Analysis and experimental study of a Seven level Inverter

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ABSTRACT

The demand for electrical energy continues to increase and has become an essential part of daily human activities. To support the use of environmentally friendly energy, the utilization of renewable energy sources such as solar panels is increasingly prioritized. However, since solar panels generate only direct current (DC), a device is needed to convert it into alternating current (AC) to ensure compatibility with most household appliances. Inverters serve as the primary solution for this conversion process. Although full-bridge inverters are commonly used, they still produce a relatively high level of harmonic distortion. Therefore, the multilevel inverter approach is considered more effective in improving the quality of the output voltage. This study proposes the design and implementation of a single-phase 7-level inverter using a cascaded H-bridge topology. This topology was chosen due to its modular structure, which allows for the generation of output waveforms that closely resemble a sinusoidal shape. The system is controlled by an Arduino Mega 2560 microcontroller using a PWM switching technique. Testing was conducted after completing simulation stages using MATLAB/Simulink and building the hardware prototype. Based on the experimental results, the inverter successfully produced stepped waveforms with relatively low harmonic distortion levels, with a current THD of 8.33% and a voltage THD of 23.95%. The system's stable performance indicates that this design has potential for application in small scale renewable energy systems, such as residential solar power generation.

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1. INTRODUCTION

The shortage of electricity supply in Indonesia has long been a persistent issue that remains unresolved [1]. The demand for electrical energy continues to rise in line with technological advancements that are increasingly integrated into everyday life. This applies to both individual needs and the industrial sector, where the use of electronic devices and modern machinery is becoming more widespread [2]. However, on the other hand, the growth in electricity supply often fails to keep up with the surge in demand, particularly in densely populated areas. If this problem is not addressed promptly, Indonesia is projected to face a nationwide electricity crisis in the coming years [3].

One alternative and renewable energy source is solar power, which is harnessed through the development of solar power plants [4]. However, electricity generated from solar energy is in the form of direct current (DC), while most electronic devices connected to the grid require alternating current (AC) voltage and current. Therefore, a power conversion device is needed to transform DC into AC [5]. One of the most commonly used power conversion devices for this purpose is the inverter [6].

An inverter is an electronic device that functions to convert direct current (DC) power sources into alternating current (AC) power sources [7]. In general, the type of inverter commonly used is the conventional full-bridge inverter. However, in practical applications, this type of inverter produces output waveforms that are less than ideal, as they contain a significant amount of harmonics that can shorten the lifespan of electronic equipment [8]. Various adverse effects may occur, including excessive heating of electrical devices, which can lead to insulation failure and ultimately increase the risk of equipment damage [9]. To address this issue, multilevel inverters have been developed, which produce more ideal output waveforms with significantly reduced harmonic content [10].

A multilevel inverter is a power converter device that transforms a DC signal into an AC signal with an output consisting of multiple voltage or current levels—more than two [6]. There are three basic multilevel inverter topologies commonly used: Diode Clamped Multilevel Inverter (DCMLI) [11], Flying Capacitor Multilevel Inverter (FCMLI) [12], and Cascaded H-Bridge Multilevel Inverter (CHBMLI) [13]. Among these topologies, the most widely implemented is the Cascaded H-Bridge Multilevel Inverter (CHBMLI), due to its simpler switching control and reduced component requirements compared to the Diode Clamped and Flying Capacitor types [14][15][16]. Considering the advantages of the CHBMLI topology, it is selected for this research project. However, on the other hand, this inverter type also has a drawback in that it requires a relatively large number of semiconductor switches, which can increase the overall cost and complexity of the system [17].

The Cascaded H-Bridge Multilevel Inverter (CHBMLI) is an inverter configuration in which multiple H-bridge units are connected in series to generate a stepped output waveform [18]. The greater the number of H-bridge units connected in series, the closer the output waveform approaches a sinusoidal form [19]. This study aims to design and implement a seven-level CHBMLI using IGBT switches, with a PWM control method realized through the Arduino Mega 2560 microcontroller.

2. METHOD

An inverter is a power electronic device capable of converting direct current (DC) electrical quantities into alternating current (AC) electrical quantities, where the frequency value of the output voltage can be adjusted[20]. The output voltage of the inverter is determined by the switching control method applied to the electronic switches within the inverter. The inverter output can be either a variable voltage or a constant voltage. The input voltage source for the inverter may originate from batteries or solar energy. Inverters are utilized in applications such as adjustable-speed AC motor drives and uninterruptible power supply (UPS) systems[21].

