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An Overview of Modular Multilevel Converter

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Abstract

Among the Multilevel Converter topologies, Modular Multilevel Converter (MMC) has been an emerging technology with a modular structure for medium or high power applications. In the last years, outstanding researches have been done regarding to operation principles and control structures of the MMC. Thus, Modular Multilevel Converter has been a significant topic for both industrial applications and academic surveys. In this paper, an overview of the power circuit analysis and operation principle of the Modular Multilevel Converter topology is discussed. Different submodule topologies are mentioned. Then, advantage sides of the MMC and that of application areas are reviewed. Finally, Control structures of the MMC are briefly handled.

Key words: Modular Multilevel Converter, control, analysis, submodule, topology,

1. Introduction

The Multilevel Converter topologies named as Diode Clamped Multilevel Converter, Flying Capacitor and Cascaded H-Bridge. Nevertheless, for more than 5 level MMC applications, difficulties related to modularity limits, scalability and stability were encountered [1]. Thus, Modular Multilevel Converter topology was suggested in 2003 [2]. The Modular Multilevel Converter topology has become one of the most crucial areas of interest for industrial applications and academicians due to possess many advantage sides. The primary objective of the paper is to ensure a better understanding of the operation and analysis of the MMC. This paper is also emphasized different aspects of the MMC than other multilevel converter topologies and that of different circuitry structures of the submodules. Application areas of the MMC are highlighted in section 2.2. Finally, control methods of the Modular Multilevel Converter are mentioned in section 2.3.

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2. General Aspects of the Modular Multilevel Converter

Three phase grid connected Modular Multilevel Converter topology is shown in Figure 1.A phase leg of the MMC is consisted of two arms which are upper arm and lower arm. Each arm has N identical series connected of the submodules or cells with cascaded structure with an arm inductor, L_{arm} and an arm resistor, R_{arm} .Thus; N+1 level MMC can be obtained. Arm inductor is used for eliminating the fault currents in the converter. Arm resistor should be selected as low as possible due to converter power losses [3]. Each submodule of the MMC can be consisted of different circuit structures and some of the examples of the submodule structures are illustrated in Figure 2. Considering half-bridge based submodule, the structure is formed a capacitor and two IGBTs with anti-parallel diodes. However, full-bridge based submodule structure is consisted of a capacitor and four IGBTs with anti-parallel diodes. Unidirectional cell circuit structure is the other one which is formed a capacitor and one IGBT with anti-parallel diode for the upper side otherwise only one diode without IGBT for the lower side [4].

Submodules are inserted or bypassed depending on the switching positions in each half-bridge circuit. Two switches work in complementary way otherwise lead to short circuit condition. When the upper switch is ON and the lower switch is OFF, submodule is inserted in the arm. Thus; the terminal voltage of the submodule is equal to the capacitor voltage, V_C . If the upper switch is OFF and the lower switch is ON position, submodule is bypassed in the arm. Therefore; the terminal voltage of the submodule is equal to zero. Depending on the arm current direction, submodule capacitor voltages are affected. If the arm current direction is positive, submodule capacitors are charged otherwise capacitor voltages are discharged. Considering the switching states and direction of the arm current, terminal voltage of the submodule capacitor and charge/discharge status are indicated in Figure 3 [5].

