A New Control Strategy for Cascaded Multilevel Inverter with Reduced Number of Switches

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ABSTRACT

For grid connection, it is troublesome to connect power converters directly. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. Among the various MultiLevel Inverter (MLI), Cascaded H Bridge MultiLevel Inverters (CHB-MLI) are gaining more importance because of their modularity and simplicity. The main drawback of the CHB-MLI is that it needs more than one isolated DC source. The CHB-MLI can't be used when a single dc source is available. However, this drawback becomes a very good feature in case of PV systems, because PV arrays can be accumulated in a no. of separate generators. The main aim of this paper is to propose a novel single phase grid connected CHB-MLI with minimum no. of power electronic devices and isolated DC sources. Simulations are carried out in MATLAB/Simulink. The proposed inverter system offers the benefit of a reduced no. of switching devices and isolated DC sources when compared to the conventional CHB and MLISPC for the same no. of output levels.

KEYWORDS: Multi level Inverter(MLI), Cascaded H Bridge Multilevel inverter CHB-MLI, PV systems, Isolated DC sources.

INTRODUCTION

Since the last decade, the world has encountering a very serious issue that has effects on every aspect of modern life. The energy from the fossil fuels is not a good resource to address all the needs of today’s human beings. This is why so much effort has been put forward researching possibilities for substitution of energy resources. Sustainable or RE sources have attracted various nations in the world because these sources are not subjected to change of price and availability which are most typical issues of non-renewable energy sources such as coal, oil, natural gas, etc. and the power generated by them is eco-friendly. RE sources make use of power electronics technology in order to effectively transfer the RE into useful power and connect it to a grid and/or to load. For example, PV cells are variable DC voltage sources, and the wind generators output is either AC voltage or DC voltage based on the type of the generator. However, irrespective of the type of the generator, wind energy is also a source of variable voltage. In order to make these RE sources beneficial, particularly in grid linked applications, a single or multi-stage power conversion is necessary.

A typical multi-stage power conversion system consist of a DC-DC converter and a DC-AC converter (inverter). DC-DC converter is used to isolate and boost the variable low-voltage input to a constant DC output, while an inverter is used to produce the sinusoidal voltage for either the grid-connected or for the stand-alone
mode of operation. Further the energy storage systems which are frequently associated with RE sources also require similar power converters. To understand the environmental and economic benefits of these RE sources, a significant amount of effort is required to develop novel power electronic converter topologies which act as interface between DG units and the grid. Additionally, the associated control strategies, as well as predictive and self-remedial control systems, which will lead to a wide-band of control methodologies to accelerate the move towards the so called micro-grid concept [1] are in need of development.

In RE conversion systems, the technical problems can be divided into two main categories. The first category concerns about the interconnection issues between power converters and the grid. The second category concerns about power flow and the power management in DG systems. These concerns are because of the flexible nature of power flow from RE sources, like solar and wind, and the fact that the power generation units are distributed in the modern power systems.

Power electronic interface circuits are needed to perform several important tasks. The first task is to boost the DC input voltage into a required (rated) voltage level and to invert the DC voltage in to an AC voltage with a fixed frequency and amplitude. In the case of PV systems, it is necessary to keep the no. of PV panels as low as possible. Thus, the amplitude of the produced DC voltage (e.g., from PV arrays and batteries) will be less than the grid voltage (in grid-connected cases) or the required load voltage (in stand-alone cases). Meanwhile, the power capability of RE sources characteristically varies due to their natures, e.g. the output voltage of PV arrays varies in a wide range according to various operation conditions such as when there is a lack of solar radiation, or even when panels are dirty or obstructed. The second task is to obtain the maximum available power of the RE sources, i.e., MPPT. Finally, the harmonic contents of the AC voltage and current have to be reduced by installing line filters.

In response to the growing demand for medium and high power applications, MLI have been drawing more attention in PV systems and variable speed Wind Turbines (WT) in recent times [2][3]. MLI enable the output voltage to be increased without increasing the voltage rating of switching components, so that they offer the direct connection of RE systems to the grid voltage without using the expensive, bulky, and heavy transformers. In addition, multilevel inverter synthesis staircase output voltage closer to sinusoidal voltage using DC link voltages compared with two-level inverter. Synthesizing a stepped output voltage allows reduction in harmonic content of voltage and current waveforms and eventually size of the output filter.

