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Modeling and Design of Five Level Cascaded H-Bridge Multilevel Inverter with DC/DC Boost Converter

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Abstract
Power electronic converters, especially DC/AC Sinusoidal Pulse Width Modulation inverters have been extending their range of use in industry because of their numerous advantages. They typically synthesize the stair –case voltage waveform (from several dc sources) which has reduced harmonic content. This paper aims to extend the knowledge about the performance of Five level Cascaded H-Bridge MLI topology with DC/DC Boost Converter using SPWM for fixed DC Source. The output voltage is the sum of the voltage that is generated by each bridge. The switching angles can be chosen in such a way that the total harmonic distortion is minimized. This topology incorporates Boost Converter in the input side which magnifies the fundamental output voltage with reduction in total harmonic distortion. It also incorporates LC filter and hence output is drawn near the sine wave because of more levels. Results of experiments proved efficiency of 95%.The performance of the proposed SPWM strategy in terms of output voltage and THD has studied successfully and shown using MATLAB/Simulink.
Keywords- Multi level Inverter (MLI), Sinusoidal Pulse Width Modulation (SPWM), insulated-gate bipolar transistor (IGBT), Cascaded H-Bridge (CHB)

I.   Introduction

Power Electronics is the art of converting electrical energy from one form to another in an efficient, clean, compact, and robust manner for convenient utilization. It has found an important place in modern technology being core of power and energy control. It is the technology associated with efficient conversion, control and conditioning of electric power from its available input into the desired output form.   Power electronics and converters utilizing them made a head start when the first device the Silicon Controlled Rectifier was proposed by Bell Labs and commercially produced by General Electric in the earlier fifties.

The simplest dc voltage source for a VSI may be a battery bank, which may consist of several cells in series-parallel combination. Solar photovoltaic cells can be another dc voltage source. A voltage source is called stiff, if the source voltage magnitude does not depend on load connected to it. All voltage source inverters assume stiff voltage supply at the input.

The first topology introduced was the series H-bridge design [1]. This was followed by the diode clamped converter which utilized a bank of series capacitors. A later invention detailed the flying capacitor design in which the capacitors were floating rather than series-connected. Another multilevel design involves parallel connection of inverter phases through inter-phase reactors. Several combinational designs have also emerged some involving cascading the fundamental topologies [3-6].

These designs can create higher power quality for a given number of semiconductor devices than the fundamental topologies alone due to a multiplying effect of the number of levels.

Recent advances in power electronics have made the multilevel concept practical [1-6]. In fact, the concept is so advantageous that several major drives manufacturers have obtained recent patents on multilevel power converters and associated switching techniques. It is evident that the multilevel concept will be a prominent choice for power electronic systems in future years. Moreover, abundant modulation techniques and control paradigms have been developed for multilevel converters such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), space vector modulation (SVM), and others. In addition, many multilevel converter applications focus on industrial medium-voltage motor drives [7], utility interface for renewable energy systems [8], Universal Power Conditioner [9] and traction drive systems [10].

II. STUDY OF CASCADED H BRIDGE MULTILEVEL INVERTER

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level.

For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells can be easily interfaced to a multilevel converter system for a high power application [1-3].

The concept of multilevel converters has been introduced since 1975. The term multilevel began with the three-level converter. Subsequently, several multilevel converter topologies have been developed [6-13]. However, the elementary concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform.

The attractive features of a multilevel converter can be briefly summarized as follows.

➢ *Staircase waveform quality:* Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses.
➢ *Input current:* Multilevel converters can draw input current with low distortion.
➢ *Switching frequency:* They can operate at both fundamental switching frequency and high switching frequency PWM.

III. FIVE LEVEL CASCADED H-BRIDGE MLI STRUCTURE

Conventional cascaded multilevel inverters are one of the most important topologies in the family of multilevel and multi-pulse inverters. The cascade topology allows the use of several levels of DC voltages to synthesize a desired AC voltage. The DC levels are considered to be identical since all of them are fuel cells or photovoltaics, batteries, etc. [20]. It requires least number of components compared to diode-clamped and flying capacitors type multilevel inverters and no specially designed transformer is needed as compared to multi pulse inverter.

