A Review of Modulation Techniques for Chopper cell based Modular Multilevel Converters

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Abstract - ***Modular multilevel converters (MMCs) are an emerging converter topology with advantages of scalability, modularity, reliability, and efficiency making high voltage and power capability possible. They are becoming a more common converter type because of the increased utilization of High Voltage Direct current (HVDC) power transmission. Its applications include Railway electric traction systems(for supplying traction motors), interfacing renewable energy power sources to the grid and motor drives etc. MMCs are beneficial for medium voltage motor drives because of its properties such as low distortion, which allows for an efficient motor drive design. The chopper cell configuration (Half bridge cell) is the simplest submodule configuration of MMC. The converter is made up of a series of IGBT half-bridge circuits with a capacitor across both devices. In this paper different modulation techniques using single reference, two reference and multiple reference used for chopper cell based MMC are reviewed.***

Key Words: *Modular multilevel converter, Modulation techniques, Chopper cell configuration, High Voltage Direct current (HVDC).*

1. INTRODUCTION

High Voltage DC transmission system using voltage-source converters provides a means of connecting distant renewable sources to a large ac power network [1],[2].Conventional VSC based HVDC systems usually use two-level or three-level converters which has disadvantages like uneven voltage distribution across each IGBT, low power quality and high switching loss. Modular multilevel converters (MMCs) can be easily implemented for obtaining high number of levels. It uses more commercially available low-rated IGBTs, so the semiconductor device cost is reduced and also reduced use of filter components. Modular design, excellent output voltage waveforms, low switching frequency, high efficiency are the advantages of MMC [3]-[5].

Multilevel converters have great demand in the electrical power industry in recent years. They have a lot of advantages that makes them suited for high voltage systems and power system applications .Its special structure makes them to work at a very high voltage with low harmonic content. For ac/dc and dc/ac conversion, which is a major requirement in high-voltage high-power applications, the Diode clamped converter topology is used [6]-[8].But, the proper use of this topology requires balancing of the dc link capacitor voltages. A two switch based MMC proposed in [9] is simpler than the cascaded 4-switch H-bridge-based converter and has advantages like modular extension to any number of levels and simplicity.

The principle of operation of the modular multilevel inverters is discussed in [9],[10].Space vector modulation with the modular multilevel converter is vague, because the converter depends on phase voltage redundancy in balancing the capacitor voltages rather than line-to-line voltage as in case of the diode-clamped inverter. Classification of modular multilevel converters, capacitor voltage balancing methods and its control systems have been discussed in [11].Reference [9] explains the importance of capacitor voltage balancing. The explanations of the necessary capacitor voltage balancing methods are discussed in [12]-[18].

2. CIRCUIT CONFIGURATION AND WORKING OF MMCs

Considering the three phase structure of a Modular Multilevel Inverter .They have several configurations, out of which Double Star chopper cell (DSCC) arrangement is chosen for the study. The chopper cell consists of two IGBT switches and a capacitor to form a single submodule .For each phase, there is an upper arm and a lower arm i.e., total of six arms are present in this configuration .Each arm has series connected string of N identical sub modules and a series inductor. Series inductor is provided to limit the arm current and/or fault currents.

