Scientific Research Publishing

Journal of Computer and Communications, 2023, 11, 71-95
https://www.scirp.org/journal/jcc
ISSN Online: 2327-5227
ISSN Print: 2327-5219

Optimized Design and Analysis of Single-Phase and Three-Phase Inverters for Efficient Power Conversion: A Comparative Study

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How to cite this paper: Alam, A., Monem, M.A. and Islam, K.K. (2023) Optimized Design and Analysis of Single-Phase and Three-Phase Inverters for Efficient Power Conversion: A Comparative Study. *Journal of Computer and Communications*, **11**, 71-95.
https://doi.org/10.4236/jcc.2023.118006

Received: May 31, 2023
Accepted: August 15, 2023
Published: August 18, 2023

Abstract

A large amount of switching loss occurs in the inverter. From this point of view, an inverter design should be optimized for which size and cost will be minimum along with increasing efficiency. The main aim of this paper is the analysis and development of single-phase and three-phase inverter to design with MOSFET and IGBT as power elements by sinusoidal pulse width modulation (SPWM) technique using MATLAB Simulink software and compare their difference with the practical inverter. This work proposes different multilevel stages for the cascaded H-Bridge inverter to enhance the output voltages. Then compare their performance, harmonic distortion, and frequency spectrum. The hardware of an inverter circuit has been developed using the SG3524 microcontroller. The main goal of this design is to generate a sine wave with fewer harmonics, while keeping the cost and complexity of the circuit low. The designed inverter has undergone testing with different AC loads and is primarily intended for low-power applications, as lamps, fans, and chargers. This design aims to provide a reliable and efficient inverter solution for these specific applications.

Keywords

Harmonic Distortion (HD), Pulse Width Modulation (PWM), Sine Pulse Width Modulation (SPWM), Total Harmonic Distortion (THD), Laboratory (LAB)

1. Introduction

The primary focus of this paper is on DC to AC power inverters, which are designed to efficiently convert a DC power source into a high voltage AC source, mimicking the power supplied by electrical wall outlets. Inverters find applications in various scenarios where low voltage DC sources like batteries, solar panels, or fuel cells need to be converted to AC power to enable devices to operate. For instance, a typical use case involves converting electrical power from a car battery to power devices, such laptops, TVs, or cell phones, which typically require AC power for operation.

In the described method, the conversion of low voltage DC power into AC is carried out in two steps. Firstly, the DC power containing low voltage is converted into AC and boosted up to 230 V voltages utilized by a transformer. The focus of this approach is on generating a modified sine wave, which offers several advantages. It decreases the noise of devices like fluorescent lights and enables faster and quieter operation of inductive loads such as motors, thanks to its low harmonic distortion.

This thesis also introduces a multilevel inverter configuration, which is designed using the phase-shifted pulse-width modulation (SPWM) method for generating control signals. The SPWM technique has gained significant attention in recent years due to its benefits in achieving high power capabilities with low switching frequency and low harmonics. The key advantage of multilevel inverters is their ability to improve the quality of the output voltage signal using low-voltage rated devices and lower switching frequencies, leading to increased overall system efficiency.

The fundamental function of a multilevel inverter is to synthesize a desired high voltage level by combining multiple levels of DC voltages. The performance of multilevel inverters surpasses that of classical inverters. To evaluate and analyze the system, a simulation model was developed using MATLAB/Simulink software, providing a means to assess the performance and characteristics of the proposed multilevel inverter design.

2. Literature Review

In recent years, pulse width modulation techniques have become popular in power electronics, microcontrollers, and microprocessors. Extensive research has led to the development of various strategies and schemes to reduce switching losses and harmonics in converters, especially in three-phase systems [1]. The development of modulation techniques can be traced back to the mid-1960s, with Kirnnic, Heinrick, and Bowes making significant contributions [2]. Over the years, there has been a significant increase in research on pulse width modulation (PWM) schemes. The main goal of modulation techniques is to attain a variable output signal with a maximum fundamental component and minimal presence of harmonics [3]. Among the different modulation methods, PWM carrier-based methods were the first to be developed and widely used in various applications. Sinusoidal PWM (SPWM) is one of the earliest modulation signals for carrier-based PWM. The method involves the comparison of a carrier signal and a sinusoidal modulation signal. The concept of sinusoidal PWM (SPWM) was originally introduced by Schonung and Stemmler in 1964 [4]. Nonetheless, traditional sinusoidal PWM exhibits a lower utilization rate of the DC voltage, reaching only 78.5% of the DC bus voltage, in contrast to the utilization rate of a six-step wave, which is 100% [5]. Design and implementation approach for a sine wave inverter using a microcontroller-based PWM technique and provides insights into the utilization of microcontrollers for efficient control and generation of sine wave output in inverters in [6]. [7] explores the utilization of carrier signals for generating sinusoidal output waveforms and provides valuable information on the design considerations and implementation aspects. [8] present a design methodology for a single-phase inverter and offers insights into the design considerations, circuit components, and overall implementation of a single-phase inverter.

