Reduced Switch Multilevel Inverter Topologies And Modulation Techniques For Renewable Energy Applications

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Abstract: Multilevel inverters (MLIs) have been extensively used and gained interest over last few decades in industrial and grid connected renewable energy applications because of its numerous merits. Besides various advantages like obtaining reduced harmonic distortion and lesser dv/dt stress across switches it has the capability of generating any number of levels. The theory of multilevel concept was initiated for high power and high/medium voltage applications as they are helpful in interfacing with renewable energy sources. By proper combination of the switches it generates a stair case output with reduced harmonic distortion because of this MLI is widely used and it became one of the advanced power converter topology. The rise of new topologies has attained importance over conventional multilevel inverter topologies, which generates more number of levels with reduced switch components. This paper presents various conventional MLI topologies and hybrid MLI topologies for renewable energy applications. Also, this review paper includes different modulation strategies which plays an important role to improve the overall performance of MLI.
Keywords: Conventional Multilevel Inverter, Reduced Switch Multilevel Inverter, Modulation Strategies, Renewable Energy Sources, Harmonic Distortion

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1. Introduction

The increasing demand for electrical energy is the basis for intense reduction in conventional energy sources. This also gave rise in extensive research in the field of renewable energy based power generation. Solar and wind are the major renewable energy sources gaining more interest among power electronics and power systems community [1] [2] [3]. This needs new power converter topologies to improve power quality for desired operation, control and power management and to extract maximum power from the renewable energy sources.

The important and essential part of power conversion in renewable energy is an inverter which is used to convert DC to AC which is required by grid/loads [4]. However, the output of the inverter contains largeharmonics, so the usage of costly and large low pass filters is used before feeding power to utility grid. Further, because of high voltage stress and switching losses these are refraining from using for high power applications. As a best substitute for medium and high power applications multilevel inverters are evolved. The MLI Concept was first introduced in the early 1975 [5] followed by different variations [6] [7]. Conventional MLI topologies are classified into three namely: Flying Capacitor MLI (FC-MLI), Diode clamped MLI (DC-MLI) and Cascaded H-bridge MLI (CHB-MLI). The key features of MLIs are: it produces output waveform with low harmonic distortion, it operates both fundamental switching frequency and high switching frequency PWM, etc.; The only disadvantage is the requirement of large number of power switching which increases the complexity and makes the system bulky. In order to overcome this MLI topology with reduced switch count has come into focus. Fig.1 shows various conventional and reduced switch MLI topologies. These are used in various applications such as renewable energy sources, drives, FACTS and electric vehicles. Fig 2. gives the overall contribution of this paper.

With the advancements in in these MLI topologies challenges have raised in control and modulation of the inverters. Lower order harmonics are present in the stepped output voltage of the inverter, which lead to disoperation, voltage fluctuations which in turn affects the power quality. So a suitable modulation technique has to be chosen in order to improve the overall performance of the system.

2. Conventional Multilevel Inverter Topologies

Conventional MLI topologies are extensively used in various industrial and grid connected renewable energy applications. The popularity of these topologies is outstanding to several advantages such as lower harmonic distortion, lower switching losses, modular structure and ease of control. In this paper the working principle of all

the three classical MLI topologies for single phase five level configuration with the help of switching tables is explained.

Classical MLI topologies are categorized into three types:

- a. Diode clamped MLI (DC MLI)
- b. Flying Capacitor MLI (FC MLI)
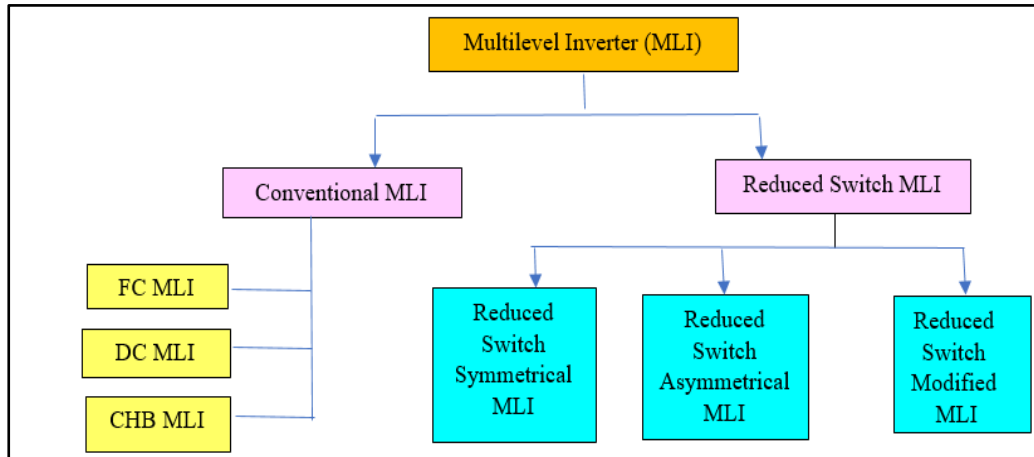- c. Cascaded H-Bridge MLI (CHB MLI)
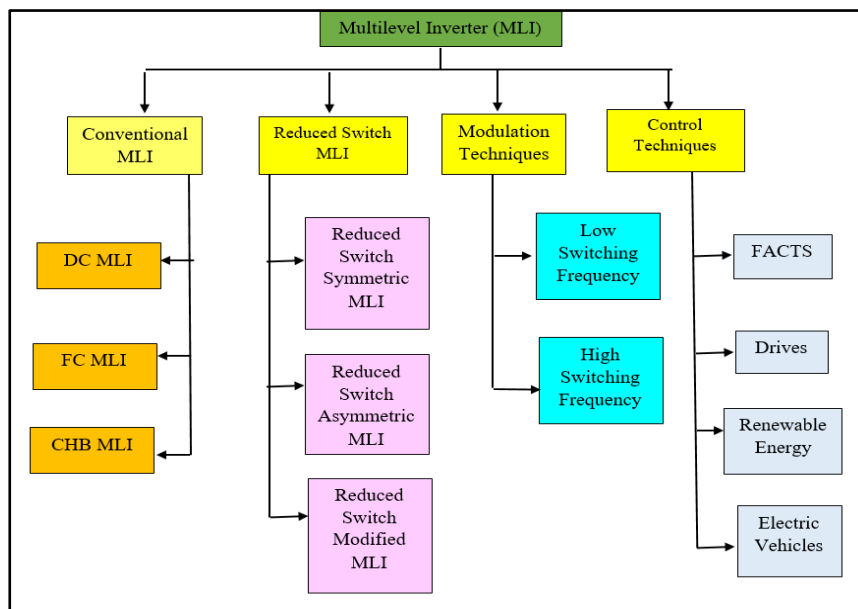
Fig 1. Classification of Conventional and Hybrid MLI

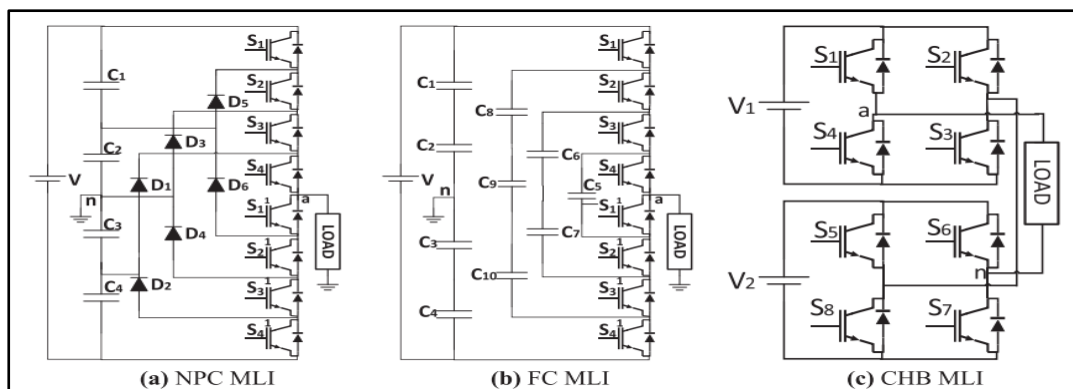**Fig 2.** Overall Contribution to the Review

