A SURVEY ON MULTILEVEL INVERTER TOPOLOGIES AND CONTROL SCHEMES WITH HARMONIC ELIMINATION

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ABSTRACT

Multi level inverters have developed as an essential converter in high power medium voltage converters and it has tremendous contribution in renewable energy field. In an attempt to report the recent advances and trends in power electronics technology, this paper presents a review of various multi level converters which are extensively used in industrial applications. The paper focuses to summarize the technological advancements in neutral clamped, cascaded H bridge topologies and flying capacitor. The paper also summarizes about various modulation techniques like fundamental modulation, carrier based PWM techniques, selective harmonic elimination technique etc.

KEYWORDS: multi level inverters, modulation schemes, pulse width modulation, total harmonic distortion (THD)

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INTRODUCTION

Over the recent years, voltage source converters and current source converters operating as rectifier or inverter have become intensive research interest and attracted many industrial application [1]. Inverter is a power semi-conductor device which is used to convert fixed DC signal into variable voltage variable frequency AC signal [2] [3].

Among the voltage source inverters, multilevel converters have arrived as a critical converter in high power applications [4]. The term multilevel denotes converter which is capable of providing two or more levels of voltage. By increasing amount of voltage level, the output voltage with additional steps can generate a staircase waveform which leads to approximated sine waveform with reduced harmonic contents. MLIs require separate DC sources which enables the use of renewable energy sources like photo voltaic(PV) cell, fuel cells, bio cells etc.,[5][6]

Among the various multilevel configurations, the most preferred ones are Flying Capacitor/Capacitor clamped, Cascaded H Bridge (CHB), and Neutral clamped. Compared to conventional two level square wave inverters, MLIs generate a sine wave with requirement of less no of filters [4].Multilevel inverters don't require transformers which eliminates magnetic interference problems. Among various multilevel inverter topologies, modular multilevel converter (MMC) plays as a game changer in various industrial applications and solutions [7]

Multilevel Inverter Topologies

MLIs have attracted numerous applications in recent decades due to increased power rating, reduced voltage stress, reduced total harmonic distortion and reduced electro-magnetic interference. Depending on the type of source used these inverters are classified as VSI (Voltage Source Inverter) or CSI (current source inverter) [8] [9].

Figure 1: Classification of Inverters.

Plenty of MLI topologies have been introduced during the last two decades. This article briefly discusses about various multilevel inverter topologies and harmonic elimination techniques which has attracted many industrial applications and found in literatures like neutral clamped, capacitor clamped, cascaded connected H bridge with split dc sources, modulated multilevel converter and asymmetric hybrid converters [10].

Figure 2: Multi Level Inverters- Classification.

Diode Clamped Multilevel Inverters

This is one of the important multi-level inverter topologies which are also known as neutral point clamped NPC inverter which utilizes series connected diodes along with capacitors to divide the input side voltage into numerous stages. For n stage MLI, $(n - 1)$ DC sources and $(n - 1)$ diodes are required. [11][12]. An example of five-stage neutral clamp multilevel inverter is shown in fig 3.

Figure 3: Diode Clamped Inverter – Five Level.

Table 1: Five Stage-Diode Clamp Inverter - Switching States

T1	T2	T3	T4	T5	T6	T7	T8	Vout
1	1	1	1	0	0	0	0	$V_{IN}/2$
0	1	1	1	1	0	0	0	$V_{IN}/4$
0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	$-V_{IN}/4$
0	0	0	0	1	1	1	1	$-V_{IN}/2$

If the input voltage is V_{IN} , the voltage across every capacitor is one fourth of the input voltage thus all the switching device voltage stress is reduced to one fourth due to the use of diodes [13].

Flying Capacitor/ Capacitor Clamped Multilevel Inverter – Fcmlt

FCMLI topology is almost identical to diode/neutral clamped MLIs, except the factor that clamping capacitors are utilized in its place of clamp diodes to clamp voltage. [14][15]. An example of five level FCMLI and its switching levels are shown in table 2 and figure 4

Figure 4: Flying Capacitor Multilevel Inverter – Five Levels.**Table 2: Five Level Flying Capacitor Topology Switching States**

T1	T2	T3	T4	T5	T6	T7	T8	Vout
1	1	1	1	0	0	0	0	$V_{IN}/2$
0	1	1	1	1	0	0	0	$V_{IN}/4$
0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	$-V_{IN}/4$
0	0	0	0	1	1	1	1	$-V_{IN}/2$