In the pursuit of enhancing the utilization rate of the DC bus voltage, researchers in power electronics have focused on various design and implementation approaches for single-phase inverters. Some recent studies have employed FPGA (field-programmable gate array) [9], Atmega (such as Atmega16, AT89S52) microcontrollers [10], DSP (digital signal processor) (such as TMS320F241) [11], and PIC (peripheral interface controller) microcontrollers (such as PIC30F4013, PCI16F877A) [12] [13]. These studies have explored different microcontroller platforms and programmable devices to develop inverters. However, it is worth noting that some of these implementations required additional driving circuits or ICs (integrated circuits) like TLP250 or other similar components, resulting in more complex circuit designs [14]. In this paper, [15] provides a comprehensive study on different space vector modulation (SVM) techniques for both single-phase and three-phase inverters. It discusses the principles, advantages, and drawbacks of various SVM strategies. Author presents the analysis and design of a single-phase quasi-Z-source inverter (qZSI) in [16] with a high voltage gain and introduces a novel control strategy for the qZSI, which enhances the voltage boosting capability and extends the output voltage range. Authors focused a highly efficient single-phase inverter with enhanced reactive power capability specifically designed for photovoltaic systems [17] in a novel control algorithm that maximizes the energy yield from the solar panels and enhances the power conversion efficiency. In this study [18], it compares the harmonic performance of single-phase PWM inverters with different carrier-based modulation strategies. It evaluates the distortion factor, total harmonic distortion, and other performance metrics. The incorporation of these additional components was necessary to fulfill specific requirements or address particular challenges in the inverter design and operation.

But AC power is not always readily available and there is a need for portable AC power solutions. In such cases, inverters are used to convert DC voltage from a battery or a solar panel into AC power. Inverters are categorized according to their output waveform, which can be broadly classified into three types:

square wave, modified sine wave, and pure sine wave. Square wave and modified sine wave configurations are commonly found in commercially available inverters. These options are more cost-effective and achieve an average voltage output to the load by altering the waveform. However, they may not be suitable for delicate electronic devices that require precise timing or sensitive equipment. Pure sine wave inverters offer a waveform that closely resembles the waveform of utility grid power. They provide high accuracy and are capable of handling high load capacities. However, pure sine wave inverters are more complex in design and tend to be more expensive compared to square wave or modified sine wave inverters. In the case of pulse width modulation (PWM) techniques, the inverted signal is composed of a series of pulse signals that encode a sine wave. By adjusting the duty cycle of these pulses, the power transmitted resembles a sine wave, allowing for efficient AC power generation. Overall, the choice of inverter type depends on the specific application requirements, cost considerations, and the sensitivity of the connected devices to the quality and accuracy of the AC waveform.

3. Simulation and Analysis

The simulation and performance is analyzed using MATLAB/Simulink Software. The gating signals for the inverter are generated by using multi-carrier pulse width modulation technique which is shown in Figure 1. This modulation technique reference and carrier signal is shown in Figure 2. The variation of their performance was analyzed by measuring the percentage of Total Harmonic Distortion. In order to achieve optimal performance, a phase-shifted carrier-based switching scheme is implemented for MMC (modular multilevel converter) inverter topologies. This scheme utilizes a carrier frequency ranging from 1 to 2 kHz and a modulation index within the range of 0.8 to 0.9.