There are three fundamental Multi Level Inverter configurations namely Neutral point clamped MLIs, Flying capacitor MLIs, and Cascaded H-bridge MLIs (CHB-MLI). The neutral point clamped and flying capacitor MLIs need only one DC source to develop a multilevel output whereas the CHB-MLI needs more than one isolated DC source. The CHB-MLI can’t be used when a single dc source is available. However, this drawback becomes a very striking feature in the case of PV or Fuel Cell (FC) systems, because solar cells or fuel cell stacks can be assembled in a no. of separate generators.

An important problem in multilevel converter design is the complexity of their control and pulse width modulator. Generally, if the no. of output voltage levels is increased, then the no. of power electronic devices and the no. of isolated DC sources will also increases. This makes a CHB inverter more complex.

In the case of the converters for PV and FC generators, another important issue is the attainment of MPPT. DC-DC converters are compulsory for each of the isolated DC sources in a PV or FC application. These converters change the variable or low quality output voltage of PV or FC stacks. In addition, the power output of PV and FC stacks has to be maximized, since it depends on ecological factors. Therefore, in order to track the MPP of the PV string or fuel cell stacks, further voltage and current sensors are required for each DC-DC converter. These sensors further increase the system complexity.

In this dissertation, a cascaded multilevel inverter with a less no. of power electronic switching devices and isolated DC sources is proposed. The no. of switching devices used and the harmonics of the output voltage waveform for the proposed inverter are reduced when compared to the inverters proposed in the literature. The proposed MLI topology can be extended for the application of grid connected PV systems, Wind Energy conversion systems, hybrid electric vehicles, etc. Theoretical analysis, numerical simulations, and experimental results are presented to demonstrate the validity of the proposed cascaded asymmetrical single phase MLI.

**Power Converters for renewable Energy Systems:**

Power electronic converters are a family of electrical circuits which convert electrical energy from one level of voltage, current, or frequency to another using power switching components [4]. In all power converter families, energy conversion is a function of different switching states. The process of switching the power devices in power converter topologies from one state to another is called modulation. Regarding different applications, various families of power converters with optimum modulation technique should be used to deliver the required electrical energy to the load with maximum efficiency and minimum cost. Three main families of power converters which are usually used in RE systems are:

1. AC-DC Converters (Rectifiers)
2. DC-DC Converters and
3. DC-AC Converters (Inverters)

Fig. 1 shows a scheme of electrical conversion according to the different family of power converters used in RE systems. In RE systems, source can be either AC or DC such as WT or PV systems, respectively. However, due to the load requirement, the power may be changed to DC or AC. Therefore, based on different applications, proper combination and control of above power converters can supply the load. As shown in Fig. 1, in residential applications or grid connected systems where the variable voltage of RE systems should be converted to desirable AC voltage and frequency, AC-DC, DC-DC and DC-AC converters may be needed. On the other hand, when the input voltage is variable DC source (Fig. 2) such as PV or FC systems, DC-DC converters combined with DC-AC converter may be used to have a regulated AC waveform for residential or grid connected systems.

A. AC-DC Converter:

A three-phase low frequency rectifier is shown in Fig. 1. The converter operates at line frequency, so that the switching happens at 50 Hz or 60 Hz. Low frequency rectifiers are made up by diode or thyristor to change the AC voltage to DC. However, rectifiers based on thyristors have a freedom to change the firing angle to switch the thyristor, so that the amount of DC voltage is controlled compared with diode rectifier. Using a capacitor at output can increase the quality of output voltage.

A three-phase controlled high frequency converter based on IGBT (Insulated Gate Bipolar Transistor) is shown in Fig. 3 (b). This circuit can change the input AC voltage into DC voltage. By controlling the duty cycle of the switches based on different modulation technique, the amount of DC output voltage can be controlled. Since the switches drive high frequency, the amount of harmonic content in current waveform is decreased. In addition, this configuration can provide bidirectional power flow from load to source and vice versa.

