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Simulation and Implementation of 7-Level and 27-Level Cascaded H-Bridge Multilevel Inverter for Reduced THD Under R and RL Loads

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Abstract

In this paper, 7 and 27 levels of cascaded H-bridge Multilevel Inverter systems are modeled and implemented, where different sub-MLI devices are interconnected in series for producing a large amount of power. The main objective in this work is to achieve a higher output voltage with less power switches. Renewable energy sources are mostly in DC form and hence should be converted properly in DC-AC to be connected to the grid. This is achieved by inverters, and multilevel inverters are preferred as they are able to produce high-quality AC. The CHB-MLI is one of the most common types due to its modularity, simplicity and high quality output, to name a few. The more the number of DC voltage levels, the better the output voltage waveform approaches a pure sinusoidal waveform, and thus lower the harmonic distortion. This research aims to achieve a close to sinusoidal output waveform and to analyse system performance in terms of comparing the Total Harmonic Distortion (THD) of different levels of CHB-MLIs. 7-level inverter is implemented in hardware and the 27-level inverter is designed and analysed using MATLAB/Simulink and hardware for both resistive (R) and resistive-inductive (RL) loads.

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Keywords: MLI - Multilevel Inverter, CHB - Cascaded H-Bridge, THD - Total Harmonic Distortion, SPWM - Sinusoidal Pulse Width Modulation, MATLAB/Simulink, Renewable Energy, R Load, RL Load.

1. Introduction

Power electronic converters are continually evolving with the increasing demand for high power and high-quality energy in industry applications today. Efficient DC-AC power conversion is necessary for variable speed drives, renewable energy power generation and medium voltage applications. Although, they are widely used, the traditional 2-level inverters (TLIs) have disadvantages like high switching losses, high THD and high waveform distortion, especially in high power applications [1].

MLIs are a solution to these problems. The stepped output voltage waveform is generated by the MLIs by synthesizing the output voltage from a number of DC voltage sources, that is, a stepped voltage signal is synthesized, which is very similar to a sine wave [2]. This results in lower THD, reduced Electromagnetic Interference (EMI) and increased efficiency. Furthermore, lower switching frequencies are employed in the MLIs, which results in lower switching losses and higher system efficiency [3].

The CHB inverter has gained considerable research interest due to its simplicity of control, low number of components and modularity compared with other multilevel inverters such as diode clamped and flying capacitor inverters. The CHB inverter is a stack of H-bridge cells with each cell receiving a different DC source, which enables a higher voltage to be generated that has a better quality waveform [4]. Efficient methods for inverting the power from renewable energy sources that output direct current (DC) power, like solar photovoltaic (PV) and fuel cells, are needed for grid integration as these technologies become more prevalent. Multilevel Inverters play a crucial role in the conversion of DC power to AC power for distribution and use.

In this, the simulation and experimental implementation of CHB multilevel inverter is presented for 7-level and higher-level (up to 27-level) inverter. The aim is to achieve a close approximation to sinusoidal waveform with minimum THD with the minimum number of switching devices. The proposed system, which includes a 7-level inverter, is simulated and implemented in hardware with a resistive load (R) and resistive-inductive load (RL) in MATLAB/Simulink [5].

The results indicate that output voltage quality and THD are higher for higher number of voltage levels, suggesting CHB-MLIs as a viable choice for high power applications and renewable energy systems [6].

2. Literature Review

There has been a growing interest in recent years in multilevel inverters which can generate high-quality output voltage with low THD [1]. In the beginning, only two-level inverters were used, which had higher switching losses and THD [7]. For these reasons, MLIs were created.

CHB inverter is well known as the most suitable inverter topology for medium and high power applications among the various types of MLIs, including diode-clamped inverter, flying capacitor inverter and CHB inverter. This is due to its modular design, ease of control and its comparatively fewer components when compared to other topologies [8].

A few researchers have focused on extending the order of the levels in order to improve the quality of the resulting outputs. The lower value of THD and much higher efficiency has been demonstrated for multilevel inverters like 7-level, 9-level and 27-level Inverters. In addition, studies have also been performed on different types of modulation techniques to enhance inverter performance [9].

But, as the number of levels increases, so does the complexity of the switching and design [10]. Hence, it is imperative to develop optimal configurations with a trade-off between performance, complexity and cost [12]. This research adds to the literature by implementing 7-level and 27-level CHB inverters and studying their behaviour with resistive (R) and resistive-inductive (RL) loads [11].