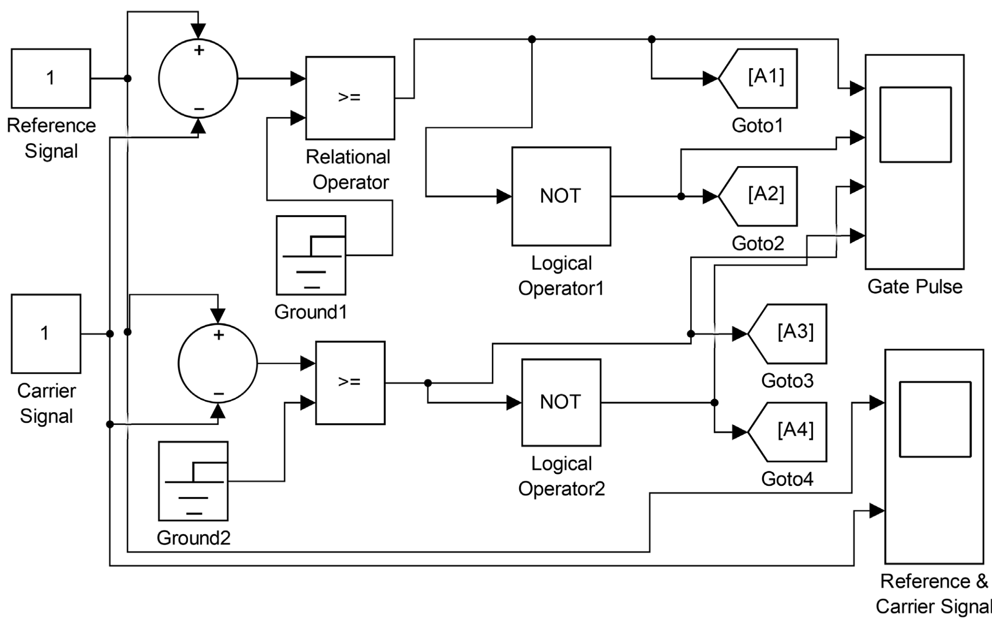

Figure 1. Gate pulse generating circuit.

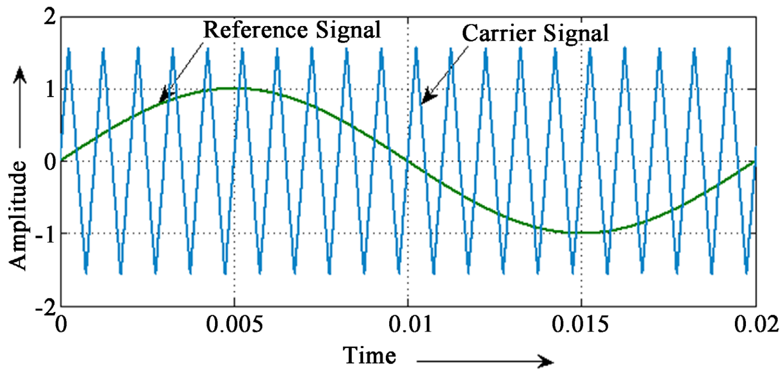

Figure 2. Carrier and reference signal.

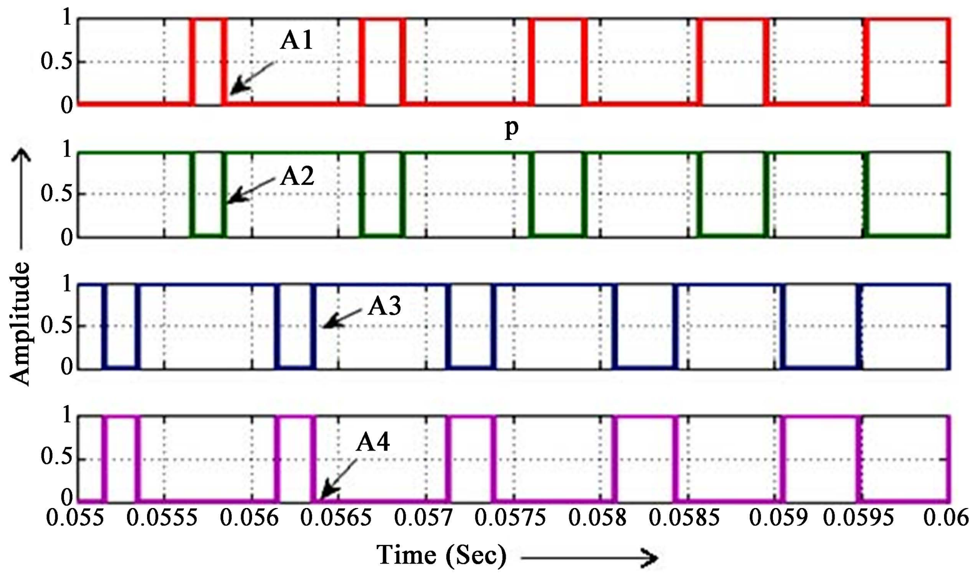

Figure 3. Gate pulse signal.

The gate pulse signals (**Figure 3**) generated by the SPWM techniques. Which is used to turn on or turn off the top IGBTs and their inverter gate pulse is used for the bottom IGBTs.

1) Single-Phase Two-Level Inverter

Analyzing circuit diagram and switching scheme of half-bridge inverter [19] getting the following output voltage waveform and frequency spectrum are shown in **Figure 4** and **Figure 5**, respectively.