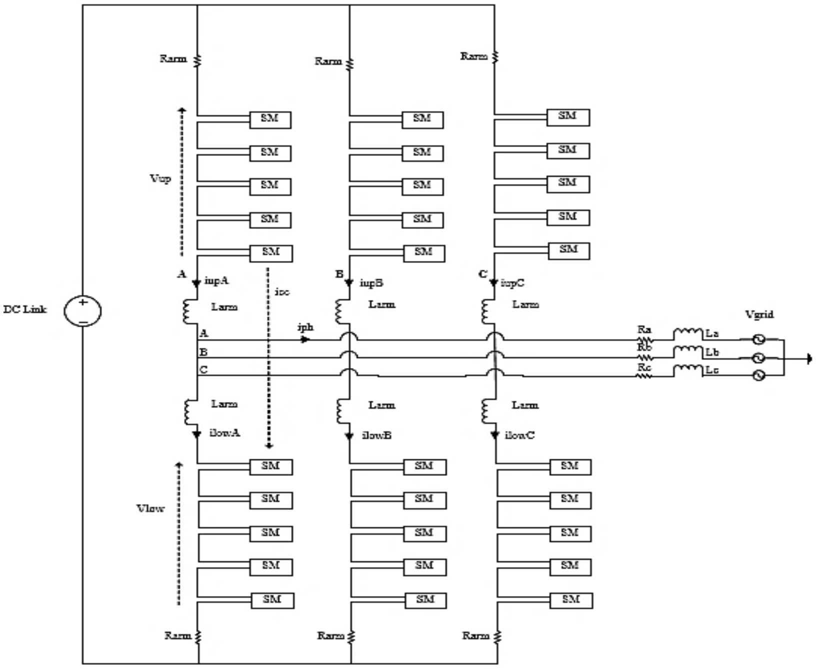


Figure 1. Three phase MMC topology

In a phase leg of the MMC, V_{up} and i_{up} represent upper arm voltage and upper arm current, respectively. V_{low} and i_{low} indicate as lower arm voltage and lower arm current, respectively. i_{ph} represents the output phase current and i_{cc} is expressed as circulating current which is originated from the phase difference between the phase legs. Equations are taken from reference [6].

The number of the submodules in a phase arm is equal to N. If the submodule capacitor is represented as C_{SM}, arm capacitance, C_{arm}, is given as in Equation (1). Thus; the each arm voltages has N+1 level ranges from zero to V_{dc} with $\frac{V_{dc}}{N}$ level crossings.

$$C_{arm} = \frac{C_{SM}}{N} \tag{1}$$

The mathematical modeling of the output phase voltage is expressed as in Equations (2) and (3) for upper arm and lower arm, respectively.

$$V_{a0} = \frac{V_{dc}}{2} - (V_{up} + L_{arm}\frac{di_{up}}{dt} + R_{arm} i_{up}) \tag{2}$$

$$V_{a0} = -\frac{V_{dc}}{2} + (V_{low} + L_{arm}\frac{di_{low}}{dt} + R_{arm} i_{low}) \tag{3}$$

Arm currents are continuous currents which are sinusoid based. Each arm current has two fundamental components. These are half of the output current at the fundamental frequency and circulating current component as shown in Equations (4) and (5). Considering steady-state condition, DC link current is divided equally between the three phase legs. Additionally, circulating current component is equal to the one third of the DC link current.

$$i_{low} = \frac{i_{ph}}{2} + i_{cc} = \frac{i_{ph}}{2} + \frac{i_{dc}}{3} \tag{4}$$

$$i_{low} = -\frac{i_{ph}}{2} + i_{cc} = -\frac{i_{ph}}{2} + \frac{i_{dc}}{3} \tag{5}$$

It is important to mention that i_{up}, i_{low} and i_{ph} are the branch currents. However, circulating current component can not be directly measured.

According to Kirchhoff current law, output phase current and circulating current component can be defined as in Equations (6) and (7).

$$i_{ph} = i_{up} - i_{low} \tag{6}$$

$$i_{cc} = \frac{(i_{up} + i_{low})}{2} \tag{7}$$

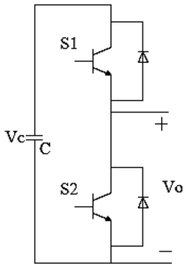
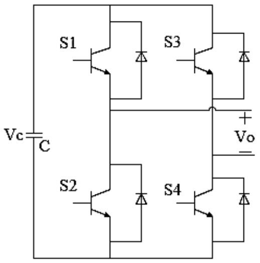
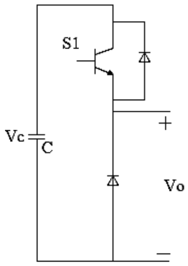
Half-bridge circuit	Full-bridge circuit	Unidirectional cell circuit
 (a)		