Fig 3: Conventional Multilevel Inverter Topologies

A. Structural Configuration of Diode Clamped MLI (DC MLI)

Diode clamped is also referred to as neutral point clamped MLI. Fig 3 (a) shows five level neutral point clamped topology. In a five level [8] [9] it consists of four capacitors of high value and DC link voltage is divided equally among the four capacitors. Mid-point is chosen as reference or neutral point. The single phase five level consists of four switches S1-S4, four complimentary switches S1'-S4' and clamping diodes D1-D6. Here the phase voltage is calculated between points a and n. Every switch of the leg is connected to the clamping diodes D1-D6 which decreases voltage rating. It generates five voltage levels -Vdc/4 to +Vdc/4 as well as –Vdc/2, 0, +Vdc/2. Table 1 below gives the switching states to generate five level output of DC MLI. For instance, to generate 0V Upper two switches S3, S4 and lower two switches S1', S2' are on. This is one of the popularly used topology in medium voltage/high power applications.

Table 1: Switching States of Five Level DC MLI

Output Voltage	S1	S2	S3	S4	S1'	S2'	S3'	S4'
$V_{dc/2}$	1	1	1	1	0	0	0	0
$V_{dc/4}$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$-V_{dc/4}$	0	0	0	1	1	1	1	0
$-V_{dc/2}$	0	0	0	0	1	1	1	1

B. Structural Configuration of Flying Capacitor MLI (FC MLI)

Single phase FC MLI is shown in fig 3 (b) [8] [9] [10]. It consists of four capacitors C1-C4 which has equal magnitude and voltage rating and splits the DC bus into four equal voltages. This topology consists of four switches S1-S4, four complimentary switches S1'-S4' and flying or clamping capacitors C5-C10 which is used to clamp the voltage across each switch. Table 2 gives the switching states of five level FC MLI. For instance, to generate 0V Upper two switches S1, S2 and lower two switches S1', S2' are on. This topology is used in high frequency applications.

Table 2: Switching States of Five Level FC MLI

Output Voltage	S1	S2	S3	S4	S1'	S2'	S3'	S4'
$V_{dc/2}$	1	1	1	1	0	0	0	0
$V_{dc/4}$	1	1	1	0	1	0	0	0
0	1	1	0	0	1	1	0	0
$-V_{dc/4}$	1	0	0	0	1	1	1	0
$-V_{dc/2}$	0	0	0	0	1	1	1	1

C. Structural Configuration of Cascaded H-Bridge MLI (CHB MLI)

Single phase five level cascaded H bridge topology is shown fig 3 (C). It consists of two cells, each having a H-bridge. Each H bridge contains four unidirectional switches and a DC source [11] [12] [13]. An H- bridge produces three output voltage levels shown in Table 3. Table 4 gives the output voltage synthesis of two H-bridges. It is widely used in battery powered applications, grid integration systems and standalone PV systems.

Table 5 gives the detailed analysis of conventional MLI topologies with respect to the power components required per phase.