The duty cycle of the square wave output from a half-bridge PWM inverter in **Figure 4** is determined by the PWM signal. The output waveform's peak voltage is the same as the DC supply voltage, and its frequency is the same as the PWM frequency. The output waveform can be filtered to lower the harmonic content and increase the output waveform's suicidality and frequency spectrum shown in **Figure 5**. At low frequency, the spectrum is very high and increasing the frequency it gradually trance to zero.

2) Single-Phase Three-Level Inverter

Analyzing the circuit diagram and switching scheme of the full-bridge PWM inverter [19] getting the following output voltage waveform and frequency spectrum are shown in **Figure 6** and **Figure 7**, respectively.

3) Single-Phase Five-Level Inverter

The circuit diagram of single-phase five-level inverter illustrates in **Figure 8** consisting of eight witching devices and two voltage source. The gate pulse signals are generated by the SPWM techniques (**Figure 9**). The output voltage is sinusoidal and due to the higher number of voltage levels, the THD is only 36%. The output

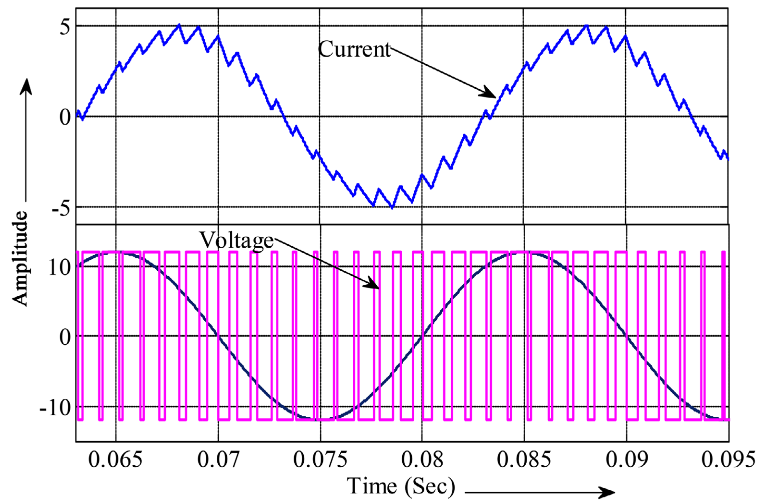

Figure 4. Output waveforms of half-bridge PWM inverter.

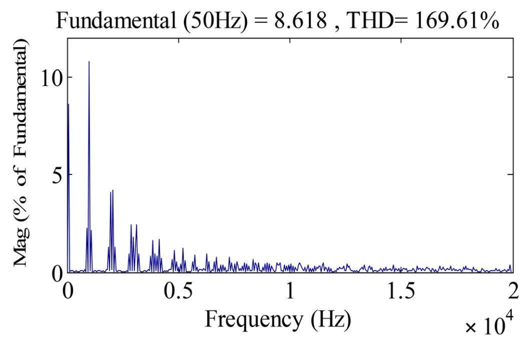

Figure 5. Frequency spectrum of two-level PWM inverter.

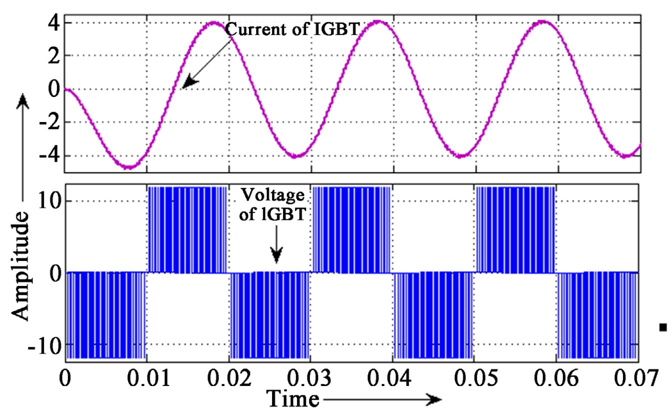

Figure 6. Output waveform of full-bridge PWM inverter.

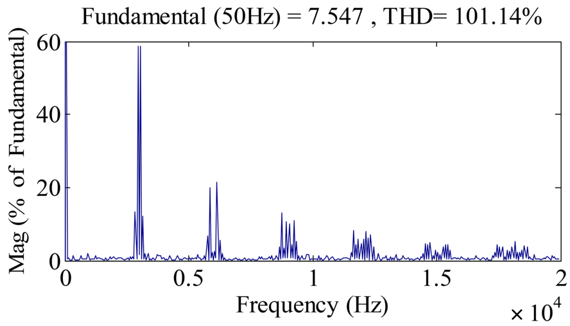

Figure 7. Frequency spectrum of three-level PWM inverter.

