Design and Simulation of Modular Multilevel Inverter Using PWM

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Abstract: Modular Inverter is a kind of new multilevel inverter topology used in HVDC system and medium voltage applications like induction motor drive. Modular Multilevel inverter can operate at high voltages and current with fewer harmonic and simple filters, and without increasing the number of switches. This paper mainly focuses on simple topology for modular multilevel inverter in order to reduce the drawbacks of conventional M- level inverters such as capacitor voltage balancing during medium voltage applications. This paper addresses the basic modes of working, carrier-based sine PWM technique and voltage balancing at each capacitor for a three-level inverter are discussed. The simulation and design was carried out using MATLAB/SIMULINK software.

Keywords – Modular Multilevel Inverter; Sinusoidal Pulse width Modulation; Capacitor voltage Balancing; Diode Clamped Multilevel Inverter.

1. Introduction

Multilevel inverter finds its application in high power system like HVDC transmission in recent years. The necessity of multilevel inverter is to give a high output power. The inputs to the inverter are medium voltage sources such as batteries and solar panel, and super capacitors etc [1]. The M - level inverter consists of many switches with different topologies. The difference is that each inverter will have different switching mechanism and also the supply voltage source may vary. Different M - level inverter topologies are:

- Diode clamped M-level inverter
- Flying capacitors M- level inverter
- Cascaded H- bridge M- level inverter

The diode-clamped converter topologies are used in many high-voltage and high KW applications, because it is posses all the advantages of two level inverters [2]. However, it has the disadvantages that imbalanced dc link capacitor voltage due to this there is an increase in number of levels and switches. The advantages of the normal diode-clamped type inverters are low value of dv/dt and low common mode voltage. The four-switch based multilevel inverter is proposed in this paper with the advantages, such as modularity can be done with reduced switches.
2. Modular Multilevel Inverter

For easiest understanding two level and two switched modular multilevel inverter is considered here for explanation. Modular multilevel converters posses several cells connected in series. The figure 1 shows the half bridge submodule along with the two level output voltage waveform. Basically there are two submodules i.e. Half bridge and full bridge submodule. The advantage of half bridge sub module is less switching losses due to reduced switches. The basic building block is the Sub module. For N-level MMI, The sub modules in each arm is N-1 [4].

![Figure 1. Half Bridge Submodule](image1.png)

The capacitors used in the modular multilevel inverter are called as floating capacitor because it does not requires any external power supply. When the capacitor voltage at each sub module is same charging and discharging of the capacitor will cancel each other. For proper operation of the inverter the SMs capacitor voltage should be balance. During the operation of the inverter circulating current is produced when the capacitor voltage is balanced. This circulating current should be reduced in order to protect the malfunctioning of the switches. The sub module capacitors provide the energy to the MMI for active power transfer to the R load. Some amount of energy is lost in the capacitor and it is satisfied by the dc component of the circulating current. Second order harmonic currents are produced due to the floating nature of the SMs capacitor voltage. And these currents will flow along with other harmonic currents through the inverter. When it is used to drive three phase induction motors it results in damaging of the capacitor during high load current.

![Figure 2. MMI Structure](image2.png)
2.1. Design of Modular Multilevel Inverter

In order to design the MMI power rating is required. From the power rating the DC link voltage is selected in concurrent with the standard voltage and current rating of the power switches. Consider that the DC link voltage is selected [6]. N is the Number of SMs per arm. $C_{sm}$, SMs capacitance is based on the low ripple voltage. When the circulating current (cc) is produced, an arm inductance is connected so that the top arm and bottom arm get isolated and it also reduces the circulating current.

2.1.1 Sub Module Capacitor

Circulating current in the arms causes charging and discharging of the capacitor. Hence arm current produces ripple voltage. Hence the ripple voltage is inversely related to the capacitor. The sub-module capacitance $C_{SM}$ is given by equation (1).

$$ C_{SM} = \frac{s}{3Nm^2\ell_2\varphi} \left(1 - \left(\frac{m\cos\varphi}{2}\right)^2\right)^{\frac{3}{2}} $$

(1)

2.1.2 Arm Inductance

In order to isolate the top and bottom arm switches from the lower arm switches an inductor is connected in series with the load. This will filters the ripples in the output current. The value is given by equation (2).

$$ L_{arm}C_{SM} > \frac{5N}{48\omega^2} $$

(2)

3. Operation of MMI

When the switch $S_1$ is on and $S_2$ is off, output voltage $V_o = 0$ V; when the switch $S_1$ is off and $S_2$ is on, voltage $V_o = V_{dc}$. Thus the operating modes of MMI is summarized in Table 1.

| $S_2$ | $S_1$ | $V_o$ | Current | Power path | State of the Capacitor |
|------|------|------|---------|------------|------------------------|
| OFF  | ON   | 0    | $i_o > 0$ | $S_m$      | No changed             |
| ON   | OFF  | $V_{dc}$ | $i_o > 0$ | $D_c$      | changed                |
| ON   | OFF  | $V_{dc}$ | $i_o < 0$ | $S_c$      | changed                |
| OFF  | ON   | 0    | $i_o < 0$ | $D_m$      | No changed             |

Figure 3. Single Phase of a Three-Level Inverter
In figure 3, $S_{a1}$, $S_{a2}$, $S_{a3}$ and $S_{a4}$ are main switches, $S_{x1}$, $S_{x2}$, $S_{x3}$ and $S_{x4}$ are auxiliary switches. At a particular instant two switches from the main switches and two switches form the auxiliary switches are ON. This will results in four complementary pairs across each phase. The voltage across the each capacitor is $1/2V_{dc}$ [1, 7].