3. System Modeling and Mathematical Analysis

The CHB-MLI consists of a number of full-bridge inverter cells of identical components, with each inverter cell being supplied by its own DC source. It is the inverter that does the thing of combining the output of each H-bridge to form a staircase output voltage.

Each H-bridge cell can produce three different voltage levels: positive, zero and negative voltage, depending on the setting of the switches. The number of output voltage levels varies with the number of cells that are cascaded. The more cells added, the closer the waveform approaches a sine wave, the better the output quality.

$$N = 2s + 1 \tag{1}$$

To get the output voltage of the cascaded inverter, add up the voltages from each H-bridge cell. If the same DC sources are used, the output voltage will be the sum of the output voltages of all the DC sources. This makes a stepped waveform whose amplitude goes up as more cells are added in a cascade.

$$V_o(t) = V_1(t) + V_2(t) + V_3(t) + \cdots + V_s(t) \tag{2}$$

$$V_o(\max) = s \times V_{dc} \tag{3}$$

For each H-bridge cell, a switching function is used to mathematically describe how it switches. This function displays whether the switching is on or off, and determines whether the output of a cell is positive, negative or zero. So, the total output voltage is the sum of all the switching states times the DC source voltage.

$$V_i(t) = S_i(t) \times V_{dc} \tag{4}$$

$$V_o(t) = \sum_{i=1}^{s} S_i\,(t) \times V_{dc} \tag{5}$$

Switching pulses for the inverter operation are generated by SPWM. According to this method, high frequency carrier signals are compared with a sinusoidal reference signal to generate gating pulses. The basic output voltage is based on the amplitude and frequency of the reference signal.

$$V_{ref}(t) = V_m \sin\,(\omega t) \tag{6}$$

$$\omega = 2\pi f \tag{7}$$

Modulation Index has an important role in controlling the magnitude of the output voltage. It is defined as the ratio of the amplitude of the reference signal to the amplitude of the carrier and therefore can be expressed in either decibels or as a ratio. The modulation index should be properly selected to operate it in linear region and to minimize its harmonic distortion.

$$M_a = \frac{V_m}{V_c} \tag{8}$$

The output voltage waveform of the inverter has harmonics, and the Fourier series analysis can be performed. The waveform consists of a fundamental and higher order harmonic component. As the number of levels increases, the quality of the waveform is enhanced and the levels of the harmonic components are reduced.

$$V_o(t) = V_1 \sin(\omega t) + \sum_{n=3,5,7\ldots} V_n \sin(n\omega t) \tag{9}$$

THD is a measurement of the harmonic content in the output waveform. A lower THD means the waveform is closer to an ideal sinusoid, which is desired for power applications.

$$THD = \frac{\sqrt{V_2^2+V_3^2+V_4^2+\cdots}}{V_1} \tag{10}$$

For a purely resistive load, the current waveform follows the voltage waveform and is directly proportional to it. This results in no phase difference between voltage and current.

$$i(t) = \frac{V_o(t)}{R} \tag{11}$$

The current waveform is affected by the inductance, which introduces a phase shift. The system behaviour is governed by a first-order differential equation, and the current lags behind the voltage waveform.

$$V_o(t) = R\, i(t) + L\frac{di(t)}{dt} \tag{12}$$

The phase angle between voltage and current depends on the ratio of inductive reactance to resistance. This phase difference plays a significant role in determining the power factor of the system.

$$\phi = \tan^{-1}\left(\frac{\omega L}{R}\right) \tag{13}$$

The RMS value of the output voltage is an important parameter used to evaluate the effective voltage supplied to the load. As the number of voltage levels increases, the RMS value approaches that of a pure sinusoidal waveform.

$$V_o(\text{rms}) = \sqrt{\frac{1}{T}\int_0^T [\,V_o(t)]^2 dt} \tag{14}$$

Thus, the mathematical modelling of the CHB multilevel inverter demonstrates that increasing the number of levels improves waveform quality, reduces harmonic distortion, and enhances system performance under both resistive and resistive-inductive load conditions.

4. System Architecture

4.1 Existing System

MLI is a topology with multiple cells that are connected to each other by a series of H-bridge inverter cells, which is widely used in the field of power electronics. Every H-bridge cell operates from a separate DC source and when all the cells work together, an H-bridge output voltage waveform is obtained. Under this configuration, the four power semiconductor switches can achieve three different switching states, which are (+Vdc, 0, −Vdc).