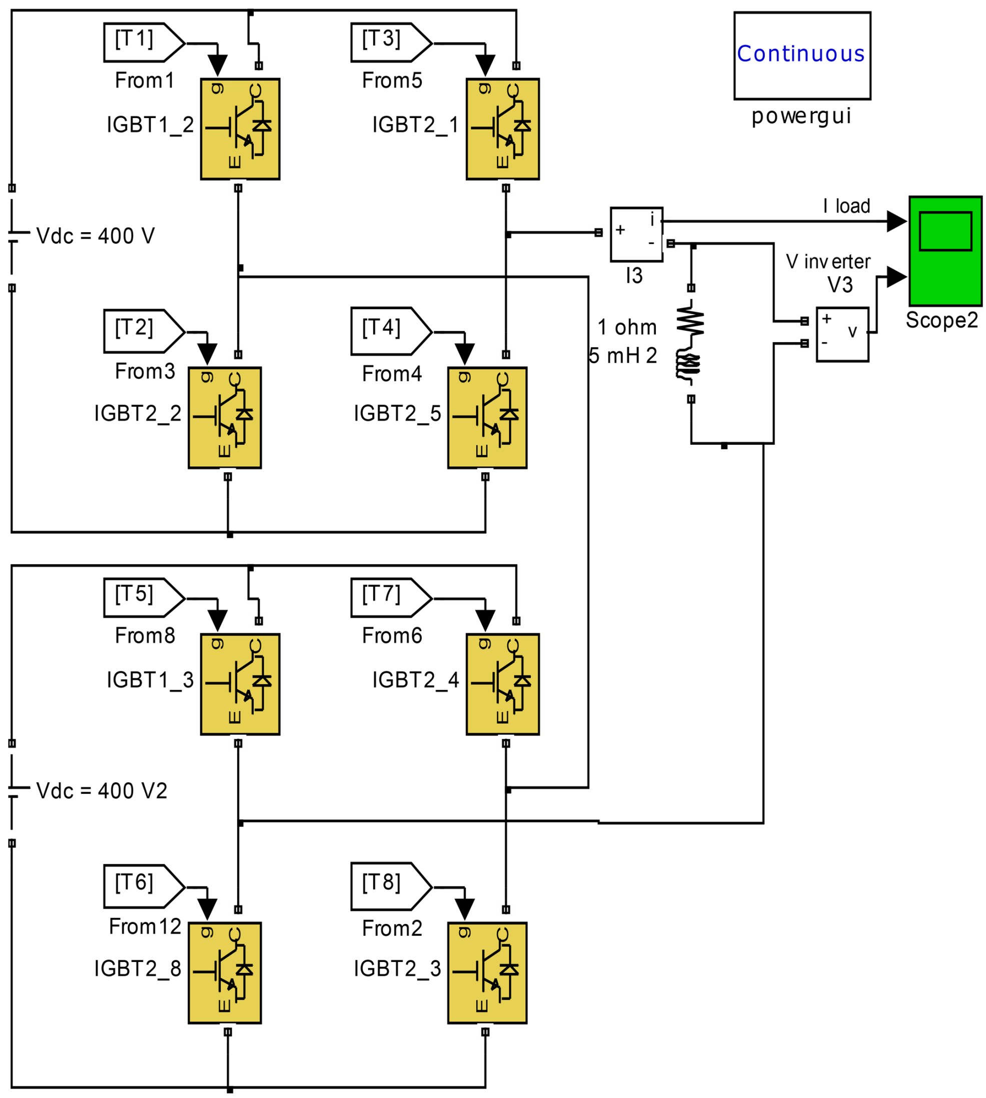

Figure 8. Circuit diagram of five-level PWM inverter.

voltage waveform and frequency spectrum of five level inverter are shown in Figure 10 and Figure 11, respectively.