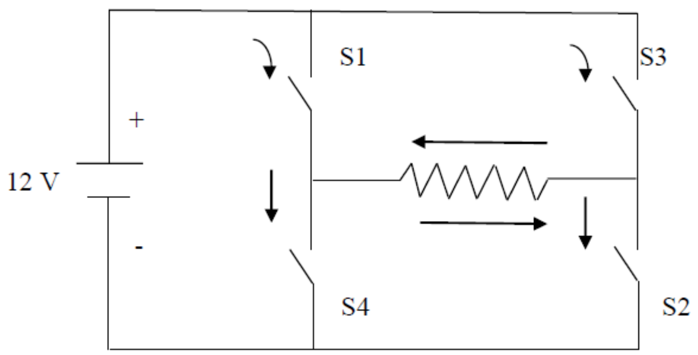


Figure 1. Principle of Operation of a Single-Phase Inverter Circuit

The operating principle of an inverter can be explained using four switches as illustrated in Figure 1. When switches S1 and S2 are activated, the DC current flows through the load R from left to right. Conversely, when switches S3 and S4 are activated, the DC current flows through the load R from right to left. Typically, inverters employ Pulse Width Modulation (PWM) circuits in their operation. PWM involves modulating the width of pulses in the output signal to regulate the output voltage and frequency, thereby generating an AC waveform that approximates a sine wave. This technique enhances efficiency, reduces harmonic distortion, and allows precise control of the inverter output [22].

As explained previously, the H-Bridge inverter operates by controlling the active switches for specific durations. According to Figure 2.2 below, when switches S1 and S2 are activated, the voltage across the load becomes positive. Conversely, when switches S3 and S4 are activated, the voltage across the load becomes negative. The alternating activation of these four switches enables the inverter to convert DC voltage into AC voltage [23].

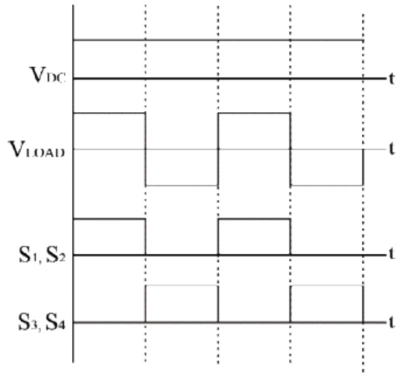


Figure 2. Output Voltage Waveform of an H-Bridge Inverter

A multilevel inverter is a power electronic device that converts direct current (DC) into alternating current (AC) with an output consisting of multiple voltage levels greater than two. The output voltage of a multilevel inverter is stepped, resembling a staircase waveform that increasingly approximates a sine wave. The greater the number of voltage levels produced, the lower the harmonic distortion in the output [5].

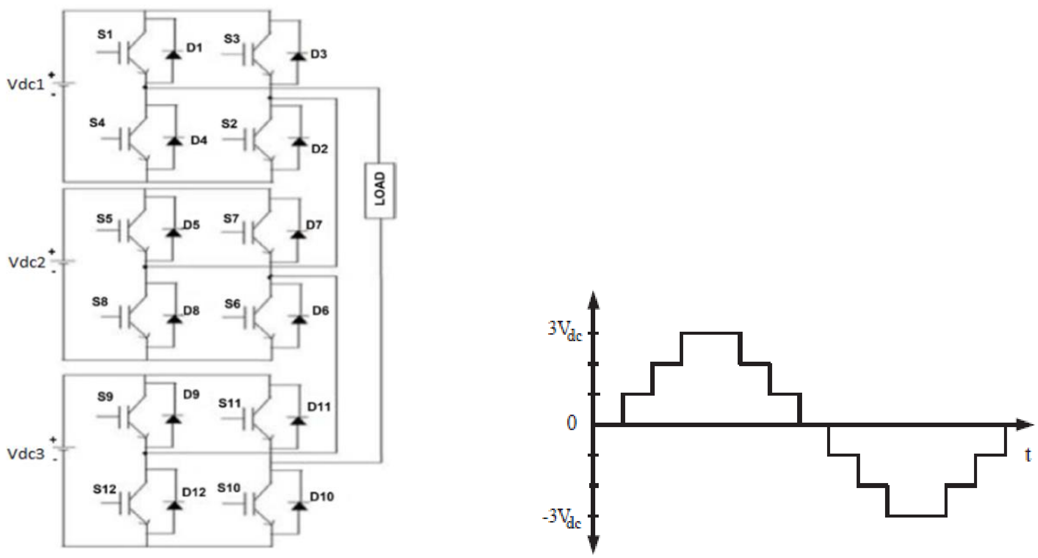
The Cascaded H-Bridge (CHB) multilevel inverter is one of commonly used inverter topologies today [6]. A cascaded H-bridge consists of two or more H-bridge inverters connected in a series configuration [24]. This type of inverter offers significant advantages, such as the ability to produce high-quality voltage waveforms, reduce harmonic distortion, and handle high power levels [6]. However, a key drawback of the cascaded H-bridge inverter is its requirement for a higher DC voltage source, which depends on the number of switches used [25]. The concept of this inverter topology is based on a series arrangement of H-bridge inverters to generate a sinusoidal output voltage. The output voltage is the result of the summation of voltages derived from DC sources [26]. The following are the formulations used to determine the number of output levels, the number of switching devices, and the number of required H-bridge cells:

$$m = 2n + 1 \quad (1)$$

$$s = 2(m - 1) \quad (2)$$

$$v = \frac{(m-1)}{2} \quad (3)$$

Where m is the number of H-Bridge levels, s is the number of H-Bridge cells and n is the number of H-Bridge modules.



(n) (b)

Figure 3. Level Cascaded H-Bridge Multilevel Inverter. a) Switch structure, b) waveform of output voltage

The calculation of a single-phase Cascaded H-Bridge inverter circuit is as follows:

$$V_{DC\,(Total)} = V_{DC\ ke-1} + V_{DC\ ke-2} + \cdots + V_{DC\ ke-n} \quad (4)$$

$$V_{out,rms} = \frac{V_{DC}}{\sqrt{2}} \quad (5)$$

$$P_{out} = \frac{Vout^2}{R} \quad (6)$$

$$I_{out} = \frac{V_{out}}{R} \quad (7)$$

Where $V_{DC\,(Total)}$ is the total input voltage, $V_{DC\ ke-n}$ is the nth input voltage, $V_{out,rms}$ is the output voltage, P_{out} is the output power and I_{out} is the output current.

The tools and materials used in this study are categorized into hardware and software components, as outlined below. The hardware components used include: Three units of 30 VDC power supply, One unit of 12 VDC power supply, Device circuitry, 100W 220V AC incandescent lamp, Oscilloskop, Power quality analyzer. The software components used include Matlab 2017b and Arduino IDE. The completion of this final project was carried out in several stages, which are generally illustrated in Figure 4.

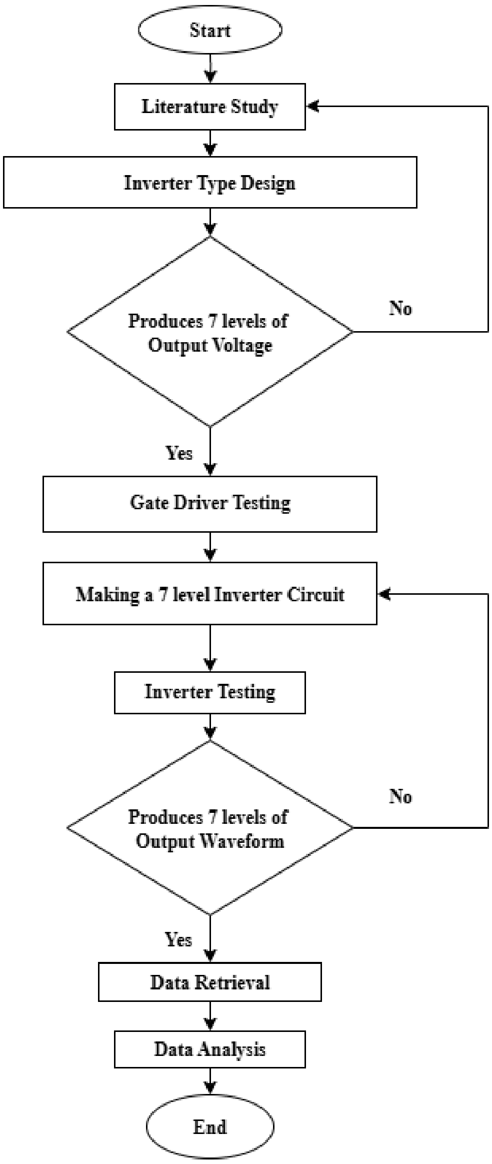


Figure 4. Research Flow Diagram

The block diagram in Figure 5 below illustrates the control flow of a 7-level multilevel inverter system based on the Arduino Mega 2560. The process begins with a PC or laptop sending commands to the Arduino Mega 2560, which functions as the main microcontroller. The Arduino then generates control signals that are forwarded to the gate driver, which amplifies the signals to control the switches in the inverter. A DC power source is used as the input to the 7-level inverter, which subsequently converts the DC voltage into stepped AC voltage and delivers it to the load. Thus, this system enables programmable and efficient control of the inverter.