The total output voltage for the inverter can be determined by the summing of the output voltage of each H-bridge cell arranged in a cascaded manner with respect to one another. For instance, in a seven-level inverter arrangement, there will be three cells arranged in cascade form, giving output voltage at various levels of +3Vdc, +2Vdc, +Vdc, 0, −Vdc, −2Vdc, and −3Vdc. While the circuit design is fairly easy, several DC supplies have to be provided. This is an added complexity for the system design. Another disadvantage is that the few voltage levels cause relatively more harmonic distortions in the output voltage waveform.

4.2 Proposed System

The proposed system uses a novel CHB-MLI configuration, which produces more output voltage level and enhanced output waveform. This method employs a pair of asymmetrical DC voltage sources, usually with a ratio of Vdc and 2Vdc, to achieve more voltage levels while requiring only a few more H-bridge modules. The inverter can deliver more voltage steps than the conventional symmetrical configuration since unequal DC sources are used. Each H-bridge inverter cell is switched ON and OFF using the four power semiconductor switches S1, S2, S3, and S4, respectively. The inverter can generate positive, negative and zero voltage levels by changing the switches combination. All the outputs of the H-bridge cells are wired in series and the load voltage is the sum of the outputs of each inverter.

With the proposed configuration the inverter can generate a 27 level output voltage waveform: from +13V to −13V and zero. The greater number of voltage levels offers good approximation of a sinusoidal shape, which means there is less harmonic distortion and better overall power quality.

The system is designed to optimise the number of hardware modules required to reach a certain number of levels, while maintaining a higher number of levels than a conventional high-level MLI. The main aim of using MLI technology with Pulse Width Modulation (PWM) techniques is to enhance the quality of the output voltage and reduce the harmonic distortions in the power system. One of the most important parameters to assess the quality of a waveform is the THD, which is the percentage of the distortion components in the signal compared to the fundamental (first harmonic). The lower the THD value, the better the performance, and the closer to an ideal sinusoidal shape the better.

4.3 Multilevel Inverter Controller Design

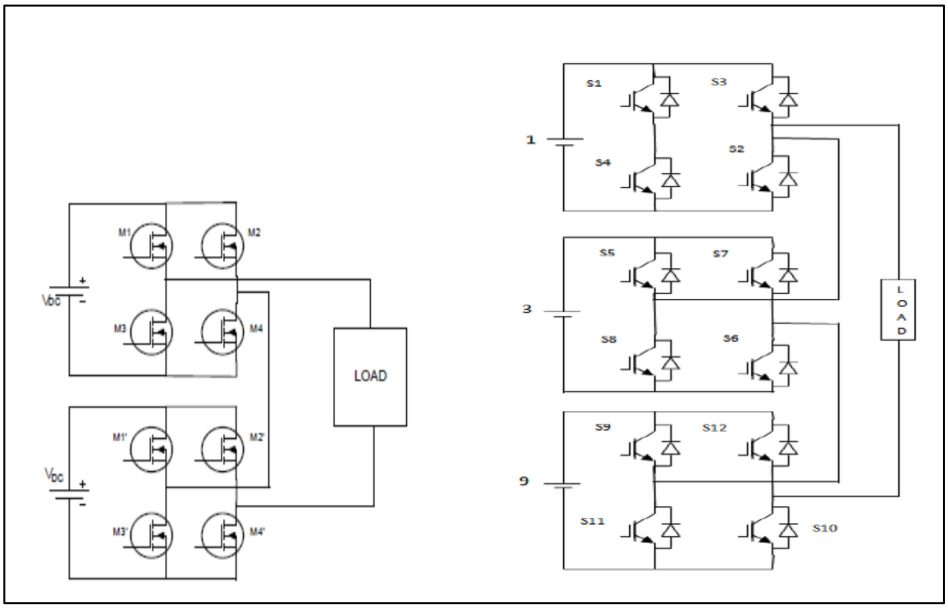

Figure 1. Cascaded and H-bridge Inverter

SPWM is one of the basic methods used to cancel out harmonics in the quasi-square waveform. However, it should be noted and considers only a triangular carrier. The idea of the simple circuit shown in Figure 1 is to create a SPWM. There are two important parameters in the modulation techniques:

Am is the reference signal, and where, w_m is the carrier frequency and w_c is the reference frequency.