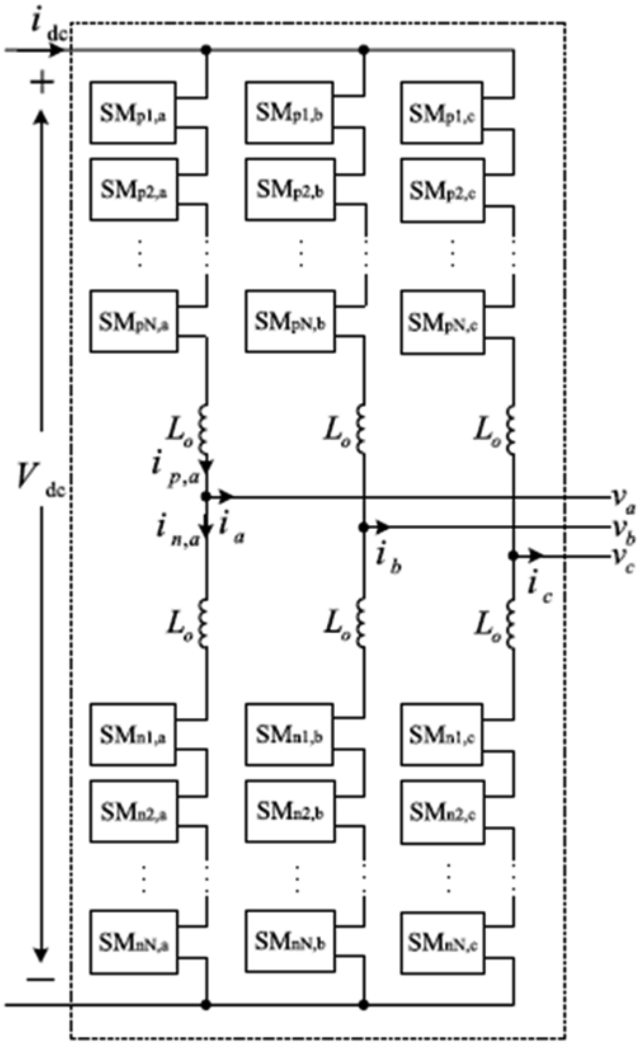

Fig -1: Schematic representation of DSCC-MMC

The structure of MMC is well explained in references [19],[20],[21].Suffixes p and n denotes the upper and the lower arms respectively of the three phases a, b and c. Lo represents the series inductor. Idc and Vdc are the dc link voltage and current respectively. The ac currents through the three phases are ia, ib and ic. Fig.2 shows the capacitor across the two devices is either directly connected into the converter or shorted out depending on the state of the driving gate signals. Some other properties of the converter topology are that this sequence of sub modules along with an arm inductor makes an arm of the converter as shown in Fig.1.The two arms make up one phase of the converter, known as a phase unit. The center point between the arm inductors are connected to the AC side while the phase units are connected in parallel to the DC bus. Every submodule acts as independent DC voltage sources. The number of sub modules chosen is based on the power levels and applications that will be utilized. A typical minimum number of levels is a 5-level MMC which has four submodules per arm. If the number of submodules is equal to N, the modular multilevel converter is described as a (N+1) level MMC. This is because 0 volts is included as a voltage level.

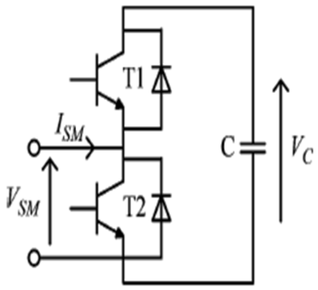

Fig -2: Chopper cell submodule

3. MODULATION TECHNIQUES

Conventional pulse width modulation (PWM) uses one reference waveform and one carrier waveform to generate a gate driving signal. The reference is compared to the carrier and if the carrier is lower than the reference, the PWM output is high and if the carrier is higher than the reference then the PWM output is low. Considering the three phase half bridge circuit discussed above, this pulse width modulation technique can be used to control a conventional voltage source converter. The PWM signal controls the top switch in the half bridge circuit while the inverse of this signal controls the bottom switch in the circuit. For modular multilevel converters, it has several of these half-bridge circuits in the converter that all need to be individually controlled. Thus the solution to this issue is to use multicarrier PWM methods. A carrier waveform is required for each half-bridge circuit, or submodule, in the converter.

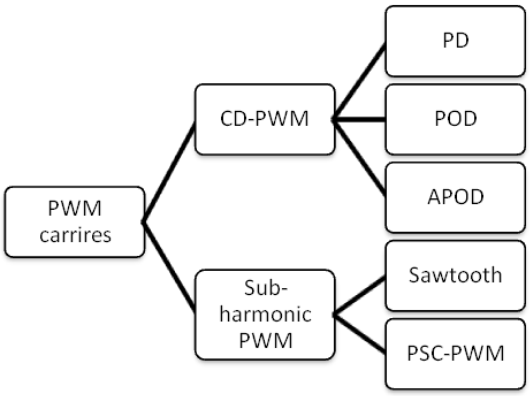

Fig-3: PWM techniques based on carriers

The modulation techniques are classified on the basis of PWM carriers and the reference signal used. The modulations based on PWM carriers are shown in Fig-3 and the techniques based on reference waveform are shown in Fig-4.