4) Single-Phase Higher-Level Inverter

The output voltage and frequency spectrum of higher order multilevel stages

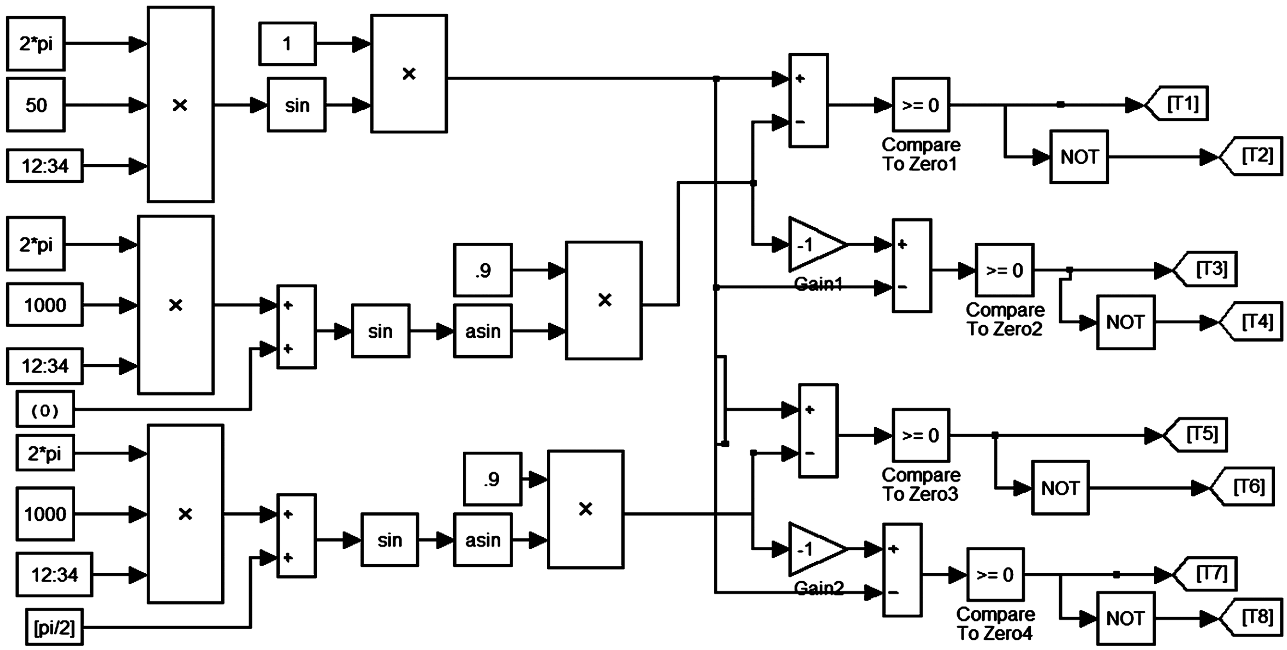

Figure 9. Gate pulse signals of five-level SPWM inverter.

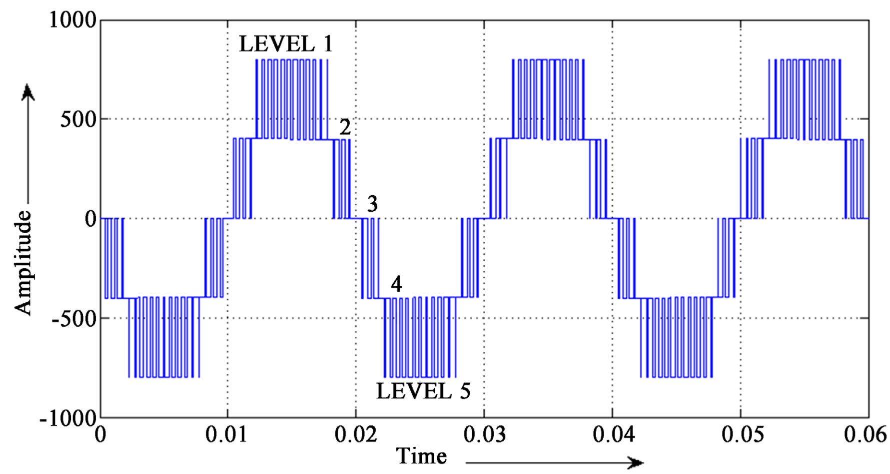

Figure 10. Staircase output of five-level inverter.

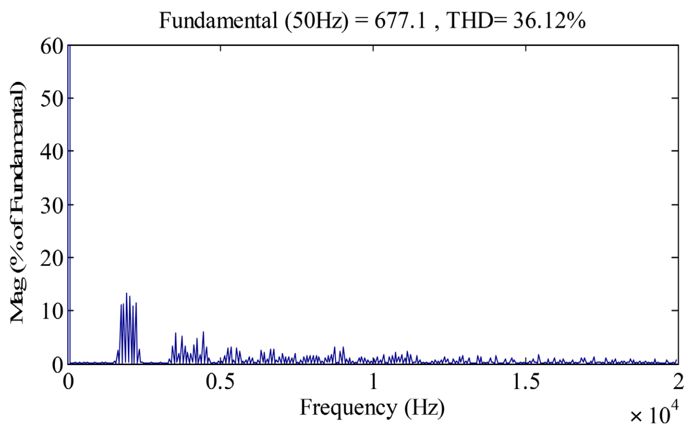

Figure 11. Frequency spectrum of five-level inverter.

e.g. seven level inverter are shown in Figure 12 and Figure 13, respectively, nine level inverter are shown in Figure 14 and Figure 15, respectively, eleven level inverter are shown in Figure 16 and Figure 17, respectively and thirteen level inverters are shown in Figure 18 and Figure 19, respectively.