For an N-level inverter, capacitor voltage is $V_{dc}/(N-1)$. Thus for three phase modular multilevel inverter the number of capacitors required is 6N-6. The negative to the negative of the DC source is connected together which forms the midpoint or as the voltage reference to the inverter. Thus from the figure 3 six different switching combinations can be formed for three level Modular multilevel inverter. The three level voltage lies between the nodes a and 0.

1. For $V_{a0} = 1/2V_{dc}$, the main switches $S_{a1}$ and $S_{a2}$ and lower auxiliary switches $S_{x3}$ and $S_{x4}$ are turned ON.
2. For $V_{a0} = 0$, the four switching combinations are
   (a) Turn on $S_{a1}$, $S_{a3}$, $S_{x2}$ and $S_{x4}$.
   (b) Turn on $S_{a2}$, $S_{a3}$, $S_{x1}$ and $S_{x4}$.
   (c) Turn on $S_{a2}$, $S_{a4}$, $S_{x1}$ and $S_{x3}$.
   (d) Turn on $S_{a1}$, $S_{a4}$, $S_{x2}$ and $S_{x3}$.
3. For $V_{a0} = -1/2V_{dc}$, the auxiliary switches $S_{x1}$ and $S_{x2}$ and all lower switches $S_{a3}$ and $S_{a4}$) are turned ON.

The switching combinations are tabulated 2. In order to reduce voltage stress, the cell capacitor who voltage is $1/2$ $V_{dc}$.

**Table.2** Switching Combinations for a Modular Multilevel Inverter

| Output Voltage $V_{a0}$ | $S_{a1}$ | $S_{a2}$ | $S_{a3}$ | $S_{a4}$ | $S_{a1}$ | $S_{a2}$ | $S_{a3}$ | $S_{a4}$ |
|-------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
| $1/2V_{dc}$             | 0       | 0       | 1       | 1       | 1       | 1       | 1       | 0       |
| $-1/2V_{dc}$            | 1       | 1       | 0       | 0       | 0       | 0       | 1       | 1       |
| 0                       | 0       | 0       | 1       | 0       | 1       | 1       | 0       | 1       |

4. **Switching Technique for Voltage Balance**

5. **Figure. 4** Modes of Operation of MMI with different load combination

In a three level, modular multilevel inverter to synthesis the zero voltage there are four switch combinations. Hence it is also called as redundant switch states. The group of switches that produce
the same phase voltage are called as redundant switch states. Thus in order to synthesis the various DC voltage $1/2V_{dc}$ or $-1/2V_{dc}$, a pole is attached either to the positive or negative thus the load has no effect on it. The different load combinations are shown in figure 4.

5. Conventional Carrier type Pulse Width Modulation

In this carrier based sinusoidal PWM, the required output voltage is obtained by comparing the sinusoidal reference waveform to the high frequency triangular waveform as shown in Fig.5. From this comparison the switching pulses are obtained. The average voltage applied across the load is equal to the amplitude of the signal for a period of one triangular cycle. The resulting waveform is a square wave. Thus the harmonic components are shifted to the higher frequency range where it is eliminated by an inductor in series with the circuit[10].

Thus modulation index is $m = A_m/A_c$

where $A_m$ amplitude of the modulating signal $A_c$ amplitude of the triangular carrier. By controlling the modulation index the amplitude of the applied output voltage can be controlled.

![Figure 5. Carrier Based SPWM with m < 1](image)

6. SIMULATION RESULTS of MMI

The simulation is carried out using MATLAB/Simulink. The load connected between the upper and lower arm is R type load which has a value of 50 Ohms.

![Figure 6. Three Level Modular Multilevel Inverter](image)
3- Level Inverter V and I waveforms

From the output waveform the output of the voltage varies from 100 V to 200 V. This output waveform consists of no of ripples.

![Figure 7. Output Voltage of MMI](image)

![Figure 8. Output Current of MMI](image)

Simulation Result Using PWM Technique

From this Modular Multilevel Inverter two systems are used. They are existing (Diode Clamped) and proposed system. In existing system no capacitors are used. In proposed system capacitors are used across the switches. To get the pure output waveform, Sinusoidal technique is used in this method. The pulses are given as per the truth table.

In this existing method capacitors are not used. So the harmonics are high in this system. In order to reduce this harmonics, capacitors are used in proposed in proposed system.
Figure 9. Output Waveform for Existing System

Figure 10. Harmonic analysis for existing system:
In this proposed system capacitors are used in this system. As compared to previous system we are getting a very low level of harmonics. So by using capacitor balance technique and sinusoidal PWM Technique we are achieved a pure sinusoidal output waveform and quality of the waveform is increased. When the quality output voltage waveform increased we are getting a harmonic less voltage.

Figure 11. Output waveform for proposed system

Figure 12. Harmonic analysis for proposed system
6. Conclusion

Thus the output of the three level modular multilevel inverter is compared with the conventional multilevel inverter. The THD of this multilevel inverter is less compared to the conventional multilevel inverter. The proposed inverter is connected to the R type of load. Which results in reduced harmonics components and the output voltage obtained is three level squared waveform. The capacitor voltage balancing technique is implemented through the Carrier based PWM technique which reduces the circulating current.

7. References

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