Table 3: Phase Voltage of Single H-Bridge

V_{an}	S1	S2	S3	S4
0	1	1	0	0
	0	0	1	1
V	1	0	1	0
-V	0	1	0	1

Table 4: Switching States of Five Level CHB MLI

V_{an}	Cell-1	Cell-2
0	0	0
	V	-V
	- V	V
V	V	0
	0	V
2V	V	V
-V	- V	0
	0	- V
-2V	- V	- V

3. Reduced Switch Multilevel Inverter Topologies

Although above mentioned classical multilevel inverters have numerous applications these topologies need more number of power components. So from last few decades the focus of the research is to reduce the switches, diodes and voltage sources that can improve the quality as well as reduce the switching losses and overall cost. In this regard various new reduced switch topologies have been introduced that are suitable for various applications such as drives, Renewable energy systems and FACTs. These are used in grid tied and standalone systems. These are classified as Reduced Switch Symmetrical (RSS) MLI, Reduced switch asymmetrical (RSA) MLI, Reduced switch modified (RSM) MLI. The modified type contains all the hybrid and topologies that are not based on H-bridge. This paper gives comprehensive review of some topologies that are developed in recent time.
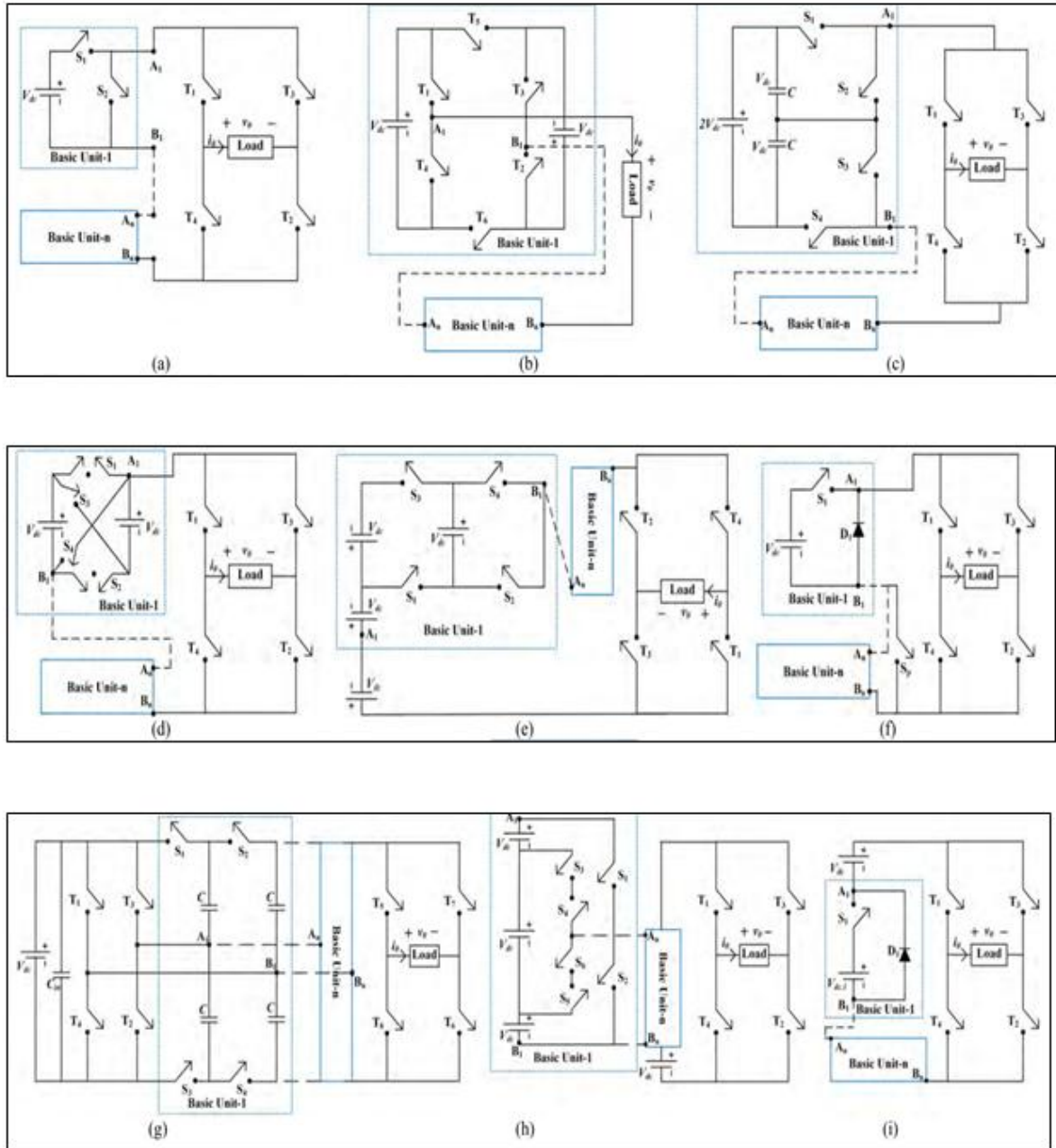
Fig 4: Generalized RSS MLI Topologies (a) RSS MLI 1 (b) RSS MLI 2 (c) RSS MLI 3 (d) RSS MLI 4 (e) RSS MLI 5 (f) RSS MLI 6 (g) RSS MLI 7 (h) RSS MLI 8 (i) RSS MLI 9