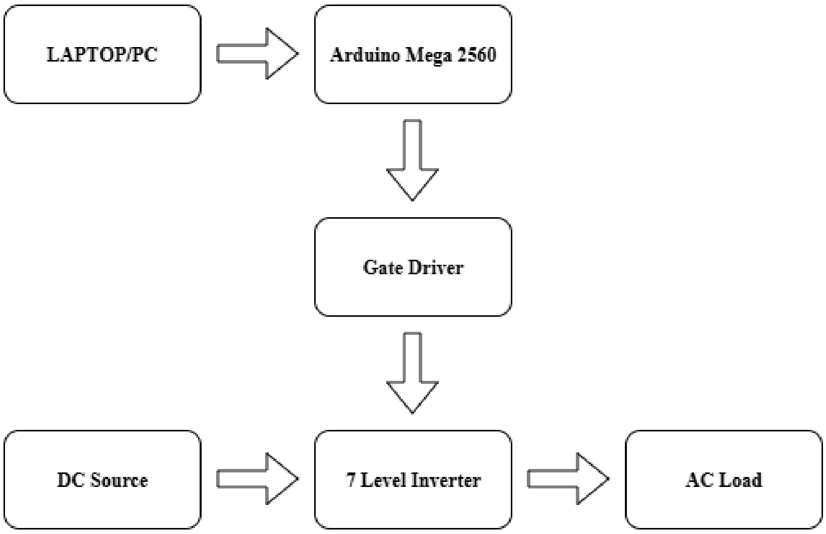


Figure 5. System Block Diagram

3. RESULTS AND DISCUSSION

Figure 6 shows the complete assembly of the 7-level Cascaded H-Bridge Multilevel Inverter (CHBMLI). The testing was conducted using three separate DC sources, each supplying an input voltage of 30 VDC. A 100-watt incandescent lamp was used as the test load.

Figure 6. Complete Structure of the 7-Level CHBMLI

Figure 7 shows the gate driver signals from S1 to S12 in sequence, as measured using an oscilloscope. The measurements were performed alternately using a single oscilloscope. The characteristics of these signals significantly influence the output waveform of the inverter and also affect the resulting Total Harmonic Distortion (THD). It can be observed that the gate driver signals exhibit square waveforms with nearly identical duty cycle patterns, and a phase shift between each signal. This indicates that the switching process of each IGBT has been properly configured and follows the correct sequence to produce a stepped (multilevel) inverter output.

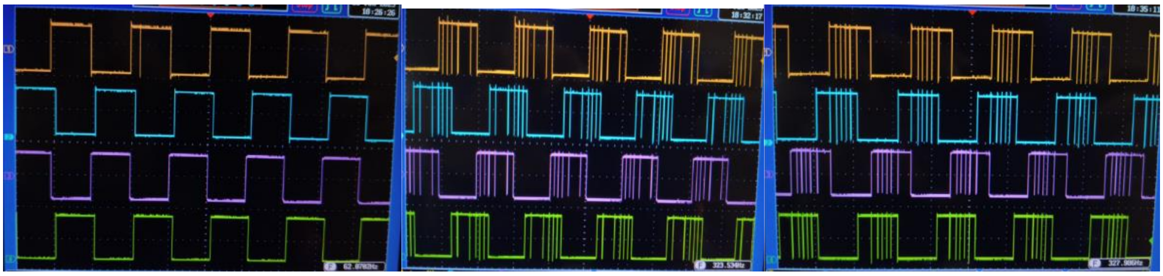


Figure 7. Gate Driver Signals S1 – S12

Figure 8 displays the output voltage waveform of the seven-level (7-level) inverter using the Cascaded H-Bridge topology. This waveform consists of seven voltage levels arranged symmetrically, forming a pattern that closely resembles a sinusoidal wave. The result demonstrates that the inverter is capable of generating stepped signals according to the design and performs well in controlling the switching timing.