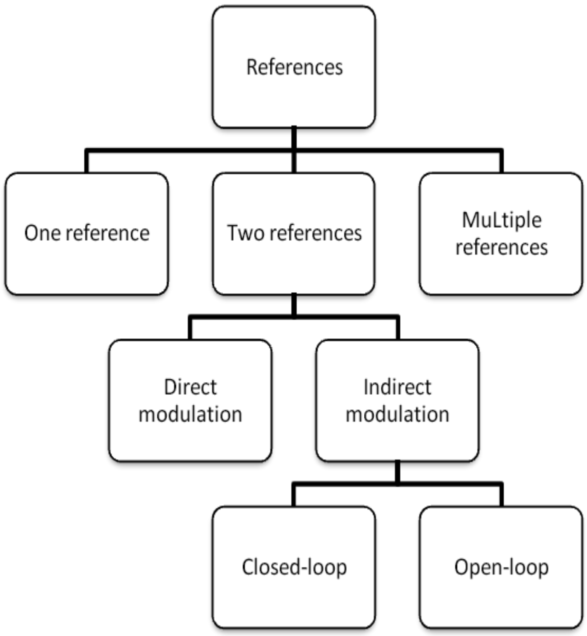

Fig-4: PWM techniques based on reference waveform

PWM techniques based on single reference waveform include:

1) Carrier Disposition PWM (CD-PWM) technique [22],[23]:It requires N triangular carriers which are identical and are equally displaced with respect to zero axis. This carriers are compared with the reference waveform to produce the desired switched output phase voltage level.The Voltage variations corresponding to a triangular carrier are associated with the insertion or bypass of a particular submodule. Based on the phase shift among the carrier waveforms, these techniques are further classified into: PD (phase disposition),POD (phase opposition disposition), and APOD (alternate phase opposition disposition).But its drawbacks include unequal distribution of voltage ripple across the SM capacitors that impact the harmonic distortion of the ac side voltages and large magnitudes of circulating currents. To mitigate the harmonic problems of the ac-side voltages, simple carrier rotation technique [24], modified carrier rotation technique [25], or signal rotation technique [22] is used to make the voltage distribution across all the SM capacitors equal. Its output voltages may have a relatively high total harmonic distortion (THD). For improving the performance of these techniques, a modified PD PWM technique with a SM capacitor voltage balancing technique is proposed in [12].In this method, voltage variations corresponding to a triangular carrier are no longer assigned to a particular submodule.

   In this technique, comparison of the reference waveform with the carrier waveforms produces an (N + 1)-level waveform which determines the number of SMs to be inserted in theupper and arms, respectively. The determined number of SMs out of the N submodules in the upper or lower arm are inserted depending upon the direction of the arm current and the status of the SM capacitor voltages, in order to minimize the difference between the SM capacitor voltages. In reference [26] a PD PWM technique with selective loop bias mapping method for balancing the submodule capacitors. This method implements carrier rotation using the feedback of the maximum or minimum SM capacitor voltages and the direction of arm current.
2) Subharmonic techniques: 2N identical carriers are used in this technique and can be either sawtooth or triangular.Each carriers are phase shifted by $360^0/N$ [22].

The PWM techniques which make use of two reference waveforms are:

1) Direct modulation technique: In this technique voltages of both the arms of phase a is controlled by using two complementary sinusoidal reference waveforms and it is given by equation

$$n_{p,a,ref} = \frac{N\frac{V_{dc}}{2} - V_{a,ref}}{Vdc} \qquad (1)$$

$$n_{p,a,ref} = \frac{N\frac{V_{dc}}{2} + V_{a,ref}}{Vdc} \qquad (2)$$

   The reference waveforms in (1) and (2) are compared with the PD carrier waveforms, which vary between 0 and N, to determine the required number of inserted SMs in the upper and lower arms.