The amplitude of the desired signal and the amplitude of the carrier signal, respectively. $P = w_c/w_m$ is called the frequency ratio,

The ratio $M = A_m/A_c$, called the modulation index,

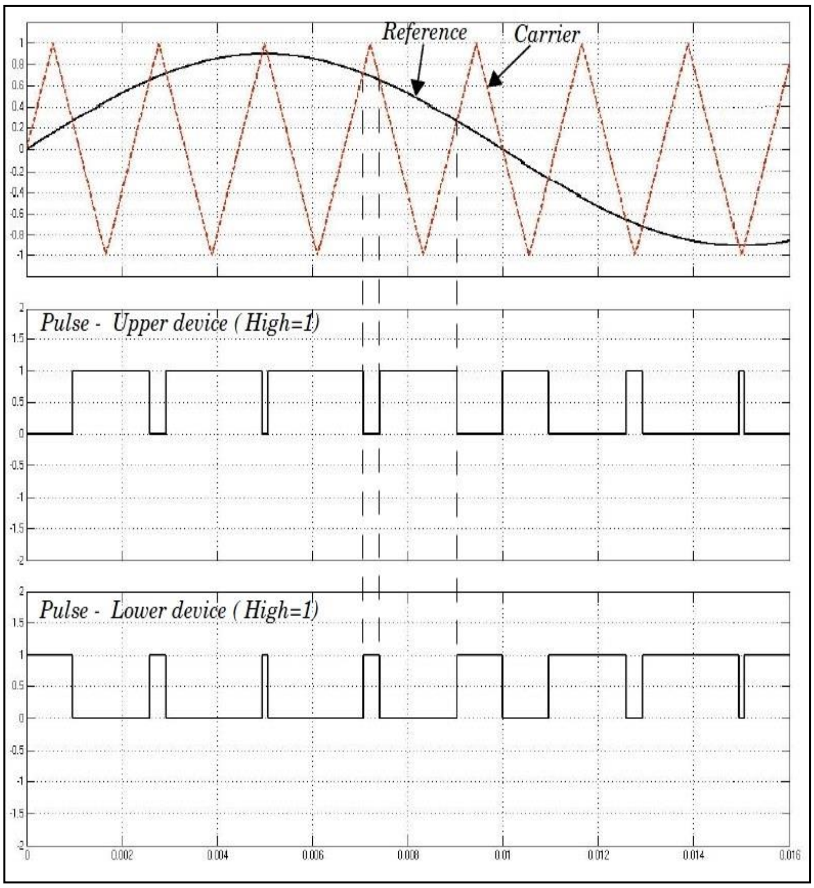

Figure 2. Sinusoidal PWM for Single Phases

In order to analyse the performance of 7-level and 27-level configuration of CHB multilevel inverter, the simulation is performed using MATLAB/Simulink with various load conditions as shown in the Figure 2. The simulation's goal is to ensure that the theoretical design is both correct and that important performance characteristics, like the resultant voltage wave, the current wave form and the harmonic distortion, are correct. The developed simulation model comprises of DC voltage sources, H-bridge inverter units in cascade, pulse generation circuits using modulation technique and load components representing both resistive and resistive-inductive conditions.

The cascaded structure is achieved by connecting multiple H-bridge cells in series in the simulation model. The H-bridge cell is fed by independent DC sources of equal magnitude, so as to get equal contribution of voltage. In the 7-level inverter configuration, three H-bridge cells are used while thirteen H-bridge cells are used in the 27-level inverter configuration. Every H-bridge contains four controlled switches which are switched with proper gate signals to produce desired output voltage levels. The output voltage is stepped by all cascaded cells as a result of the combined operation, which is a good approximation of the sinusoidal voltage.

The switching pulses needed to operate the inverter are produced by the SPWM technique. In this method a sinusoidal signal is compared with several high frequency triangular carrier signals to generate the gating signals for the switches. The fundamental frequency of the output signal will be determined by the reference signal and the switching frequency will be set by the carrier signals. To get several levels of voltage, a level-shifted carrier scheme is employed, which guarantees a correct distribution of switching actions across the cascade of H-bridge cells.

The amplitude of the output voltage is varied by changing the modulation index which is in turn controlled by the ratio of the amplitude of the reference signal to the amplitude of the carrier signal. Well-chosen will keep the inverter in the linear region and result in a good output signal with minimal distortion.

The simulation includes both resistive (R) load and resistive-inductive (RL) load, to assess the performance of the inverter under various loading conditions. For a purely resistive load the output current is in phase with the voltage and follows the shape of the voltage. When, however, a capacitive component is added to the load the current wave becomes smoother, and there is a phase shift between the current wave and the voltage wave. This is a behavior that can be observed in a practical operating condition of many power system applications.