Figure 2. Submodule structures

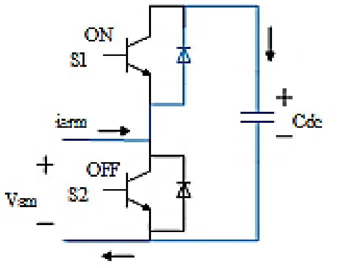
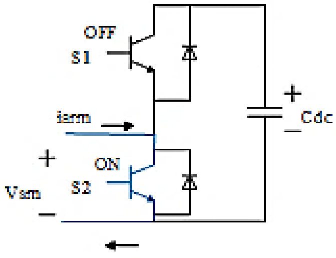
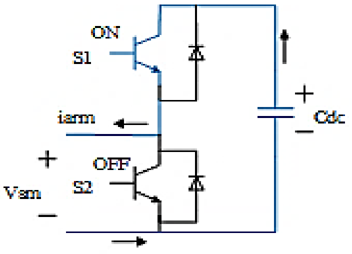
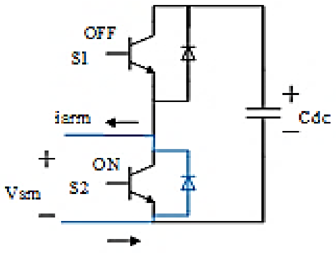
$i_{arm}>0$	 (a) *Charging state* Vout= Vsm	 (b) *By-passed state* Vout= 0
$i_{arm}<0$	 (c) *Discharging state* Vout= Vsm	 (d) *By-passed state* Vout= 0

Figure 3. Submodule states and current paths

2.1. Advantage sides of the MMC

In comparison with other multilevel converter structures, the main advantageous of the Modular Multilevel Converter can be summarized as in below [6]:

- Modularity and making it easy to scale in any voltage level by using cascaded structure,
- Higher efficiency. Thanks to low switching frequency,
- Low THD performance. Due to use many submodules in the arm,
- High reliability. Due to use redundant submodules in the event of submodule failure,
- Absence of AC filters and DC link capacitors. Due to all the submodules share the common DC link.

2.2. Application Areas of the MMC

HVDC systems can be mentioned one of the application areas of the MMC [7,8]. Due to reduced filter size and low switching frequency in each cell, MMC has been taken a significant role in HVDC systems instead of 2 or 3 level converters.

Medium voltage motor drives is one of the other application areas of the MMC [9,10]. Principally, the main purpose of the studies regarding to Motor Drive applications is to find a solution of the large ripple magnitude of the SM capacitor voltages at low frequencies [11].

Power Quality applications are one of the other application areas of the MMC and that can be listed as follows:

- MMC based STATCOM [12],
- MMC based shunt active power filter [13],
- MMC based unified power flow controller [14].

2.3. Control Structures of the MMC

Control structures can be stated as the most complex part of the MMC**.** Principally, control structures can be grouped as follows:

1. Active and Reactive power control of the MMC
2. DC link control of the MMC
3. Circulating current control of the MMC
4. Capacitor voltage balancing of the MMC

2.3.1. Active and Reactive Power Control of the MMC

The most commonly used power flow control method is dq synchronous reference frame as shown in Figure 4. To be able to analysis dq synchronous reference frame, the complex power is given in Equation (8). Using complex power, active and reactive powers can be obtained [15] as in Equations (9) and (10). When PLL aligns d-axis with grid voltage vector, E_q becomes zero. Thus, power terms shown in Equations (9) and (10) reduce to the Equations (11) and (12) as shown in below [15]. Moreover, reference active and reactive currents are indicated as in Equations (13) and (14). In here, i_d* and i_q* represent the active and reactive currents, respectively. $P*$ and $Q*$ represent the active and reactive powers, respectively.

$$S_{dq} = \frac{3}{2} V_{dq} I_{dq}* = \frac{3}{2} (V_d + jV_q)(i_d - ji_q) \tag{8}$$