B. DC-DC Converter:

DC-DC Converters are a kind of high frequency converters which convert unregulated DC power to regulated DC power. Since the output voltage of RE systems or rectified converter is basically unregulated DC voltage, as shown in Fig. 4, DC-DC converters are necessary to adjust the DC voltage for different applications. Three basic configurations of DC-DC converters are buck, boost, and buck boost converters.
In buck converter, the output voltage is normally less than input voltage. However, a boost converter has the ability to increase the input voltage based on duty cycle of the switch. A buck boost converter can either buck or boost the input voltage. A boost converter is usually applied in RE systems as the output voltage of these systems is low and unregulated. Configuration of the boost converter is illustrated in Fig. 5. In this converter, output voltage is a function of the duty cycle of switch (S) which can be defined by a proper modulation technique. When the switch is on, the inductor can be charged by the current flowing through it. However, in the next subinterval when the switch is turned off, the capacitor will be charged by the inductor current. Second order LC filter in this configuration can regulate the output voltage and remove the high frequency harmonics.

C. DC-AC Converter:
A block diagram of voltage source inverter is shown in Fig. 6. In this configuration the input is a voltage which is stored in DC link capacitor. This converter chops the input DC voltage and generates an AC voltage with required magnitude and frequency with respect to the pulse pattern and modulation techniques. Different current and voltage control methods have been proposed to generate a high voltage high current rectangular waveform based on reference voltage characteristics [5].

One leg of the classical voltage source inverter is shown in Fig. 7 (a). Based on this configuration, when \( S_1 \) turns on, leg voltage \( V_{\text{an}} \) is \( V_{\text{dc}} \), and when \( S_1 \) is turned off, \( V_{\text{an}} = 0 \). Therefore, two different voltage levels appear at the leg voltage. Single phase and three-phase structure can be constituted by the connection of one and two legs to this structure, respectively. Fig. 7 (b) shows a single phase inverter. Output voltage levels based on different switching states are given in Table I. As shown, three voltage levels appear in output voltage. Different high and low frequency PWM (Pulse Width Modulation) techniques can be applied to generate the reference voltage. Leg voltages and output voltage waveforms of a single-phase inverter are shown in Fig. 8.
It can be observed from the Fig. 9, that the Total Harmonic Distortion (THD) of the Single phase inverter is around 64% for switching frequency of 1 KHz, which is a very high value when compared to the standards of IEEE 519-1992 as given in Table II. Obviously if the switching frequency is increased further, the THD value can be brought down, but this can be done by sacrificing the power handling capability of the inverter. Alternatively, THD can be decreased by adding a bulk filter at the output side of the inverter, which increases the size and cost of the entire system.

Table II: IEEE STANDAD 519-1992 Harmonic Voltage Limits

<table>
<thead>
<tr>
<th>Bus voltage at Point of Common Coupling (PCC)</th>
<th>Individual Voltage distortion</th>
<th>Total Voltage Harmonic Distortion (THD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69kV and below</td>
<td>&lt;3.0%</td>
<td>&lt;5.0%</td>
</tr>
<tr>
<td>69.001 kV through 161 kV</td>
<td>≤1.5%</td>
<td>≤2.5%</td>
</tr>
<tr>
<td>161.001 kV and above</td>
<td>≤1.0%</td>
<td>≤1.5%</td>
</tr>
</tbody>
</table>

**Multilevel Inverter Topologies:**

The conventional single phase inverter suffers from a drawback of higher THD. Hence, it is not suited for grid connected applications. MLIs have many advantages for medium and high power systems as they synthesis a higher output voltage rating of each switching device. Stepped output voltage allows a reduction in harmonic content of voltage and current waveforms, switching frequency and semiconductor voltage level. The presented merits make MLIS appropriate for RE applications. The best well known multilevel inverter topologies [6] are diode clamped, flying capacitor and cascaded MLIS. Operation and structure of the three main types of MLIS are discussed in the following section.

