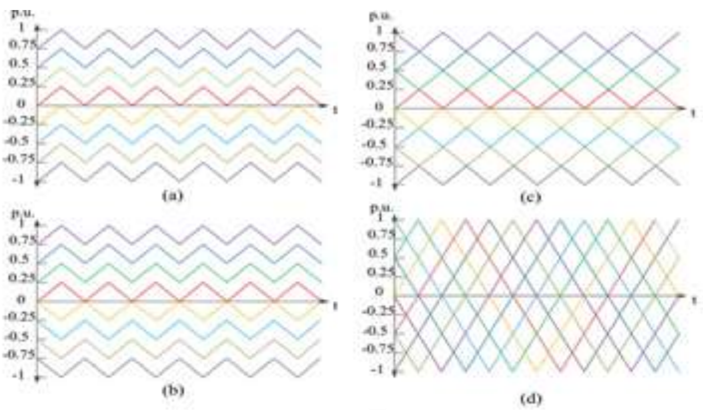

Figure 3.Multilevel carriers: (a) PD, (b) POD, (c) APOD, (d) phase-shifted carriers

In addition to the above modulation techniques the SHE-PWM technique is proposed [13] in which the switching pattern is determined to eliminate the low order harmonics in the output voltage. The modulation technique based on fundamental switching frequency has been investigated. The nearest level control modulation technique is proposed [14] in which voltage level nearest to the desired voltage is considered. This technique is very easy to implement and can be operated at the fundamental switching frequency. The technique proposed is based on a fixed pulse pattern fed into the sub module to maintain the stability of the stored energy, without measuring the capacitor voltages or any other feedback control, and to remove certain output voltage harmonics at any arbitrary modulation index and output-voltage phase angle. The optimized modulation technique is proposed [15] that optimize the pulse pattern to minimize the harmonic distortion at the output. This technique is opposed to the PWM technique where the carrier frequency has effects on the output voltage frequency. Based on the above literature on modulation techniques in MMC it is known that the phase shifted PWM is easy to implement with reduced THD.

Table 1. Key contributions on different modulation techniques

Modulation technique Proposed	Contribution of the authors
Carrier disposition technique	The desired output voltage is obtained with low harmoincs with this technique. The carrier signal that are displaced proportionally with respect to zero axis. They are classified into PDPWM, PODPWM, and APODPWM.
Simple carrier rotation and modified carrier rotation PWM techniques	This modulation technique equalized the voltage distribution among the sub module.
Modified PD-PWM technique	The capacitor voltage balancing is carried out with equal voltage distribution among the sub-module with low THD. In this technique reference signal is compared with the carrier signal produce N+1 level in the output side. The gating signals are assigned to specified sub module for the desired output.
PD-PWM with selective loop bias mapping	The sub module capacitor voltage balancing is done with this method. The main advantage of this method is that absence additional reference signal to control capacitor voltage and also easy implementation.
Phase shift carrier modulation technique	The desired output voltage is obtained compared to other modulation techniques with very low THD.

3.3. Voltage Balancing Control

It is necessary to balance the sun module capacitor voltage at V_{dc}/N. The voltage balancing technique based on PSC-PWM was proposed [12] to balance the sub module by providing appropriate PWM signals to each sub module. This voltage balancing technique does not need to measure the arm current which reduces the complexity in the control strategy. The closed loop voltage balancing method is proposed [3] in which the closed loop control method is implemented for each sub module for the voltage balancing. The predictive strategy was proposed for the control of MMC in which the sub module voltage is balanced based on the predefined cost function. The voltage balancing based on the sorting method is proposed [12] in which the voltage balancing is carried out by measuring the voltage of each sub module and sorting. In this method if the upper/lower arm current is positive the sub module with lowest voltage are identified and inserted among sub module present in each arm. The inserted sub module is charged and the corresponding voltage is increased. Similarly if the upper/lower arm current is negative the sub module with highest voltage are identified and inserted among sub module present in each arm. The inserted sub module is discharged and the corresponding voltage is decreased. The main drawback of this method is that increased switching frequency, power loss and provides switching transition among the sub module. The other voltage balancing methods are proposed to reduce the switching frequency. An open loop method for the voltage balancing is carried out [16] based on the selective harmonic elimination PWM technique. A hybrid balancing method [17] based on the predictive error sorting method and the conventional voltage sorting algorithm is implemented for the voltage balancing of MMC. It is based on the sorting of error between the predicted capacitor voltage and nominal voltage value and the sub module with minimum error is inserted.