A. Reduced Switch Symmetrical H-Bridge MLI (RSS MLI)

As the name itself indicates it consists of all DC sources with equal magnitude. In [14] *Babaei et al.* proposed a new MLI shown in fig 4 (a). This topology was designed with reduced cost and installation area and has used fundamental switching technique. When compared to conventional MLI there is significant reduction in switches. A novel MLI topology shown in fig 4 (b) and 4 (c) discussed in [15] [16]. This is used for low voltage applications. The MLI shown in fig 4 (d) [17] can be operated both in symmetric and asymmetric modes. Author developed a new cascaded H-bridge topology with four switches connected in cascaded form and two DC sources using vertical phase shifted sinusoidal PWM. Another MLI topology shown in fig 4 (e) is proposed in [18] which contains three dc sources of equal magnitude with four switches which uses Multi carrier sub harmonic PWM. This can be used in sigh power and high toltage applications. It is used as an alternative to conventional topology for RES applications.

Wang et al. proposed a new topology in [19] new switched diode MLI shown in fig 4 (f) with reduced size, cost and removal of high voltage spikes from the output voltage and has used clock phase shifted one cycle

control. In [20] author developed MLI based on switched capacitor in order to improve the power density and energy conversion efficiency and has used basic SPWM technique shown in fig 4(g). In [21] S. S. Lee et al. developed an improved sub module based MLI with reduced number of switches using SHE-PWM. It can be used in renewable energy applications, especially PV and fuel cells which is shown in fig 4 (h). In [22] *K. P. Panda et al.* developed a reduced a reduced switch MLI which require less number of active switches and mitigate dominant lower order harmonics using Modified PSO based SHE technique. This is used in renewable energy and drive applications. The topology is shown in Fig 4 (i).

B. Reduced Switch Asymmetrical H-Bridge MLI (RSA MLI)

An Asymmetric MLI topology is that it contains dc voltage sources of different magnitudes. The main aim is to generate higher number of voltages with reduced number of switches. Asymmetric structure of cascaded H-bridge topology with DC sources of different magnitude was discussed in [23] shown in fig. 5 (a). In [24] author has developed a reduced switch MLI shown in fig. 5 (b) in order to generate more number of output voltages using isolated DC sources. This topology is used in medium voltage applications. In [25] author developed MLI topology which is used for both symmetric and asymmetric modes which is modular and uses crisscross connection. This topology shown in fig. 5(c) is used in Renewable energy applications and used for high voltage applications.

N. Prabaharan et al. [26] developed a new MLI topology shown in fig. 5 (d) using unipolar PWM strategy which is especially used in PV applications. *R. S. Alishah et al.* [27] developed a MLI topology which has reduced number of switches, shown in fig 5 (e) used for both symmetric and asymmetric configuration using fundamental switching Technique. This topology is used renewable energy integration. The advantages of reduction in blocking voltage and reduced switch count are the reasons that this topology can be used for high power applications, the only drawback of this topology is by increasing the number of levels additional diodes are required.