The simulation model also includes measurement blocks that can record the output voltage, current and harmonic content. The output waveform is analysed in terms of its harmonic content using Fast Fourier Transform tools in MATLAB/Simulink. This analysis is used to calculate the THD - an important measurement of the quality of the waveform. Signals with lower harmonic distortion are better, and require fewer components in the outside filter. The values of different simulation parameters like the DC source voltage, switching frequency, load resistance and inductance are carefully selected to ensure stable operation and realistic simulation performance. The developed simulation framework makes it possible to evaluate and compare the 7-level inverter configuration to the 27-level inverter configuration in terms of the quality of the sinusoidal waveforms and harmonic performance.

In general, the simulation method gives a complete solution to analyze the operation of H-bridge multilevel cascaded inverter. It's an important component in design validation prior to hardware implementation and is useful in recognizing how the voltage levels affect system performance.

4.4 Block diagram for the Proposed system

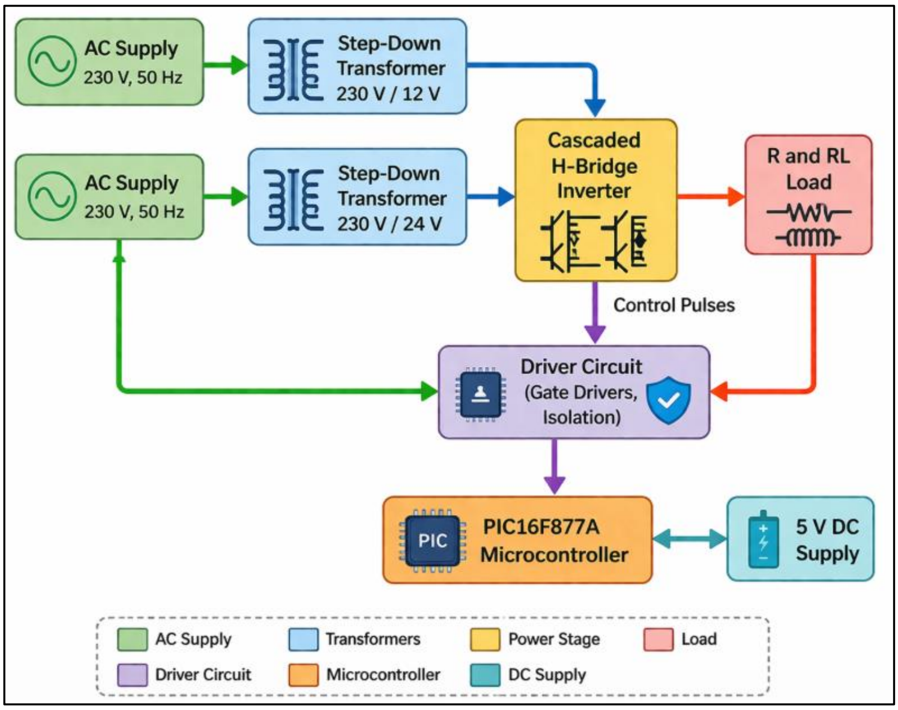

Figure 3. Block Diagram for the Proposed System

The block diagram shows the overall structure of the CHB multilevel inverter system. The system is intended to transform the given AC supply to a controlled multi-level AC output for driving any Resistive (R) or Resistive-Inductive (RL) loads. Architecture includes power conversion stages, control circuits and a load interface, which allow for efficient operation and better output wave form quality.

The input to the system is from a single-phase AC supply of 230 V and 50 Hz. This AC input is applied to step-down transformers to get the desired lower voltage levels in the cascaded inverter. There are two transformer units for independent and stepped-down voltage output, usually 230/12 V and 230/24 V. These transformers can not only reduce the voltage, but also offer electrical isolation, improving the safety and reliability of the system. The output of the transformers is given to the CHB-MLI. The inverter at the heart of the system is used to create several different voltage levels by summing the outputs of each individual H-bridge cell.

The output of each H-bridge is based on a controlled switching signal and each helps to create a stepped output signal. The more the H-bridge cells are increased the more the voltage level can be increased, for example to 7-level output and 27-level output, which gives better quality of the waveforms as seen in Figure 3. and causes less harmonic distortion.

The multilevel AC output generated is applied to the load, which may consist of resistive or/and inductive components. There is a strong dependence of the output current properties on the nature of the load. For an RL load the inductive part causes a phase shift and makes the current wave smoother; this represents a realistic loading condition in power systems. A switching circuit controls the switching operation of the CHB inverter. This driver circuit is an interface between the low power control signals and the high power switching devices. It can offer the required signal amplification, electrical isolation and gate drive ability to enable reliable switching operation of the power semiconductor devices. A microcontroller, PIC16F877A, is used to produce the control signals for the driver circuit. The inverter operation can be controlled by the microcontroller which is programmed to produce accurate pulse width modulation (PWM) signals. These pulses control which H-bridge cells are switching in what sequence, and have a significant influence on the output voltage waveform.