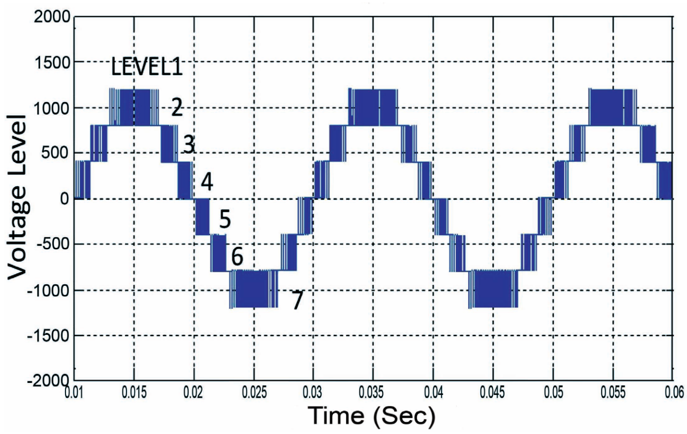

Figure 12. Staircase output of seven-level inverter.

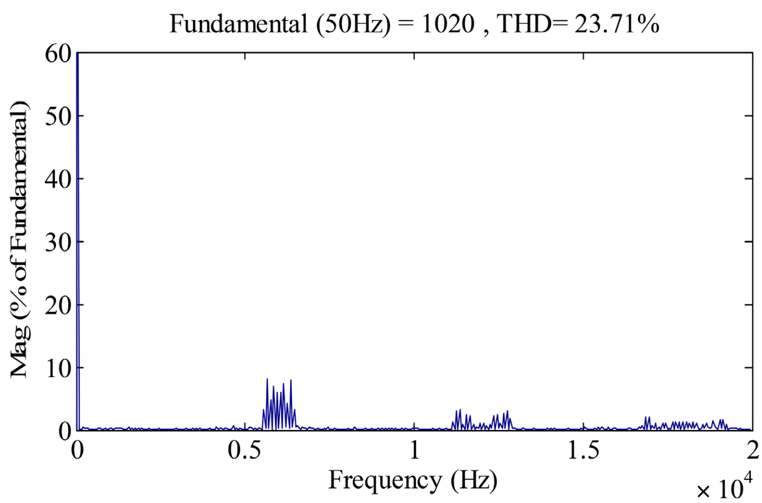

Figure 13. Frequency spectrum of seven-level inverter.

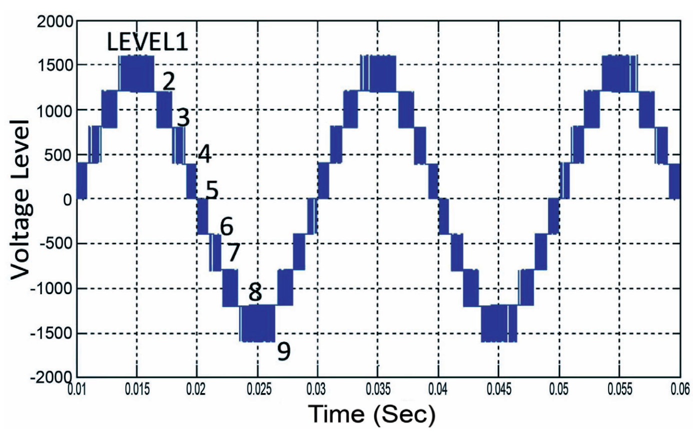

Figure 14. Staircase output of 9-level inverter.