In [28] author has introduced a new topology using stair case modulation technique which is complex. It is used in permanent magnet drives, distributed PV power generation. The topology is shown in Fig 5 (f).

E. Babaei et al. [29] a basic unit was developed which can operate both in symmetric and asymmetric configuration using fundamental switching scheme. This is used in medium and high voltage applications. The topology is shown in Fig 5 (g).

J. Liu et al.[30] developed a topology based on switched capacitor module which is best suited for high switching frequency power distribution network. This topology is used in grid connected PV applications and EV applications. The topology is shown in Fig 5 (h).

C. Reduced Switch Modified MLI (RSM MLI)

Topologies without H-Bridge are studied in this category. Basically, H-bridge topologies are used in medium and low voltage applications. The voltage stress on H-bridge switches narrows down the application in high voltage applications. If it is used in high voltage applications the efficiency reduces. Therefore, some new topologies are developed to overcome this drawback. In this section various such topologies will be discussed.

In [31] author has developed a Modified MLI topology shown in fig 6 (a) consisting of floating input DC sources connected in opposite polarity alternatively. In this reduced switch count is achieved, but modularity and fault tolerant capability are less compared to conventional CHB MLI. In [32] a new topology shown in fig. 6(b) has evolved which can also be operated in symmetric and asymmetric modes. This topology is used in high and medium voltage applications. *C. I. Odeh et al.[33]* has developed modified MLI topology with reduced switch count shown in fig 6(c) used for integration of renewable energy sources. In this topology significant reduction in the number of active switches is achieved, but at the cost of extra diodes and bidirectional switches. *S. Xu et al. [34]* has developed a novel modified MLI shown in fig 6(d) for high efficiency and medium voltage applications with reduced number of switches and redundant switching states.

E. Samadaei et al.[35] has developed an E-type module based MLI shown in fig 6 (e) that can generate a staircase output with reduced number of switches using SHE PWM technique. This topology is popular in high voltage/power applications because of low voltage stress and reduced switch count. In [36] author has developed a novel square type MLI shown in fig 6 (f) using unequal DC sources and less number of components and has used NLC PWM technique. Because of its ease of control and modularity more number of voltage level can be obtained with less number of switches and low voltage stress across the switches. This topology is used for high voltage and power applications, especially in PV applications. In [37] a new modularized topology was developed with less voltage stress and reduced number of switches. This topology shown in fig 6 (g) is used for renewable energy applications.

In [38] [39] a semi cascaded MLI topology was developed which can be used for both symmetric and asymmetric configurations shown in fig 6 (h) (i) using fundamental switchingtechnique. These topologies are used in medium voltage applications, especially with PV.

4. Modulation Techniques

Different modulation techniques are proposed in the literature [40] [41] and the same is modified in [41]. Basic classification of the schemes is presented in the below Fig. 7. The classification is based on the switching frequency. In [42] the author enhanced the performance of the seven level symmetric MLI using Multicarrier PWM Technique.

As the number of levels are more than 5 space vector modulation becomes difficult to implement so in this paper carrier based PWM for 11 level will be discussed in detail.
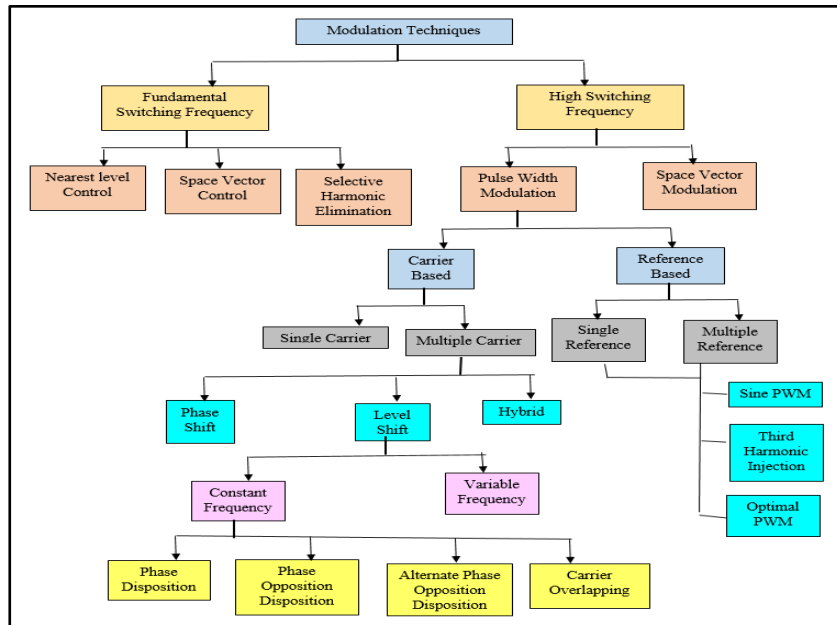