The primary advantage of *FCMLI* topology is that it allows switching redundancies i.e. two are more switching combinations can yield the particular voltage level which is not feasible in case of neutral/ diode clamped inverter. [16] The auxiliary diodes are precharged to required voltage levels which ensure the usefulness of the converter to allow it to generate multi step waveforms. The major advantages of FCMLI are it reduces the requirement of filter and also controls real and reactive power flow in addition to phase redundancies. But with increasing voltage levels, the charging and discharging of the capacitors are not accurate and also leads to increase in cost due to increased number of levels.[17][18]

Cascaded H Bridge Multilevel Inverters CHBMLIS

Among available various MLI topologies, the CHBMLIs provide a promising alternative with modular design which enables transformer less connections. The idea of H bridge MLI is derived from connecting full CHBMLI in succession to obtain a sinusoidal voltage quantity. [19][20] The resultant output is the summation of voltages contributed by individual H Bridge. By properly selecting the switching states, each CHB inverter would generate three voltage levels i.e. positive $+V$, negative $-V$ and zero -0 level. The number of cells / H bridges required depends on operating voltage and manufacturing cost [14]. In any CHB MLI, if $2n+1$ is the desired output voltage level then n would be the number of separate cells required. The CHB multilevel inverters might use equal or unequal dc sources accordingly; there exist symmetrical or asymmetrical CHB MLI topologies.

The basic structure of five level symmetrical CHB MLI topology and switching possibilities are shown in the figure 5 and table 3.

Figure 5: Symmetrical Chb Mli - Five Stage.

Table 3: Five Level CHB Topology Switching States

S1	S2	S3	S4	S5	S6	S7	S8	Output voltage
1	1	0	0	1	1	0	0	$V_{IN}/2$
1	1	0	0	1	0	1	0	$V_{IN}/4$
0	1	1	0	1	0	1	0	0
0	1	1	0	0	0	1	1	$-V_{IN}/4$
0	0	1	1	0	0	1	1	$-V_{IN}/2$

Apart from providing redundancies in switching states, the CHB MLIs require lesser amount of switching elements compared to capacitor clamped or diode clamped topologies which results in less manufacturing cost and weight of the converter[21]. Moreover CHB MLIs are available with higher voltages(13.8kV) and power levels (30MVA) which attracts many researchers and industrial collaborators.[22]

Emerging Multilevel Inverter Topologies

Apart from the existing topologies, there are several hybrid configurations which are finding wide applications in voltage control. Few of the upcoming topologies are mentioned below.

Hybrid Multilevel Cells

Instead of cascaded H bridge inverters, it is feasible to have cascaded multilevel capacitor clamped or neutral point clamped inverters in various applications. Such combinations of above mentioned conventional multilevel inverter topologies leads to hybrid multi-level inverters. These proposed multilevel inverters mainly aims at reducing the number of separate DC sources required [23] [24].

One such hybrid nine level mixed multilevel inverter using capacitor clamped is shown below.

Figure 6: Nine Level Hybrid Cell Configuration using Clamping Capacitor to Increase Voltage Level.

Asymmetric Hybrid Multilevel Cells

In most of the CHB multi level inverter configurations, the separate DC sources used will be of equal magnitude. However it is possible to have different voltage sources and such a converter is called as asymmetric multilevel converter. The primary objective of this asymmetric inverter topology is to use less number of semi-conductor switches compared with symmetrical configuration with an interesting feature of achieving higher voltage level with same number of cells i.e., in case of symmetrical topology the number of level increases proportionately to the number of cells whereas herein asymmetrical topology it becomes exponentially. [25][26]

Soft Switched Multi Inverters

Soft switching schemes are becoming popular due to reduced switching losses and increased efficiency. With conventional

hard switching inverters electromagnetic interference is a major problem. Even though zero current switching is feasible utmost the literature proposes zero voltage switching topology for multilevel inverter voltage control. [27]

Three Phase Hybrid Inverters:[28]

Several three phase hybrid inverters are now a days proposed by various researchers. One such example of hybrid inverter suitable for three phase loads with reduced switching components in comparison with traditional three phase cascaded H bridge topology is shown in the figure

Figure 7: Hybrid three phase DC link Multi Level Inverter.

In conventional topology, 36 switches are required whereas this proposed hybrid topology uses fewer switches i.e. for m level output voltage $m+3$ switches per phase is only required. For this topology, the preferred modulation techniques are sub harmonic and SVPWM methods. The per phase switching states for hybrid inverter is shown in the table 4.