The power to the microcontroller and the control electronics is through a regulated 5 V DC supply. This makes the control unit work reliably and precisely generates switching pulses. Control and power stages are integrated to make efficient conversion of input power to high quality Multilevel AC output possible. The overall system is a modular and scalable power conversion system for multilevel applications. The H-bridge and cascaded H-bridge topology, together with the isolation provided by the transformer and the control by the microcontroller, provide enhanced performance, lower harmonic distortion, and suitability for high power applications as well as renewable energy applications. The microcontroller and control circuit are powered by a regulated 5 V DC supply. This helps ensure the stability of the control unit and accurately generates switching pulses. Combining control and power stage allows for efficient conversion of the input power to a high quality, multilevel AC output. The proposed system is a modular and scalable solution for multilevel power conversion overall. The H-bridge cascaded with transformer isolation and microcontroller control provides better performance, less harmonic distortion and compatibility with high-power, renewable energy applications.

5. Result and Discussion

5.1 Simulation Results of 7-Level CHB-MLI under R and RL Loads

The simulation results of the 7-level CHB-MLIs are presented, showing the output voltage stepped close to the sinusoidal output voltage. It is seen from the output voltage waveform that the inverter successfully creates seven different voltage levels, which is a good sign of the proper switching of the CHB cells (Figure 4). There are however only a few levels and there are still some noticeable harmonic components in the waveform.