**A. Diode Clamped Multilevel Inverter:**

Concept of the diode clamped topology was proposed by [14]. This topology has found wide acceptance for its capability of higher voltages and high efficiency operation. A phase leg of a three-level diode clamped inverter is shown in Fig. 10(a). It consists of two pairs of switches and diodes. Each switching pairs works in complementary mode and the diodes are used to provide access to mid-point voltage. The DC bus voltage is split into three voltage levels by using two series connection of DC capacitors, $C_1$ and $C_2$. Each capacitor is supposed to have an equal DC voltage and each voltage stress will be limited to one capacitor level through clamping diodes ($D_{C_1}$ and $D_{C_2}$). If assumed that total DC link voltage is $V_{dc}$ and mid-point is regulated to half of the DC link voltage, the voltage across each capacitor is $V_{dc}/2$ ($V_{C_1} = V_{C_2} = V_{dc}/2$). Based on the structure of the diode clamped inverter, there are three different possible switching states which apply the staircase voltage...
on output voltage relating to DC link capacitor voltage rate. Switching states of the three-level inverter are summarized in Table III.

To study the effect of the no. of output voltage levels in diode clamped topology, Fig. 10(b) shows a phase leg of a four-level inverter. If converter works in balance condition, DC link voltage split into three different values by the series capacitor \( V_{C1} = V_{C2} = V_{C3} = V_{dc}/3 \). There are seven different combinations shown in Table IV, which can generate four different voltage levels in output leg voltage \( V_{ab} \). According to Fig. 7, by connecting leg named as leg (b) to the below configurations, five and seven voltage levels can be achieved in the output voltage \( V_{ab} \) of three and four voltage inverters. Fig. 11 and 13 show the leg voltage and phase voltage of five and seven level inverters in the balance condition, respectively.

Improvement in quality of the output voltage is obvious by increasing the no. of voltage levels as the voltage waveform becomes closer to sinusoidal waveform [7]. However, capacitor voltage balancing will be the critical issue in high level converters due to the existence of DC currents in the middle points of the DC link. Thus, capacitors are either charged or discharged for some intervals which limit the practical operation of the high level diode clamped converters in some conditions. This issue should be taken into account in this inverter.

In general in a converter with n series DC link capacitors, \( m = (n+1) \) leg voltage levels and \( l = 2m-1 \) phase voltages can be achieved in output waveforms.

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**Fig. 10:** One leg of diode clamped inverter (a) three-level (b) four level

**Table III:** Switching States in One Leg of the Three-Level Diode Clamped Inverter

<table>
<thead>
<tr>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>Leg Voltage ( V_{ab} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>ON</td>
<td>( V_{dc} )</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>( V_{dc}/2 )</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table IV:** Switching States in One Leg of the Four-Level Diode Clamped Inverter

<table>
<thead>
<tr>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( S_3 )</th>
<th>Leg Voltage ( V_{ab} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>( V_{dc} )</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>( 2V_{dc}/3 )</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>( V_{dc}/3 )</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
</tr>
</tbody>
</table>

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**Fig. 11:** Output voltage in three-level diode clamped inverter Leg voltage (b) output voltage
Fig. 12: Harmonic spectrum of output voltage of three-level inverter (a) Simulation (b) Experimental

Fig. 12 shows the harmonic spectrum of the output voltage of the three-level diode clamped inverter obtained from simulation and experiment. It can be observed that the THD of the three-level inverter is almost 100% less when compared to the THD of the conventional single phase inverter for same switching frequency of 1 KHz. Hence, the filter size requirement in order to meet IEEE 519-1992 standards also become lesser when compared to the conventional inverter.

Fig. 13: Output voltage in four-level diode clamped inverter

(a) Leg voltage (b) output voltage:

The THD of the four-level diode clamped inverter further reduces to 19% which is less when compared to the diode clamped three-level inverter, which in turn reduces the size of the filter to meet the harmonic standards. Thus, increasing the no. of levels will decrease the THD, but on compromising the efficiency, because to increase the no. of levels more no. of power electronic switches has to be added in the circuit.

B. Flying Capacitor Multilevel Inverter:

Fig. 14 shows the leg structure of a flying capacitor multilevel inverter. This configuration is an alternative to the diode clamped inverter; however, voltage across an open switch is constrained by clamping capacitors instead of clamping diode in diode clamped topology [8]. Therefore, it can avoid the use of multiple diodes at the higher voltage levels. Although this type of converter shares the advantages of all MLIS, it faces with some problems.