Table 4: Per Phase Switching States Hybrid CHB Inverter

V_o	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0	1	0	0	1	0	1	0	1	0	1
E	1	0	0	1	0	1	0	1	1	0
2E	1	0	0	1	0	1	1	0	1	0
3E	1	0	0	1	1	0	1	0	1	0
-E	0	1	1	0	0	1	0	1	1	0
-2E	0	1	1	0	0	1	1	0	1	0
-3E	0	1	1	0	1	0	1	0	1	0

Control and Modulation Approach

Overview & Classification - Modulation Approaches

The choice of modulation strategy for MLI is an essential issue for any multilevel inverter control. The modulation approaches are classified as fundamental and high frequency methods based on switching frequency used for pulse generation[29].The fundamental switching frequency technique which is also called as low switching frequency requires less commutations of switches for one cycle-operation. SHE (selective harmonic elimination) technique and SVM (space vector modulation) technique are examples of low switching frequency. High switching frequency modulation technique requires many commutations of power switches during one cycle of the output voltage. Carrier based PWM technique is the most preferred switching technique among the high switching frequency methods, which needs phase shifting technique so that harmonic components are reduced in load voltage [30].

Selective Harmonic Elimination Modulation Technique

In low frequency switching modulation techniques, all the power switches are turned on and off only once per fundamental cycle, therefore compared to carrier based PWM techniques switching losses are less. The drawback of fundamental switching frequency is that the range of modulation index is narrow which leads to increase in total harmonic distortion THD [31],[32]. SHE can be utilized at low switching frequencies without compromise on quality of power and it is also one of the most preferred modulation techniques for medium and high power applications. As the side band frequency near the carrier frequency produces lower order harmonics distortions, techniques like carrier based pulse width modulation should not be used for applications which requires low switching frequencies. [33]

Cascaded H bridge inverter used to produce 7 output voltage level taken as case study [34] is shown in the figure

Figure 8: Cascaded H Bridge Mli - Seven Level.

The voltage derived using Fourier analysis is given below,

$$V(\omega t) = \sum_{n=1}^{\infty} V_n \sin n\omega t \quad \dots\dots (1)$$

In the above equation, V_n represents the amplitude of n th harmonic component.

Figure 9: Output Voltage Waveform 7 Level CHB MLI.

Even order harmonics are zero, since the waveform has odd quarter symmetric,

Consequently V_n becomes [35],

$$V_n = \frac{4V_{dc}}{n\pi} \sum_{i=1}^s \cos n\theta_i \text{ for odd } n \quad (2)$$

$$= 0 \text{ for even } n$$

To eliminate fifth and seventh order harmonics, the non linear equations can be written as,

$$V_1 = \frac{4V_{dc}}{\pi} [\cos\theta_1 + \cos\theta_2 + \cos\theta_3]$$

$$V_5 = \frac{4V_{dc}}{5\pi} [\cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3] \dots\dots\dots (3)$$

$$V_7 = \frac{4V_{dc}}{7\pi} [\cos 7\theta_1 + \cos 7\theta_2 + \cos 7\theta_3]$$

To eliminate 5th and 7th order harmonics V_5 and V_7 should be set to according to the modulation index range given below,

$$M \cong \frac{V_1}{12V_{dc} / \pi} \dots\dots\dots (4)$$

Using (3) and (4), the equations can be simplified as follows,

$$M = \frac{1}{3} [\cos\theta_1 + \cos\theta_2 + \cos\theta_3]$$

$$0 = \cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3 \dots\dots\dots (5)$$

$$0 = \cos 7\theta_1 + \cos 7\theta_2 + \cos 7\theta_3$$

The above equations can be simplified using iterative methods like Newton- Rapson to find the angles θ_1 , θ_2 & θ_3 corresponding the range of M .

The drawback of SHE is that for different levels different switching angles should be calculated according to chosen M which involves tedious calculations [36]. The major challenge with the technique is to find the detailed solutions of equations that contain complicated terms like trigonometric terms which might provide different set of solutions.[37],[38] [39]

Multicarrier PWM Techniques

There exist several PWM techniques for multi-level inverters [40] which can be generalized into two categories as mentioned below,

- Single carrier sinusoidal PWM
- Sub harmonic or level shifted PWM

The sub harmonic or level shifted PWM is widely used modulation strategy [41] [42] which can be further classified as shown below in the figure 10

Figure 10: Classification of Level Shifted PWM.

In order to evaluate and describe different PWM modulation techniques, the following definitions are useful.

$$\text{Frequency modulation index } m_f = \frac{f_{cr}}{f_m},$$

where

f_{cr} represents carrier signal frequency

and f_m represents reference signal frequency.

$$\text{Amplitude modulation index } m_a = \frac{v_m}{v_{cr}(m-1)}, \text{ where } v_m \text{ represents peak amplitude of modulating wave and}$$

v_{cr} represents peak amplitude of carrier wave.