Table 2. Key contributions on different voltage balancing method

Volatge Balancing Method	Contribution of the authors
Voltage balancing technique based on PSC-PWM	In this method voltage balancing is carried out without measuring the arm current that reduces the complexity.
Closed loop voltage balancing method	The sub module voltage balancing is carried out with closed loop control.
Predictive control method	Voltage balancing of the MMC is carried out based on calculating the amount of charge stored in sub module capacitor
Voltage balancing based on the sorting method	Voltage balancing is carried out by measuring the voltage of each sub module and sorting it.
Open loop method for the voltage balancing	Voltage balancing is done based on the selective harmonic elimination PWM technique.
Hybrid balancing method	The voltage balancing is implemented by using predictive error sorting method and the conventional voltage sorting algorithm.
Fundamental-frequency balancing strategy,	Voltage balancing is carried out based on the conventional sorting method, executed at the pre-specified phase angles.
Optimized capacitor balancing algorithm	In this method a maintaining factor is introduced and multiplied by the capacitor voltages of the sub module with higher capacitor voltage to maintain the voltage balance of the sub module.
Closed-loop modified sorting method	In this technique phase-shifted carrier PWM strategy is implemented, in which the insertion/bypassing of the sub module is carried out based on measuring the capacitor voltage.

A fundamental-frequency balancing strategy, which is based on the conventional sorting method, executed at the pre-specified phase angles. A predictive algorithm is proposed for voltage balancing by calculating the amount of charge stored in the SM capacitors.

The optimized capacitor balancing algorithm is implemented in which the sub module capacitor voltage is adjusted before sorting. The sub module with higher voltage that exceeds the certain limit is considered. A maintaining factor is introduced and multiplied by the capacitor voltages of the sub module with higher capacitor voltage to maintain the voltage balance of the sub module. Apredictive control method [18] is implemented for voltage balancing of the MMC based on calculating the amount of charge stored in sub module capacitor. A closed-loop modified sorting method is proposed with combination of phase-shifted carrier PWM strategy, in which the insertion/bypassing of the sub module is carried out based on measuring the capacitor voltage. In this method, only a limited number of sub modules are sorted within each control cycle. If the sub module needs to be ON/OFF to obtain the required voltage level the sorting is carried out within the sub module with OFF/ON state in each arm.Many voltage balancing methods are proposed by various researchers and it is compared and listed in Table 2.

3.4. Circulating Current Control

The voltage difference between the three phaseMMC leads to circulating current flow through each leg. The circulating current contains negative sequence components with the frequency twice the fundamental frequency [19]. The presence of circulating current may lead to increase in the peak and rms value of phase current in each leg and also increase in the power loss and ripple content in the sub module capacitor voltages. Hence the circulating current controller technique is proposed to limit these issues. To control the circulating current various techniques have been carried out in the technical literature. The circulating current model is proposed based on controlling then circulating current as the current controlled voltage source [20]. It is used to control the voltage to reduce the presence of ac components in the circulating current. The first order model is proposed to model the circulating current along with dc and ac components which is used to model the control system easily. The design of arm inductor and sub module capacitor which limits the circulating current by estimating the percentage of ac components present in the arm current and circulating current. The indirect modulation technique [21] is proposed which limits the circulating current in the MMC. The proportional controller is proposed to limit the circulating current by introducing the active resistance in each arm.

Table 3. Key contributionson different circulating current elimination method

Circulating Current Control	Contribution of the authors
Circulating current control model	In this method the sub module voltage is controlled to reduce the presence of ac components in the circulating current.
First order model	In this model the design of arm inductor and sub module capacitor are designed which limits the circulating current by estimating the percentage of ac components present in the arm current and circulating current.
Indirect modulation technique	In this technique the circulating current is eliminated indirectly by controlling the total energy in each phase of the system.
Proportional controller technique	This method limits the circulating current by introducing the active resistance in each arm.
Double line frequency abc-dq transformation	This method is used to eliminate circulating current, the control of the dq components using PI controller.
PR controller technique	In this technique the circulating current is eliminated by limiting the ac components present in it.
Modified switching function method	This technique circulating current is eliminated based on the predicted voltage ripple estimation.