Fig. 14: A leg of flying capacitor multilevel Inverter (a) three-level (b) four level

One of the main problems is the requirement of complicated control strategy due to regulation of floating capacitor voltages [9]. Another problem is associated with converter initialization that means before the flying capacitor inverter can be modulated, the clamping capacitors must be set up with the required voltage level. By increasing the no. of levels, more capacitors are needed [10]. If the input DC link is $V_{dc}$ and the flying capacitor
works in balance condition mode, in order to have equal step voltages at output voltage, clamped capacitor should be regulated at $V_{C1} = V_{dc}/2$ in the three level inverter and $V_{C2} = V_{C1} = 2V_{dc}/3$ in the four-level inverter. It is noted that along with increasing the output voltage quality in four-level structure, voltage stress on switching components reduces by $V_{dc}/6$.

**Table V:** Switching States of Three-Level Flying Capacitor Inverter

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_2$</th>
<th>Leg Voltage ($V_{m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>ON</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>ON</td>
<td>OFF</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table VI:** Switching States of Four-Level Flying Capacitor Inverter

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>Leg Voltage ($V_{m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>$2V_{dc}/3$</td>
</tr>
<tr>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>$2V_{dc}/3$</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>$V_{dc}/3$</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>$V_{dc}/3$</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
</tr>
</tbody>
</table>

Different leg voltage levels associated with different switching states in three and four-level flying capacitor inverters are given in Tables V and VI, respectively. It is clear that one more voltage level is available in four-level inverter. Although the output voltage levels in the flying capacitor inverter is similar to the diode clamped inverter, there are more than one switching state available to achieve the specific level which is called redundant switching states. These redundant switching vectors give freedom to balance the clamped capacitor voltages as they may provide different current loops through the capacitors.

**C. Cascaded Multilevel Inverter:**

The third topology for a multilevel inverter is the cascaded inverter, which can be synthesized by a series of single phase full bridge inverters. Assuming that the DC voltage of each full bridge cell is same and equal to $V_{dc}/2$, each full bridge inverter can switch between $-V_{dc}/2$, 0 and $V_{dc}/2$. Therefore, by adding and subtracting the output voltage levels of the two cascaded full bridge inverter cells, five different voltage levels can be achieved in the output voltage in Fig. 15(a). Switching states associated with different output voltage levels for the cascaded inverter with two full bridge cells are demonstrated in Table VII. Three phase configuration can be easily implemented by three single phase structures. Cascaded configuration has been attracted for medium and high voltage RE systems such as PV, due to its modular and simple structure [11]. A higher level can easily be implemented by adding conventional H bridge cells in this configuration. However, it needs additional DC voltage sources and switching devices which can increase the cost of the system.

By adding each cell, two more voltage levels can be achieved in output voltage which can reduce the harmonic distortion. Fig. 15(b) demonstrates the cascaded inverter with three full bridge inverter cells where each cell endures $V_{dc}/3$ of the total input voltage ($V_{dc}$). It is clear that in comparison with two cell cascaded inverter, to achieve two more voltage levels at output and reduce the voltage stress on each cell in cascade inverter topology, four extra switches and one isolated DC source should be added. In general, cascaded converters with $n$ full bridge inverter cells can synthesis $l = (2n+1)$ voltage levels at the output voltage of each single-phase structure.
Fig. 15: One phase leg of cascaded inverter (a) five level (b) seven level

The hybrid converter proposed by Manjrekar [12] is a cascaded structure that has been modified, such that the DC link of full bridge inverter has unequal DC source voltages. Therefore, based on different switching states it is possible to achieve more voltage levels in output voltage by adding and subtracting DC link voltage compared with conventional multilevel inverter with same no. of components. Diverse topologies have been studied based on a variety of H bridge cascaded cells and DC voltage ratio to enhance the output voltage resolution compared with the same DC voltage ratio of the cells.

Table VII: Switching States of Five Level Cascaded Inverter

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
<th>Leg Voltage ($V_{an}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>$-V_{d}/2$</td>
</tr>
<tr>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>$V_{d}/2$</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>$V_{d}$</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>$-V_{d}$</td>
</tr>
</tbody>
</table>

MLIs are a suitable configuration in transformer less grid connected systems [13]. Multilevel converters synthesize a higher output voltage than the voltage rating of each switching device so that they can provide a direct connection of RE systems to the grid.