Since this topology consist of series power conversion cells, the voltage and power level may be easily scaled. The concept of this inverter is based on connecting H-bridge inverters in series to get a sinusoidal voltage output. The output voltage is the sum of the voltage that is generated by each cell. The number of output voltage levels are $2n+1$, where n is the number of cells. The switching angles can be chosen in such a way that the total harmonic distortion is minimized. An n level cascaded H-bridge multilevel inverter needs $2(n-1)$ switching

devices where n is the number of the output voltage level.
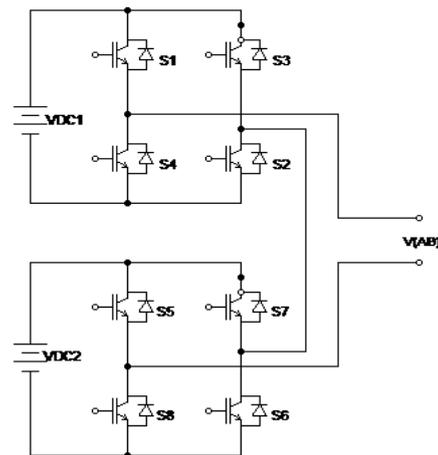
Fig.1 Five level CHB inverter

Cascade topology proposed in [21] uses multiple dc levels, which instead of being identical in value are multiples of each other. It also uses a combination of fundamental frequency switching for some of the levels and PWM switching for part of the levels to achieve the output voltage waveform. This approach enables a wider diversity of output voltage magnitudes; however, it also results in unequal voltage and current ratings for each of the levels and loses the advantage of being able to use identical, modular units for each level.

IV. THE PROPOSED MULTILEVEL INVERTER

The single phase cascaded five level inverter topology [22] has been proposed in Fig.1 .The circuit consists of eight main switches in two series connected H-bridge configuration S1~S4, and S5~S8. The number of dc sources are two so the output voltage of the cascaded multilevel inverter is Vo= V1+V2. The output waveforms of multilevel inverters are in a stepped waveform therefore they have reduced harmonics compared to a square wave inverter.

Each separate dc source (SDCS) is connected to a single-phase full-bridge, or H-bridge inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$ by connecting the dc source to the ac output by different combinations of the four switches, S_1, S_2, S_3, and S_4. To obtain $+V_{dc}$, switches S_1 and S_2 are turned on, whereas $-V_{dc}$ can be obtained by turning on switches S_3 and S_4. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. Similarly S5 and S6 for $+V_{dc}$, switches S_7 and S_8 are turned on for $-V_{dc}$. The ac outputs of each of the different full-bridge inverter levels are connected in

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series such that the synthesized voltage waveform is the sum of the inverter outputs. As given below

Switches Turn On	Voltage Level
S1, S2	+Vdc
S1,S2,S5, S6	+2Vdc
S4,D2,S8,D6	0
S3,S4	-Vdc
S3,S4,S7,S8	-2Vdc

Table 1   the switching states of Five Level CHB

A single-phase structure of a five level cascaded inverter with DC/DC boost converter is illustrated in Figure 3. The operation of this topology is as same as conventional 5-level CHB, difference lies in the voltage level which is due to presence of DC/DC boost converter which boosts the input voltage the designed value.
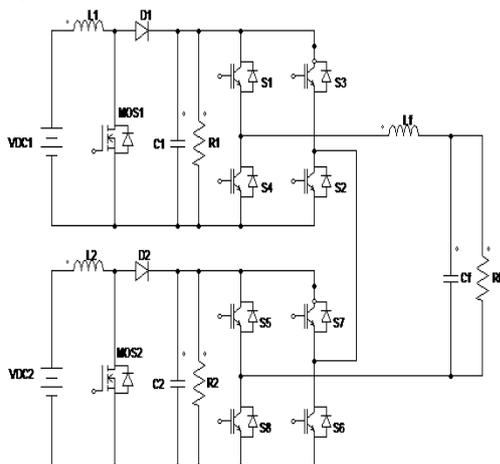
Fig.2   Five-level CHB MLI with DC/DC Boost Converter

V. DESIGN OF PROPOSED TOPLOGY

5.1 DC/DC BOOST CONVERTER

Boost converter steps up the input voltage magnitude to a required output voltage magnitude without the use of a transformer [23]. The main components of a boost converter are an inductor, a diode and a high frequency switch as shown in fig 3.3.1[24]. These in a coordinated manner supply power to the load at a voltage greater than the input voltage magnitude.
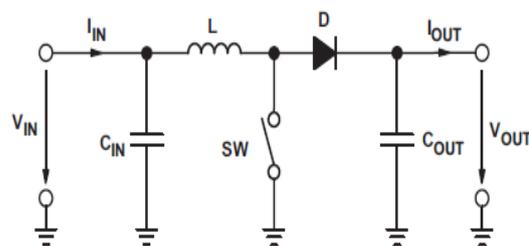
Fig.3   Boost Converter power stage