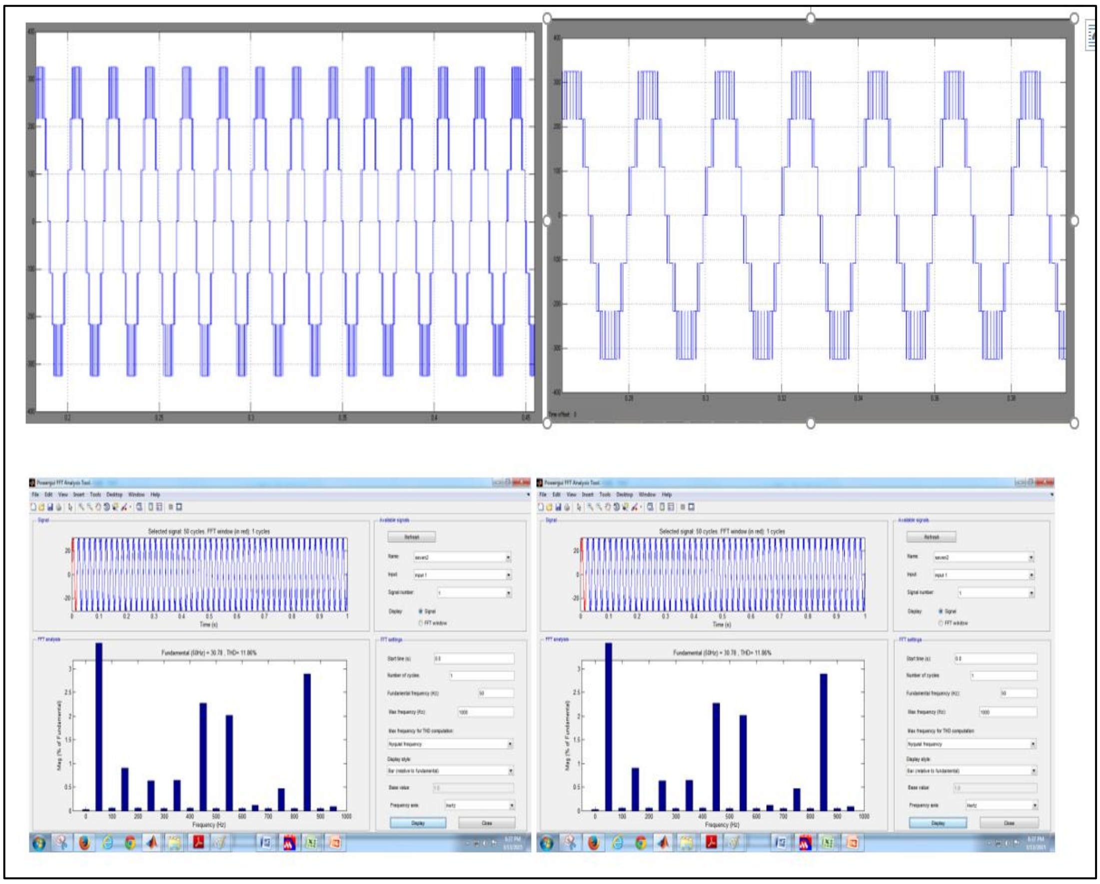

Figure 4. 7-Level Inverter Output Waveform and THD Analysis for R and RL Loads

For the resistive (R) load, the output current wave becomes very similar to the output voltage wave and is in-phase with the output voltage wave. This behavior is evidence that the system is behaving as it should with only a resistive load. The Fourier Frequency Transform (FFT) spectrum of the output voltage shows the presence of harmonic components and a prominent fundamental frequency component. For the inverter with R load, the THD is around 18% to 22%, which is considered as moderate distortion in the inverter's output waveform.

The output current waveform for the resistive-inductive (RL) load is smoother than that of the resistive load, because of the filtering effect of the inductance. Also, the voltage and current are 'out of step', the current is lagging the voltage. Inductive loads show this behavior consistent with the proper system response. The harmonic content of the voltage waveform is still comparable to the R load case, but the current waveform is slightly smoother, thanks to the inductive smoothing.

The FFT analysis of the RL load condition reveals that the harmonics are somewhat reduced in the current wave, but the voltage THD is almost the same. The THD value for the 7-level inverter with RL load is observed to be in the range of 16% to 20%, which is a little lesser in terms of current distortion because of this inductive effect.

Overall, the results show that the inverter with 7 levels is a reasonable approximation of a sinusoidal form of output, but the harmonic distortion is still high compared to the higher-level inverters. When using RL load, performance is enhanced in terms of the smoothness of current, but the voltage distortion is still characteristic of the small number of levels. These observations demonstrate the importance of higher levels of inverters, for example, the 27-level configuration, to obtain better waveform quality and lower THD.

5.2 Simulation Results of 27-Level CHB-MLI under R and RL Loads

The output waveform of the 27-level CHB-MLI is shown in the simulation results, which shows a remarkable improvement in the output waveform compared to the lower-level configuration. It can be seen from the waveform of the output voltage that the output of the inverter consists of several sinusoids that are very close together, and the resulting output appears to be very close to a pure sinusoidal signal. The larger number of levels means small voltage steps between transitions and thus minimises distortion and overall performance.