Fig 7: Overall Representation of Modulation Techniques in MLI

A. Phase Disposition PWM Strategy: In this method, all the carrier signals above and below zero reference are in same phase. The arrangement is shown in Fig. 8
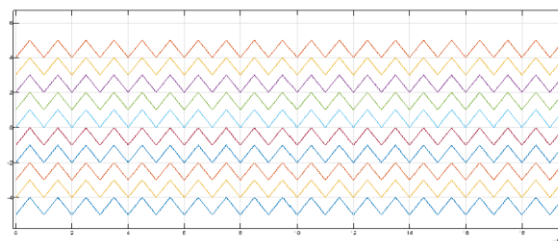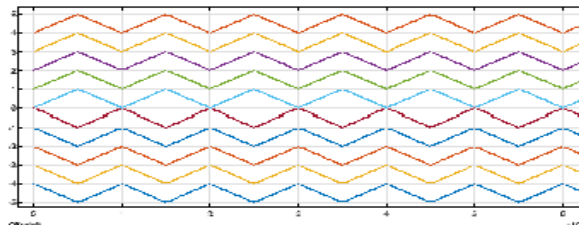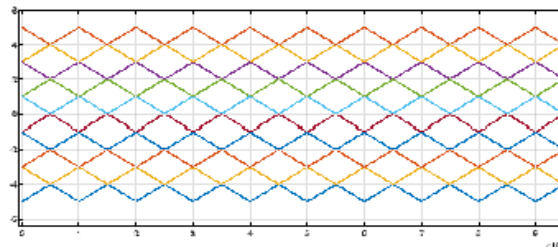

Fig 8: Multi carrier signals for PD-PWM

B. Phase Opposition and Disposition PWM Strategy: In this method, all the carriers have same amplitude and frequency. All the carriers above zero reference are in same phase and all the carriers below zero reference are in same phase but 180 degrees' phase shifted with respect the above carriers. The arrangement is shown in Fig 9.
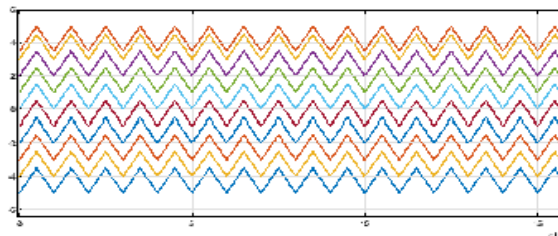
Fig 9: Multi carrier signals for POD-PWM

C. Alternate Phase Opposition Disposition PWM Strategy: In this method, all the carriers havesame amplitude and frequency. All the alternate carriers are in same phase and the others are phase shifted by 180 degrees. The arrangement is shown in Fig 10.
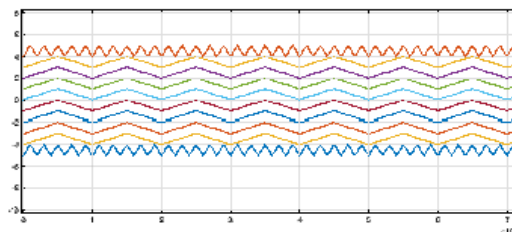

Fig 10: Multi carrier signals for APOD-PWM

D. Carrier Overlapping PWM Strategy: In this method, the carriers are overlapped with each other as shown in Fig 11.


Fig 11: Multi carrier signals for CO-PWM

E. Variable Frequency Carrier PWM Strategy: In this method, the frequency of the carriers is not same. Some carriers have same frequency others have different frequency. The arrangement is shown in Fig 12.