Displacement angle Φ , the angle of displacement between reference sine signal and the first appearing positive carrier signal.

Single Carrier SPWM

Reference sinusoidal voltage waveform is compared with carrier triangular waveform in order to generate gate pulse signals for the switches of the inverter in this technique [43] [44]. The carrier signal is a triangular waveform with frequency f_c and amplitude A_c . The reference signal is a sine waveform with frequency f_m and amplitude A_m . The modulation index is given by

$$m_i = \frac{A_m}{MA_c}$$

Where

M represents – number of required converter cells

i.e. M = 3 for seven level converter

Figure 11: Single Carrier Sinusoidal PWM.

Phase Shifted Carrier PWM Method PSCPWM

The phase shifted carrier PWM [45] [46] technique is the commonly used modulation strategy for cascaded H Bridge MLIs. The major advantages of PSC PWM are equal switch and power utilization. There exist phase differences between each carrier signals which can be calculated by the given equation (6), in which m is the number of level in cascaded H bridge topology. Hence if there are seven levels, the six carrier signals require 60° phase difference between each.

$$\phi_{cr} = \frac{360}{m-1} \dots\dots\dots (6)$$

Carrier Disposition or Level Shifted PWM

In carrier disposition method, the various carrier signals are placed at different levels with respect to each other and reference signal. The most widely used level shifted PWM techniques [47] [48] [49] are

- Phase Disposition PWM (PDPWM)
- Phase Opposition Disposition (POD PWM)
- Alternate Phase Opposition Disposition (APOD PWM)

PDPWM

In phase disposition method, all carrier signals are in- phase. For i level inverter, (i-1) identical triangular carrier signals are placed one upon the other and compared with modulating signal. The frequency of the carrier signal is calculated by

$$f_c = 3 * (2k+1) f_m$$

Where k is a positive integer and f_m is the frequency of the modulating signal. Compared to other carrier disposition methods, it is found that this method gives rise to lower order harmonics with higher modulation indices. The arrangement of carrier signals and reference signal for a seven level cascaded H bridge inverter [50] is shown in fig 12

Figure 12: Carrier and Modulating Waveforms PD PWM – 7 Level CHB MLI.

POD PWM

In phase opposition disposition technique, [51] the carrier signals above the sinusoidal reference zero point are 180° out of phase with those below the zero point. i.e. the carrier signals above the zero reference line are in phase and below are also in phase but are 180° phase shifted from those above zero as shown in fig 13. [52][53] Compared to PD PWM method, the harmonic performance is better.

Figure 13: Carrier and Modulating Waveforms PODPWM – 7 Level CHB MLI.

APOD PWM

In this modulation technique, which is believed to have better harmonic spectrum has [54] each carrier signal phase shifted by 180° from its adjacent one. The comparison of carrier and modulating signals is shown in fig 14.

Figure 14: Carrier and Modulating Waveforms APOD PWM – 7 Level CHB MLI.

The harmonic performance of CHB MLI from 3 to 9 levels using various phase shifted PWM techniques has been summarized in the table 5 [55] [56] [57]

Table 5: Comparison of Thd using Different PWM Techniques

S NO	Number of Levels	PWM Technique	THD %
1	3 level	PD	52.06
2		POD	54.17
3		A-POD	54.17
4	5 level	PD	26.69
5		POD	26.96
6		A-POD	37.13
7	7 level	PD	18.05
8		POD	22.48
9		A-POD	25.20
10	9 level	PD	16.77
11		POD	17.08
12		A-POD	17.10

From the table [58] it can be concluded that with increasing levels the harmonics are getting reduced

CONCLUSIONS

This paper has analyzed different multilevel inverter topologies and control strategies suited for engineering applications. From the literature it is concluded that with increasing number of levels, the harmonic content THD gets reduced but requires more switching devices which results in increased cost and switching losses. So the designer is in a need to have tradeoff between voltage level and number of switching devices required. The conventional topologies which serve as the basis of several hybrids modern converters are given emphasis. The paper also reviewed emerging hybrid topologies with reduced switching devices including three phase topology. Compared to traditional topologies, the above mentioned hybrid topologies appear to have low total harmonic distortion and also requires less number of power semi-conductor components. It is strongly believed that this review article might serve as a source of literature for various new upcoming researchers in the multilevel voltage source inverter field.

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