➢ **Inductor Selection**
Often data sheets give a range of recommended inductor values. If this is the case, it is recommended to choose an inductor from this range. The higher the inductor value, the higher is the maximum output current because of the reduced ripple current. The lower the inductor value, the smaller is the solution size.
The following equation [36] is a good estimation for the right inductor:

$$L = \frac{Vi*(Vo-Vi)}{Fs*Vo*\Delta IL} \qquad \dots\dots\dots (1)$$

➢ **Rectifier Diode Selection**
To reduce losses, Schottky diodes should be used. The forward current rating needed is equal to the maximum output current.

$$I_F = I_{OUT(max)} \qquad \dots\dots\dots\dots(2)$$

I_F = average forward current of the rectifier diode
$I_{OUT(max)}$ = maximum output current necessary in the application

➢ **Output Capacitor Selection**
Best practice is to use low ESR capacitors to minimize the ripple on the output voltage. Ceramic capacitors are a good choice.

$$Cb = \frac{Po}{\omega\, Vo} \qquad \dots\dots (3)$$

Po= output power; Cb= input capacitor
For a good practice choose Cf= 5% of Cb

Here input voltage is 12+12=24V. Due to the presence of DC/DC boost Converter voltage will increase to 48+48=96V.

5.2 Measured Parameters

1.	Input voltage	24V
2.	Output voltage	95V
3.	Input current	8.3A
4.	Output current	2A
5.	Input power	24*8.33 = 200W
6.	Output power	95*2=190W

Table 4 DC/DC Boosted 5 level Inverter Parameters

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$$\%\eta = \frac{Output\ Power}{Input\ Power} = \frac{190}{200} = 95\ \%$$

5.3 Firing pulse analysis

SPWM or sinusoidal pulse width modulation is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches. The pulse width modulation inverter has been the main choice in power electronic for decades, because of its circuit simplicity and rugged control scheme SPWM switching technique is commonly used in industrial applications SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period. The width of this pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. Sinusoidal pulse width modulation or SPWM is the mostly used method in motor control and inverter application.
Specificataions:

Type; SPWM
Carrier frequency =3Khz
Operetaing Frequency=50Hz,
Gain=K=6500
Phase delay= 0,-pi/3

VI. SIMULATION RESULTS

6.1 Modeling of CHB MLI

Fig.4 shows the Matlab/Simulink Model of five level Cascaded H-Bridge multilevel Inverter with DC/DC Boost Converter. Each H-bridge DC voltage is 12 V. Hence total input is 24volts
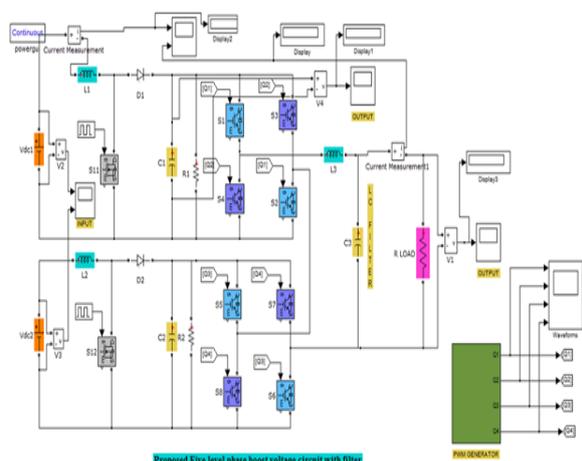
Fig.4 DC/DC Boosted Five level Inverter with Filter

Fig.5 shows the Matlab/Simulink pulse generator model. The Switches are turned ON and turned OFF with a phase delay of 0 and –pi/3 respectively. Fig.6 shows Simulated Reference and Carrier Wave
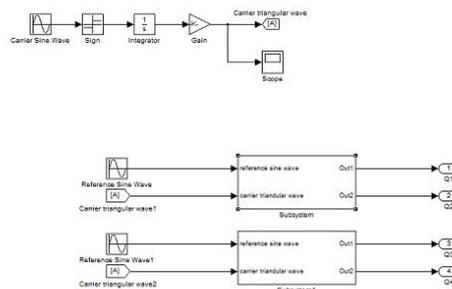
Fig. 5   Pulse Generator Model
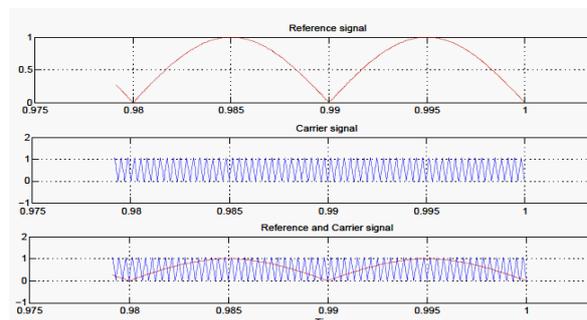
Fig.6 Simulated Reference and Carrier Wave