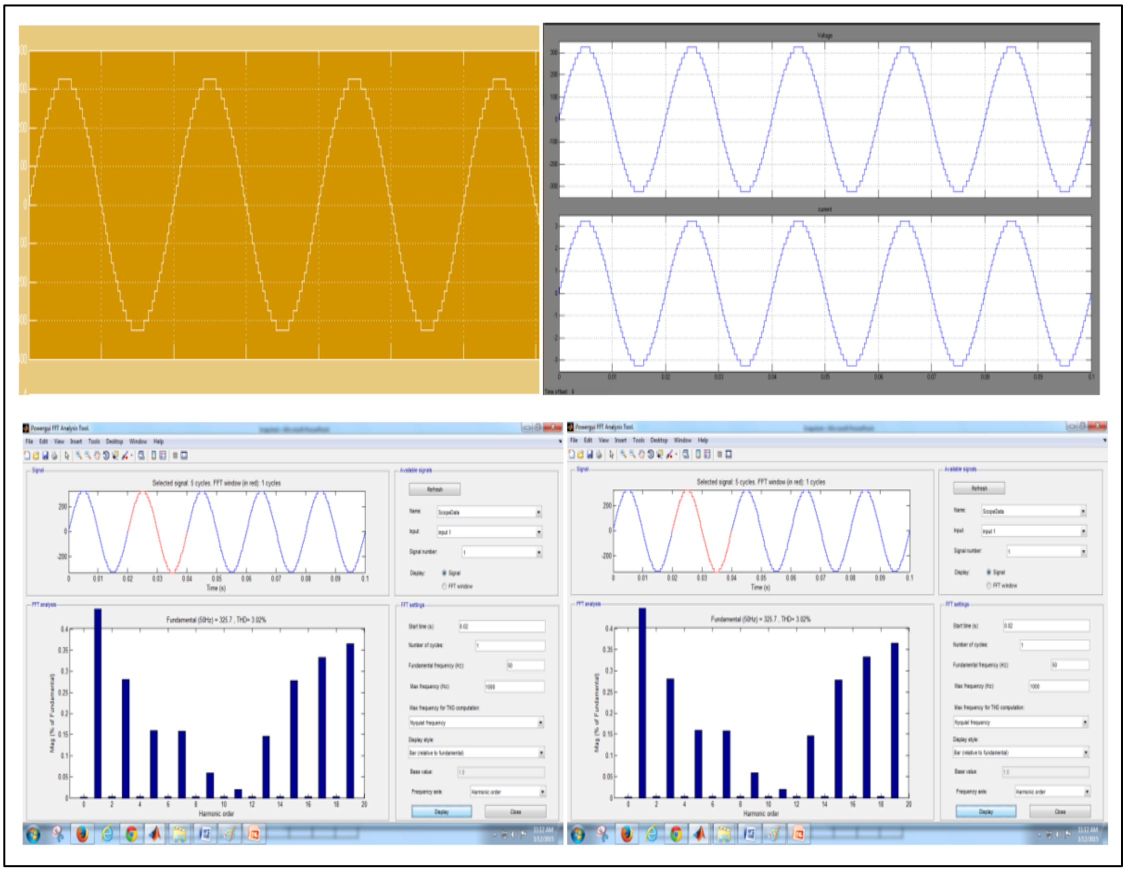

Figure 5. 27-Level Inverter Waveform and THD Analysis for R and RL Loads

For the resistive (R) load, the current through the load is in phase with the voltage across the load, and the current through the load is proportional to the voltage across the load. The high number of voltage levels creates a smooth current waveform that is almost sinusoidal. The Fourier analysis using FFT reveals that the fundamental component is the predominant one, and higher-order harmonics are considerably suppressed. It can be seen that THD of the 27-level inverter with R load is in the range of 3% to 5%, which means that the inverter has a very good waveform quality.

The output current waveform is even smoother for the resistive-inductive (RL) load, thanks to the smoothing action of the inductance. There is a phase difference between the voltage and current, and current is lagging behind voltage, typical of inductive loads. The inductance causes high-frequency ripple components in the current to be greatly reduced so that the waveform produced is very stable and continuous.

The FFT analysis for the RL load case demonstrates that there is further reduction in the harmonic content of the current waveform, while the voltage THD is close to the same as in the resistive load case. This typical range is 2% to 4% for the current of the 27-level inverter with RL load, which is due to the inductance improvement provided for filtering. Generally, the results depicted in Figure 5 and Table 1 indicate the performance of a 27-level CHB inverter with respect to the resultant waveform and harmonic reduction. The 27-level configuration is compared to the 7-level inverter: THD is considerably lower and the output waveform is very close to an ideal sinusoidal. This makes it ideal for high-power systems for which high-power quality standards are required.

Table 1. Performance Analysis of 7-Level and 27-Level CHB Multilevel Inverter

Configuration	Switch count	Voltage levels	THD (R-Load)	THD (RL-Load)
7-Level Inverter	8	7	11.06%	11.86%
27-Level Inverter	12	27	3.02%	3.09%

6. Conclusion

In this study, the simulation and implementation of two different 7-level and 27-level CHB-MLIs connected with resistive (R) and resistive-inductive (RL) loads were presented. The study was aimed at enhancing the quality of the output voltage waveform and also minimizing the harmonic distortion in the output voltage by increasing the number of voltage levels. The CHB topology was chosen, because of its modularity, flexibility and use in high power applications. The 7-level inverter was analyzed and implemented to show the basic working operation of the multilevel inverter, which yield a stepped output waveform with moderate harmonic distortion. However, the results showed that the harmonic components were still present in the waveform, but were minor, due to the limited number of levels. The 27-level inverter, on the other hand, demonstrated very much better performance; it produced a wave shape that is quite close to a sinusoidal output. The higher the voltage level, the smaller the step, the less the harmonic distortion. The MATLAB/Simulink simulation results showed that as the number of levels increases then the THD decreases. The 27-level inverter showed much less THD than the 7-level inverter, which has a positive effect on the power quality and also reduces the need for any additional filtering components. Moreover, current waveforms for RL load conditions showed smoother current waveforms with phase shift caused by inductance, thus proving the practicality of the system. In conclusion, the CHB-MLI seems to be an efficient and effective solution for high quality DC-AC conversion. It is evident from the results that the performance of the higher level inverters in terms of the quality of the output waveform, harmonic distortion and efficiency is better. Hence, the 27-level inverter is more suited to more complex power electronic applications such as renewable energy systems and high power industrial drives.

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