2) Indirect modulation technique: Here the upper and lower arm reference waveform of phase a is given by,

$$n_{p,a,ref} = \frac{N\frac{V_{dc}}{2} - V_{a,ref} - V\sum_{reg,a} - V\sum_{reg,a}^{circ}}{\sum_{i=0}^{N} V_{cp,i,a}} \qquad (3)$$

$$n_{n,a,ref} = \frac{N\frac{V_{dc}}{2} + V_{a,ref} - V\sum_{reg,a} - V\sum_{reg,a}^{circ}}{\sum_{i=0}^{N} V_{cn,i,a}} \qquad (4)$$

   where where $V_{cx,I,a}$ represents the capacitor voltage of ith submodule in arm-x of phase a, and the terms $V\sum_{reg,a'}^{circ}$ and $V\sum_{reg,a}$ are used to control the total energy in the phase a leg and balance the energy between the arms, respectively. Similar to the direct modulation technique, the reference waveforms are compared with the PD carrier waveforms to determine the number of inserted SMs in the upper and lower arms. This technique can be further classified into closed loop control and open loop control.

3) Phase shifted carrier PWM (PSC-PWM):In this technique, each SM of the MMC is controlled independently, and the voltage balancing task of the SMs is divided into an averaging control and a balancing control. The reference waveforms of each SM in the upper and lower arms are given by

$$m_{p,i,j} = \frac{\frac{Vdc}{2N} - \frac{V_{j,ref}}{N} + v_{a,j} + v_{b,j,i}}{v_{cp,i,j}} \quad (5)$$

$$m_{n,i,j} = \frac{\frac{Vdc}{2N} + \frac{V_{j,ref}}{N} + v_{a,j} + v_{b,j,i}}{v_{cn,i,j}} \quad (6)$$

Here $v_{a,j}$ is the averaging controller output and $v_{b,j,i}$ is the individual balancing controller output. The averaging and balancing techniques control the average SM capacitor voltage in each phase-leg and the individual SM capacitor voltage, respectively. Comparison of each SM voltage reference waveform with its triangular carrier generates the switching signals for the corresponding SM. The triangular carrier waveforms of each phase-leg are implemented based on the sub harmonic techniques. The main drawbacks of this technique are its implementation effort that significantly increases as the number of SMs increases and instability under certain operating conditions [20],[27].

4. SIMULATION AND REUSLTS

Fig.5 shows the Simulink model of a single phase three level MMC. Modulation techniques based on single reference waveform was developed and compared. Line to line voltage total harmonic distortion for three carrier disposition strategies was compared and the results were tabulated. Parameters are given below.

Parameters	Specification
DC supply voltage	140V
DC capacitance	3mF
Buffer inductance	1mH
Rated frequency	50Hz
Carrier frequency	1KHz
Load inductance	0.1mH

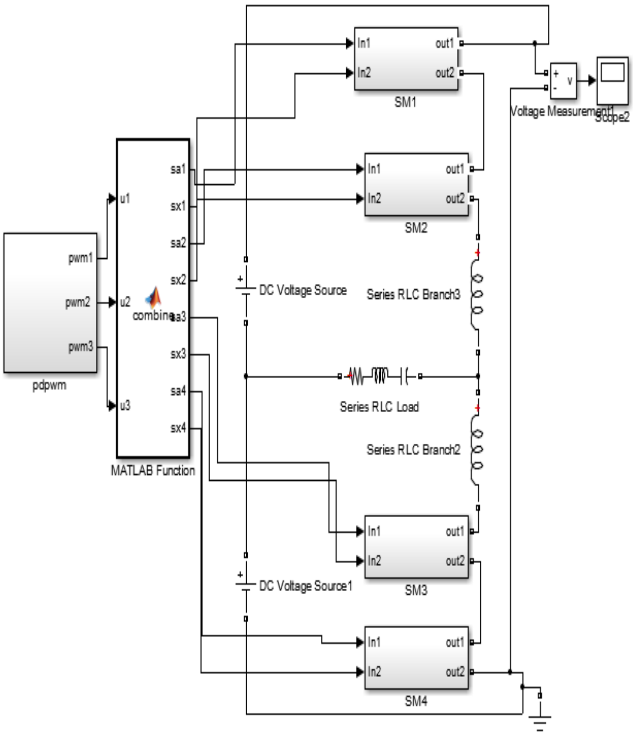

Fig-5 : Simulation diagram of MMC

This paper discusses the comparison of In phase disposition, phase opposition disposition and alternate phase opposition disposition strategies and their effect on line to line THD. The simulation for a 5-level MMC requires 4 carriers and a single sinusoidal reference waveform.Fig.6 shows In phase disposition PWM strategy where all carriers are in phase.