Fig.7 shows the Matlab/Simulink model Boosted 5-level CHB MLI output voltage without filter, having Magnitude of 96V in staircase(stepped) AC, to get pure sine wave an LC filter is added which is shown in figure 8

Fig. 7 Basic Five level CHB MLI output voltage

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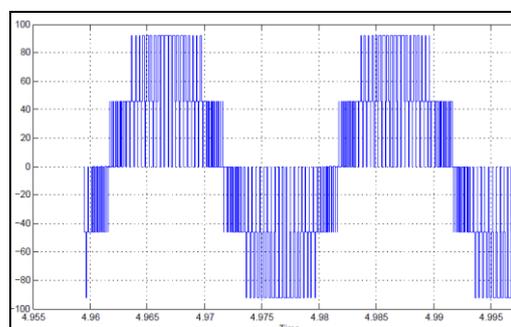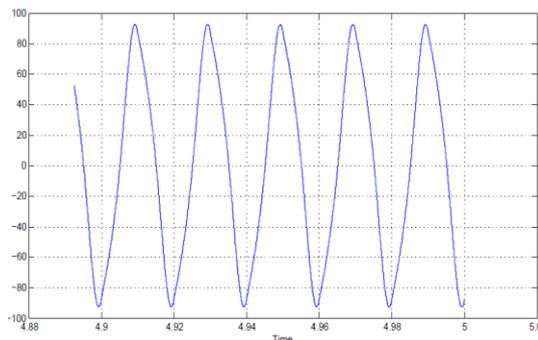
Fig. 8 Basic Five level CHB MLI output voltage with DC/DC boost converter and filter

6.2 THD Analysis

Total harmonic distortion, or THD, is the summation of all harmonic components of the voltage or current waveform compared against the fundamental component of the voltage or current wave. THD calculations can be obtained from the SIMULINK. The switching pattern that is used in this project for all of the multilevel inverters is Sinusoidal PWM technique. In this method the switching angles for switches should be calculated in such a way that the dominant harmonics are eliminated (minimized). For a 5-level inverter the 5th harmonic will be eliminated.

$$\% \ THD = \frac{\sqrt{V2^2 + V3^2 + V4^2 + V5^2 + V6^2 \ ..... \ Vn^2}}{V_1} * 100 ...... (4)$$

Where, V_1= Fundamental Voltage magnitude
             V_2 = Magnitude of 2nd Harmonic
             V_3 = Magnitude of 3rd Harmonic
                          .
             V_n = Magnitude of nth Harmonic

The formula above shows the calculation for THD on a voltage signal. The end result is a percentage comparing the harmonic components to the fundamental component of a signal. The higher the percentage, the more distortion that is present on the mains signal.
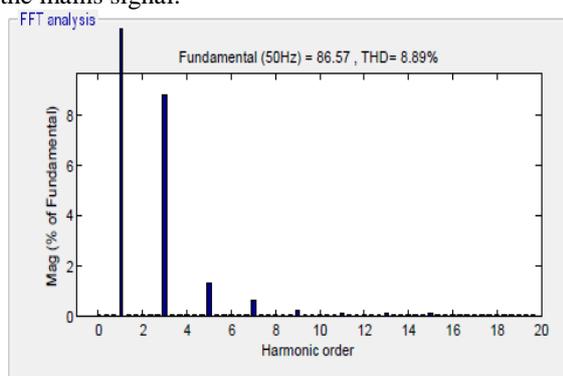
Fig.9 %THD of DC/DC Boosted Five level Inverter with filter

VII. CONCLUSION

It has been observed from the simulation results that the overall efficiency of the developed five level inverter is 95% which is more than the conventional DC to AC inverter. The two-level inverter has the lowest cost and weight in comparison with the other topologies. But it has very high THD and it is not practical to have an output voltage with high such THD. The design of the 5-level multilevel inverters seems to be better than the 9-level multilevel inverters. By increasing the number of levels, the cost and weight of the multilevel inverter will be increased. So this topology is well suited for industrial drives.

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