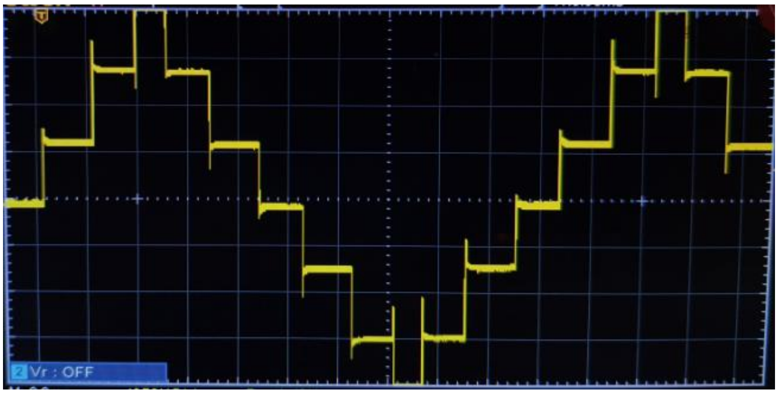
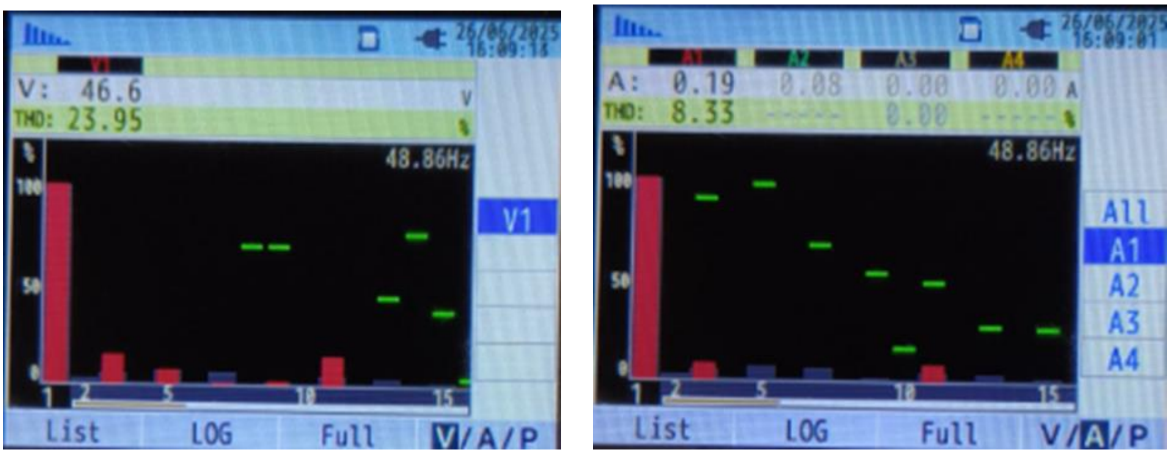


Figure 8. Inverter Output Voltage Signal

Although slight distortion is still present at the waveform edges, this is most likely caused by the IGBT switching process, the existence of dead time, or the characteristics of the gate driver itself. With a higher number of voltage levels, the 7-level inverter can produce a waveform that more closely approximates a pure sine wave and significantly reduces Total Harmonic Distortion (THD), making it highly suitable for applications requiring high power quality.

. Based on Figure 9(a), the inverter produced an output voltage of 46.6 volts with a frequency close to 50 Hz, specifically 48.86 Hz. The measured Total Harmonic Distortion (THD) was 23.95%, indicating that although the waveform closely resembles a stepped sine wave, there are still significant harmonic components present. This could be attributed to non-smooth switching transitions, the absence of filtering, or suboptimal phase angle tuning. Nevertheless, the achieved voltage indicates that the inverter is functioning and capable of delivering power. The THD value can still be improved through control optimization and the addition of harmonic filters on the output side. Based on Figure 9(b), the measured output current of the inverter was 0.19 A at a frequency of 48.86 Hz. The Total Harmonic Distortion (THD) of the current was recorded at 8.33%, indicating that the current waveform is cleaner compared to the previously observed voltage waveform. This suggests that the inverter performs well in delivering current to the load, with relatively low harmonic distortion. The low current value is likely due to the type or rating of the load used during testing. However, the low current THD indicates that the control system design and switching mechanism have functioned effectively in maintaining the quality of the output current.



(a) (b)

Figure 9. Inverter performances. a) Voltage and THD, b) Current and THD

4. CONCLUSION

Based on a series of research activities, testing, and analyses conducted in this final project, it can be concluded that a single-phase 7-level multilevel inverter has been successfully designed and constructed using the Cascaded H-Bridge (CHB) topology, employing 12 IGBTs as power switches. Test results show that the inverter system is capable of functioning as intended by converting a DC voltage source into a stepped AC output. For the 7-level inverter, the measured output voltage was 46.6 V, with a current THD of 8.33% and a voltage THD of 23.95%..

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