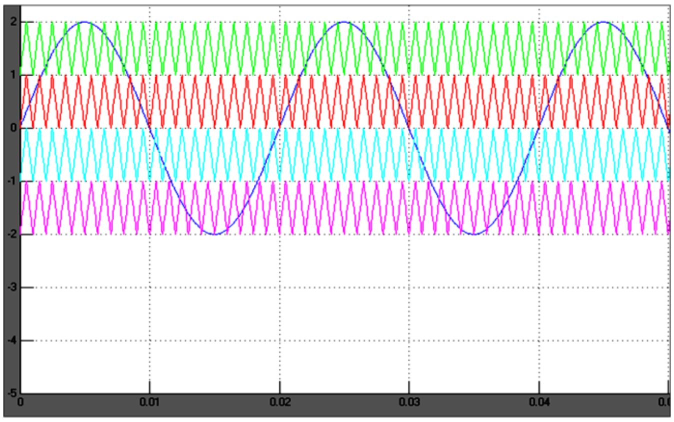

Fig-6 : In phase disposition PWM

In Phase opposition disposition strategy shown in Fig.6, all the carriers below the zero reference is 180 degree phase shifted from those carriers above zero reference. In alternate phase disposition method, all the adjacent carriers are phase shifted by 180 degrees. It is shown in Fig.8.

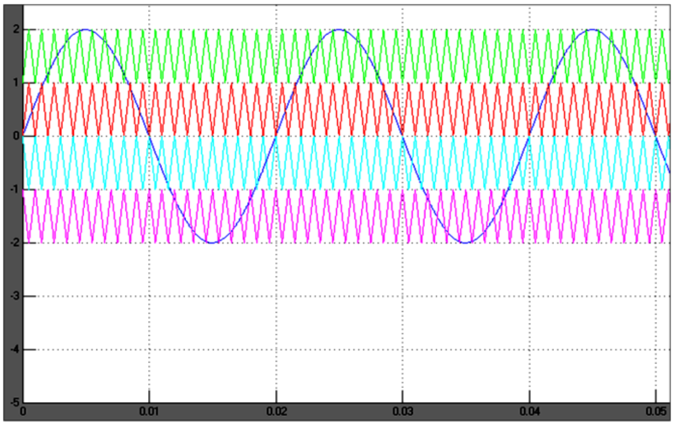

Fig-7 : Phase opposition disposition method

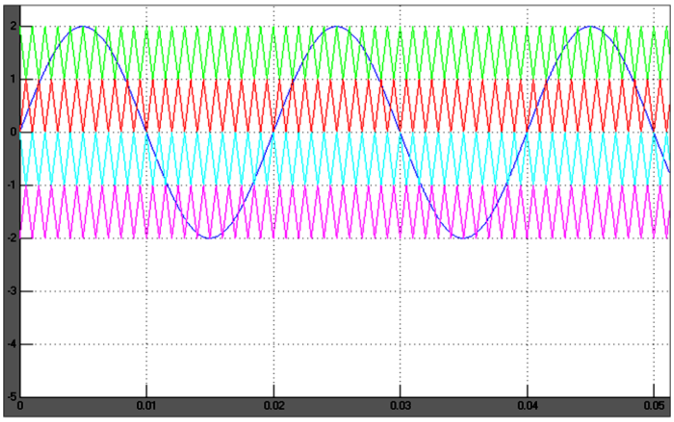

Fig-8 : Alternate phase opposition disposition method

The table shows the comparison of line to line voltage THD of the MMC with the above said modulation strategies.

Table -1: Comparison of modulation strategies

Modulation methods	**Vab**	**Vbc**	**Vca**
PD	17.37%	17.12%	16.91%
POD	22.25%	17.12%	22.30%
APOD	25.29%	26.02%	25.35%

5. CONCLUSIONS

In this paper different modulation strategies used for chopper cell based Modular multilevel converter was discussed. Modulation techniques based on single reference waveform was analyzed separately on the basis on line to line total harmonic distortion. From eliminating harmonics point of view, the In phase disposition method was found to be the best and alternate phase disposition method is the worst.

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BIOGRAPHIES

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