Fig 12: Multi carrier signals for VF-PWM

F. Phase Shift PWM Strategy:In this phase shift multicarrier PWM strategy four carrier signals are phase shifted by 90 degrees, which has same frequency and amplitude to generate a five level output. The arrangement is shown in Fig 13.
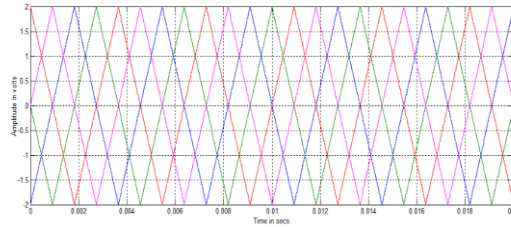
Fig 13: Multicarrier arrangement in Phase Shift PWM

G. Pure Sinusoidal PWM Strategy: This is the most common modulating signal used with triangular carrier signal to generate pulses. A sinusoidal modulating signal is shown in Fig 14.
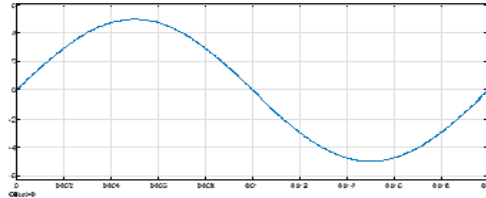
Fig 14: Pure Sinusoidal modulating signal

H. Third Harmonic Injection PWM Strategy: In this technique the effect of third harmonic is cancelled in the output voltage spectrum. The gain is increased by the addition of third harmonic component to the fundamental. The arrangement is shown in Fig 15.
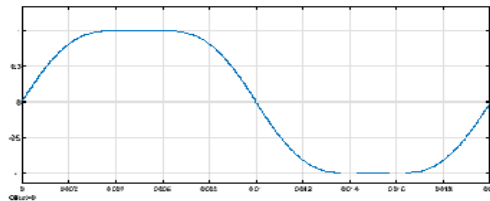
Fig 15: Reference signal of Third Harmonic Injection –PWM

I. Optimal PWM: This PWM Strategy is used to reduce the switching losses and reduce the harmonic content in the inverter output voltage. The main aim is to add variable offset signal to modulating wave to generate modified control pulses, which in turn changes the harmonic profile of the inverter output voltage. The offset signal is given in eq (1)

$$Voffset = \frac{[\min(Vr, Vy, Vb) + \max(vr, vy, vb)]}{2} \text{ -- (1)}$$

Where Vr Vy Vb are modulating signals of three phases of three phase system. The new modulating signals obtained are given in eq (2) – (4)

$$Vr, SFO = Vr - Voffset \text{ ---- (2)}$$
$$Vy, SFO = Vy - Voffset \text{ ---- (3)}$$
$$Vb, SFO = Vb - Voffset \text{ ---- (4)}$$

5. Conclusion

The multilevel inverter topologies play a major role in high power and high/medium voltage applications. Different reduced switch MLI topologies have been evolved for different applications such as Drives, Electric Vehicles and renewable energy sources. The key advantages of reduced switch MLI topologies is that it has reduced switch count, low switching losses, cost effectiveness, high resolution output voltage and ease of control when compared to a conventional two level inverter. Therefore, this review paper focuses on various reduced switch MLI topologies namely reduced switch Symmetric MLI, reduced switch Asymmetric MLI and reduced switch Modified MLI topologies. Also, modulation techniques are discussed in detail. The main objective of this review is to cover conventional and reduced switch that has been effectively carried out.

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