The main drawback of this technique is that the steady state error is obtained due to proportional controller. Based on the double line frequency abc-dq transformation to eliminate circulating current, the control of the dq components using PI controller is carried out. The main issue of this technique is that robustness under ac side imbalance. The PR controller [22] is proposed to eliminate the ac components in the circulating current. The control method was proposed to control dc components of circulating current to improve the stability of the system under unbalance condition. The reference for dc components is determined from the average sub module capacitor voltage. The modified switching function method was proposed to eliminate the circulating current in MMC. This technique is based on the predicted voltage ripple which is difficult to calculate under all operation condition. The model based predictive control method was implemented to limit the circulating current. The main drawback of this method is that estimation of circulating current components is difficult with large number of sub modules. Table 3 explains the different methods on circulating current elimination in MMC.

3.5. Sub Module Capacitor Voltage Ripple Reduction Control Methods

The sub module capacitor voltage ripple is mainly due to fundamental and second harmonic components. The sizing of sub module capacitor is also main factor in maintaining the voltage ripple within the certain limit. Many techniques have been carried out for the reduction of voltage ripple in the sub module capacitor. Some of the techniques are discussed below. The ripple content of then sub module capacitor can be reduced by adding the harmonic content in the circulating current [23]. By calculating the power produced by each arm a suitable second harmonic circulating current is determined to reduce the ripples in the capacitor voltage. By injecting second and fourth harmonic components in circulating current it optimises the energy variation in each arm which also reduces the ripple in capacitor voltage. The ripple of sub module capacitor is reduced by optimizing the rms value of sub module capacitor ripple using second harmonic in the circulating current. The closed loop control method is proposed to eliminate second harmonic component of the capacitor voltage ripple [24]. The above techniques in reduction of ripple in sub module capacitor voltage may lead to increase in the peak and rms value of the arm current and increase in power loss. A technique is proposed to reduce the ripple in capacitor voltage by maintaining the rms value of arm current within certain limit thereby limiting the power loss. The sine wave technique was proposedfor the reduction of ripple in the capacitor voltage. In this technique a common mode voltage and circulating current is injected in each phase. It is given by

$$m_{cm} = M_{cm} \sin \omega t \tag{14}$$

$$i_{circ,x} = i_x \frac{1 - m_x^2}{M_{cm}} \sin \omega t + \frac{m_x i_x}{2} - \frac{i_{dc}}{3} \tag{15}$$

where, M_{cm} and ω are the magnitude and angular frequency of common mode voltage.

The reference waveforms of the sine PWM technique is used to control the upper and lower arms of each phase which generates the common-mode voltage. Appropriate phase shift is given to each sub module so that the low frequency components are not present in sub module capacitor voltage. In this technique the magnitude of circulating current increases which increases the power loss in this system. To overcome this issue the square wave technique [25] was proposed to reduce the peak and rms value of circulating current by square wave common mode voltage and circulatigng current injection technique. A hybrid technique is the combination of square-wave common-mode voltage and a sinusoidal circulating current. The advantage of this technique over the sine-wave technique is the reduction in peak and rms value of circulating currents and the sub module capacitor voltage ripple.

3.6. Applications of MMC

The MMC was introduced mainly for HVDC applications. The MMC is used in medium voltage variable speed drives due to its advantages over other multilevel converter. In recent years the MMC has been used in grid connected application due to its advantage of medium and high voltage application. The MMC with integrated energy storage to interface low/medium voltage batteries to grid is proposed [26]. The study of optimal design of MMC for transformer less grid connected standalone high power energy storage system. A power electronic transformer based on an MMC followed by an isolated dual-active-bridge dc–dc converter and an inverter is proposed [27]. The possibility of using MMC as an interface between the grid and photovoltaic panels was discussed. A family of medium/high voltage dc–dc converters based on the MMC topology has been recently introduced and investigated [28]. A methodology to optimize the design of the dc–dc converter based on MMC with regard to silicon area was proposed.

4. CONCLUSION

The significant features of MMC such as its modularity and scalability may lead to any number of voltage levels with reduced harmonic and higher efficiency. In recent years the MMC has become more superior than other power converters for various medium to high voltage/power systems and industrial applications including HVDC transmission systems, FACTS, medium-voltage variable-speed drives, and medium/high voltage dc–dc converters. There are many techniques discussed based on voltage balancing of sub module capacitor and also eliminating the circulating current in each arm. The capacitor voltage ripple reduction techniques are also discussed without sacrificing the converter efficiency and cost effective. Many modulation techniques have been discussed in many literatures that enable high efficiency and reduced stress on the device. Considering the benefits of MMC in recent application in present scenario it is known that the development of novel modulation and control strategies will be a major driving factor for the use of MMC in future applications. This paper gives a comprehensive reviewon the control strategies of MMC while choosing the topology for a particular application.

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