$$P = \frac{3}{2} (V_q i_q + V_d i_d) \tag{9}$$

$$Q = \frac{3}{2} (V_q i_d - V_d i_q) \tag{10}$$

$$P = \frac{3}{2} (V_d i_d) \tag{11}$$

$$Q = -\frac{3}{2} (V_d i_q) \tag{12}$$

$$i_d* = \frac{2}{3V_d} P* \tag{13}$$

$$i_q* = -\frac{2}{3V_d} Q* \tag{14}$$

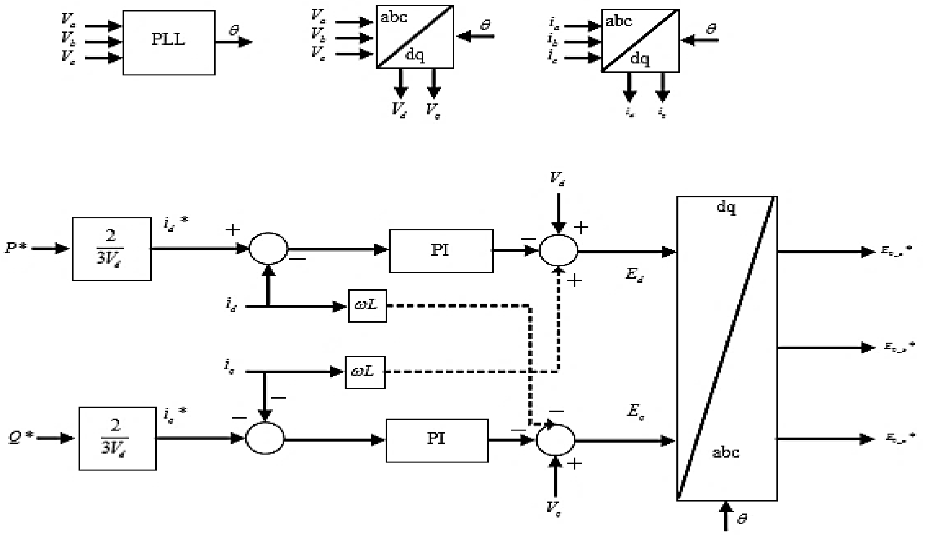


Figure 4. Decoupled based active and reactive power control method

2.3.2. DC Link Control of the MMC

DC link voltage control is illustrated in Figure 5. DC link control is applied to the active current control component. In here, measured DC link voltage is compared with a reference DC link voltage. DC link voltage is calculated as 19kV. Additionally, PI parameters of the DC link control are taken as 0.8 for K_P, 10 for K_I.

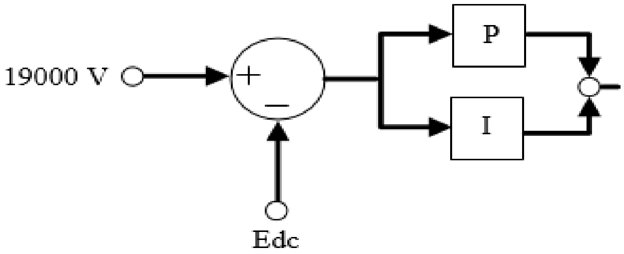


Figure 5. DC link voltage control

2.3.3. Circulating Current Control of the MMC

Circulating current originates from the phase difference between the MMC legs. Additionally, Different submodule capacitor voltage can be lead to circulating current among the upper and lower arms of a phase leg. Circulating current control is one of the most crucial parts of the control system in the MMC. As in the Equation (15)[3], it consists of a dc component of the circulating current which is equal to one third of the DC link current and AC component of the circulating current. DC component of the circulating current is responsible for active power transferring to the the output terminal of the converter. Considering AC part of the circulating current control system, the role of the AC part is to provide reactive power flow among the MMC legs. However, it leads to decreasing the efficiency of the MMC. Thus, it must be suppressed. Several methods are proposed for suppressing AC part of the circulating current.

$$i_{cc} = i_{cc,dc} + i_{cc,ac} = \frac{i_{dc}}{3} + i_{cc,ac} \qquad (15)$$

2.3.4. Capacitor Voltage Balancing of the MMC

Capacitor voltage balancing structures can be classified into two groups as direct modulation based methods and Phase-shifted PWM based control method as illustrated in Figure 6. Direct modulation methods can be grouped as sort and selection method and reduced switching frequency sort and selection method. In these methods, the aim is to charge the submodules with the lowest capacitor voltages and on the other side, discharge the submodules with the highest capacitor voltages depending on the arm current direction.

Considering phase-shifted PWM, the aim of the method is based on the equal arm energy share among the submodule capacitors. Considering direct modulation based sort and selection methods, each arm is represented by one reference voltage. On the other hand, in phase-shifted

PWM based control method, each submodule is represented by its own voltage reference that is the main difference part of the method. Phase-shifted PWM method can be listed as Averaging control, Balancing control and Arm balancing control.