Even in grid connected systems with transformer, MLIs are suitable topologies due to low THD and low voltage stress (dv/dt) which minimize EMI (Electro Magnetic Interference), and also switching losses compared to traditional converters. In addition, the above advantages will lead to reduction of the cost and size of the output filter in the systems based on MLIs.

Proposed Inverter:

As stated earlier the three fundamental MLI configurations are neutral point clamped, flying capacitor MLIs, and CHB-MLI. The neutral point clamped and flying capacitor MLIs need only one DC source to develop a multilevel output whereas the CHB-MLI requires more than one isolated DC source. The CHB-MLI can’t be used when a single dc source is available. However, this drawback becomes a very attractive feature in the case of PV or FC systems, because solar cells or fuel cell stacks can be assembled in a no. of separate generators. A most significant problem in multilevel converter design is the complexity of their control and pulse width modulator.
Generally, if the no. of output voltage levels is increased, then the no. of power electronic devices and the no. of isolated DC sources are also increased. This makes a CHB inverter even more complex.

In this paper, a multilevel inverter with a minimum no. of power electronic switching devices is proposed. It is a modified version of a Multi-Level Inverter using the Series/Parallel Conversion of DC sources (MLISPC). In the proposed multilevel inverter, an auxiliary circuit comprising of four diodes and a switch is introduced instead of the series/parallel switches of the inverter found in the MLISPC. However, only two isolated voltage sources are needed to output the same no. of voltage levels when compared to conventional CHB inverters and the MLISPC.

Fig. 16, shows the circuit configuration of the proposed cascaded H-bridge multilevel inverter with two H-bridge inverters connected in cascade (upper and lower H-bridge inverters).

**Simulation Results:**
To authenticate the proposed inverter topology, simulations are carried out for the proposed inverter in Matlab/Simulink. The control strategy is implemented in the simulations up to 43 levels and it can be extended to any essential level. Fig. 17 shows the simulation results for the load voltage of the 11-level inverter together with the upper and lower inverter voltages for a modulation index of Ma= 1 when Vdc1=Vdc2=Vdc3=2Vdc0. When the modulation index is reduced from 1, the no. of voltage levels at the load also decreases.

Fig. 17: (a) Voltage across the load (11 Levels) (b) Voltage across the upper inverter Vup (c) Voltage across the lower inverter Vlow (d) Load Current waveform for modulation index Ma=1

Fig. 18 shows the resultant waveforms of a 15-level inverter along with the upper and lower inverter waveforms for a modulation index of Ma= 1 (i.e. A = 7). Any further decrease in the value of ‘A’ leads to a reduction in the output voltage levels. For example, when A =5, it generates an 11- level output as shown in Fig. 17.
Fig. 18: (a) Voltage across the load (15 Levels) (b) Voltage across the upper inverter Vup (c) Voltage across the lower inverter Vlow (d) Load Current waveform for modulation index Ma=1

Fig. 19 shows the simulation results of a 43-level inverter along with the upper and lower inverters, in which the load voltage is very close to sinusoidal.

Fig. 19: (a) Voltage across the load (43 Levels A = 21) (b) Voltage across the upper inverter Vup (c) Voltage across the lower inverter Vlow (d) Load Current waveform for modulation index Ma=1

The above results are obtained by considering each capacitor of the lower H bridge inverter as individual isolated DC source.

Conclusion:
This paper presents a novel single phase multilevel inverter with minimum switching devices and isolated DC sources. Simulations are carried out in MATLAB/Simulink. By using the generalized switching algorithm that can be used for any no. of levels is also presented. By properly adjusting the modulation index, the required no. of levels for the inverter output voltage can be attained. The proposed inverter system offers the advantage of a less no. of switching devices and isolated DC sources when compared to the conventional CHB and MLISPC for the same no. of output levels. In addition, the high frequency switching devices are operated at a low voltage and the low frequency devices are operated at a high voltage. Thus, it can be concluded that the proposed novel multilevel inverter can be used for medium and high power applications particularly for renewable energy sources.

REFERENCES