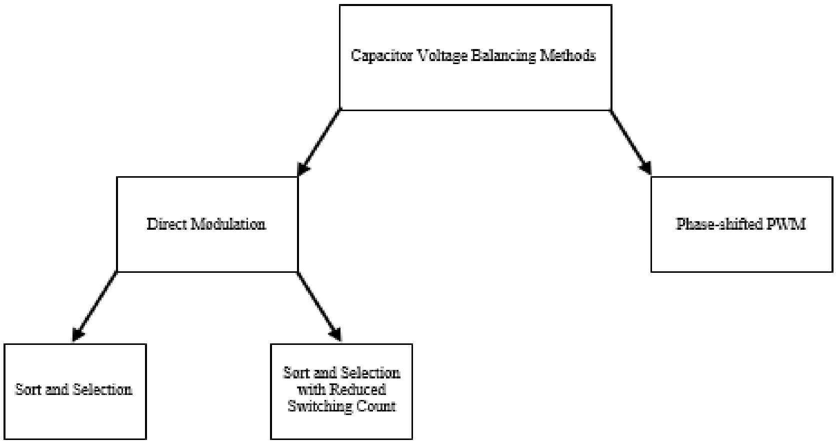


Figure 6. Capacitor voltage balancing methods

3. Results and Discussion

General aspects of the Modular Multilevel Converter such as power circuit analysis and operation principles, advantage sides, application areas and consequently control structures are analyzed in detail as shown in Figure 7. The significance of the results shows that among the other multilevel converter topologies, Modular Multilevel Converter has many advantages and it has several wide application areas.

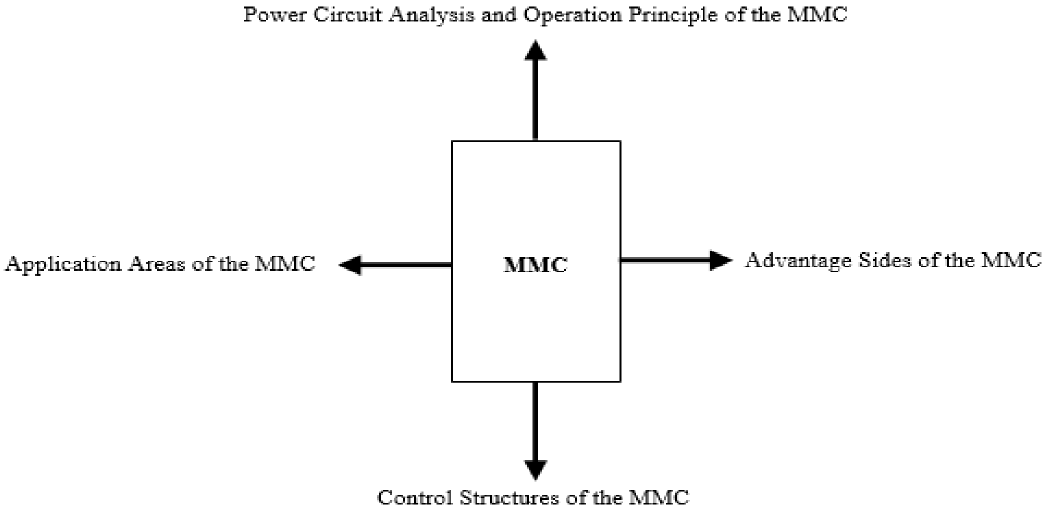


Figure 7. The whole analysis scheme of the MMC

Conclusion

Considering Voltage Source Converters, technical limitations are encountered when higher voltage and power levels. Thus, Multilevel Converter structures are emerged. The unique aspect of the Multilevel converters can be pointed out as lower switching frequency due to low voltage stress on the power switches. Diode clamped, Flying capacitor, Cascaded H-Bridge Converters are represented in Multilevel Converter structures. However, the foot-print of the system in these Multilevel Converters are so high and higher efficiency is required. Hence, Modular Multilevel Converter structure is proposed. Among the other Multilevel Converters, Modular Multilevel Converter has many advantages and application areas for higher voltage and power level implementations as reviewed in this paper.

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