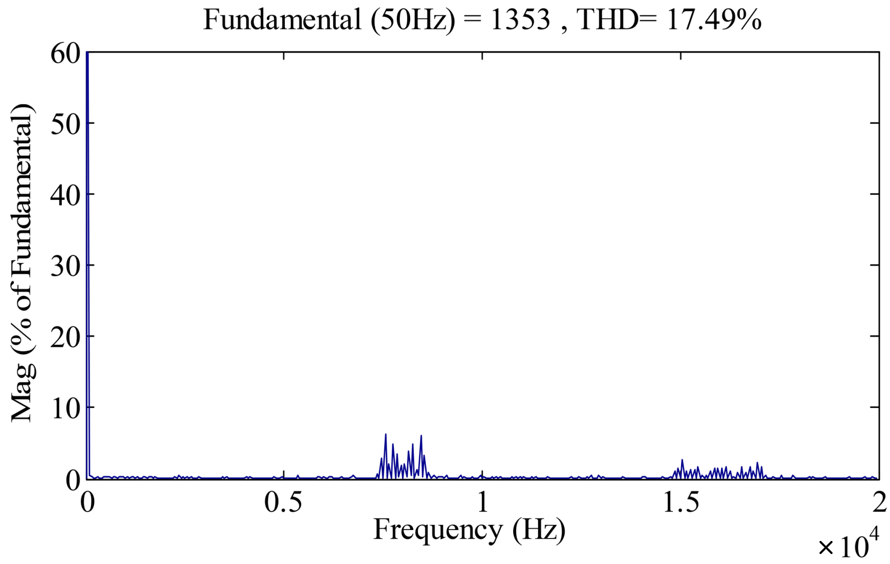

Figure 15. Frequency spectrum of 9-level inverter.

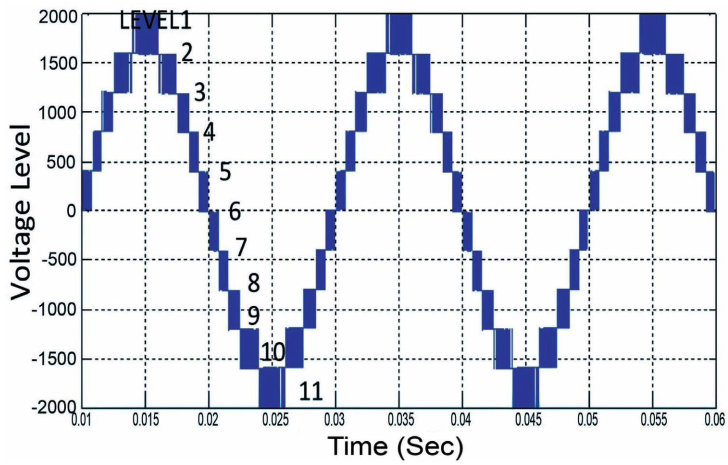

Figure 16. Staircase output of 11-level inverter.

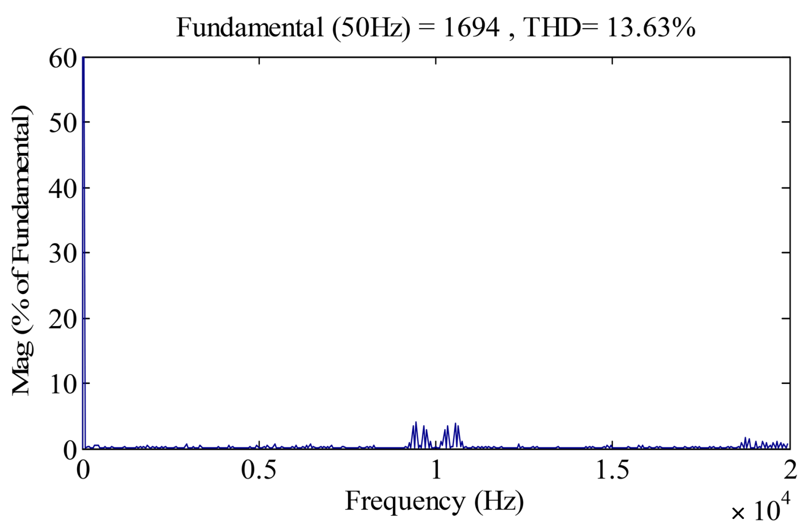

Figure 17. Frequency spectrum of 11-level inverter.

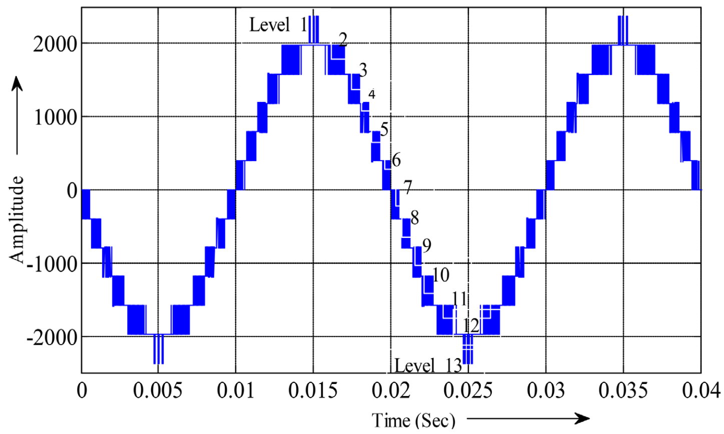

Figure 18. Staircase output of 13-level inverter.

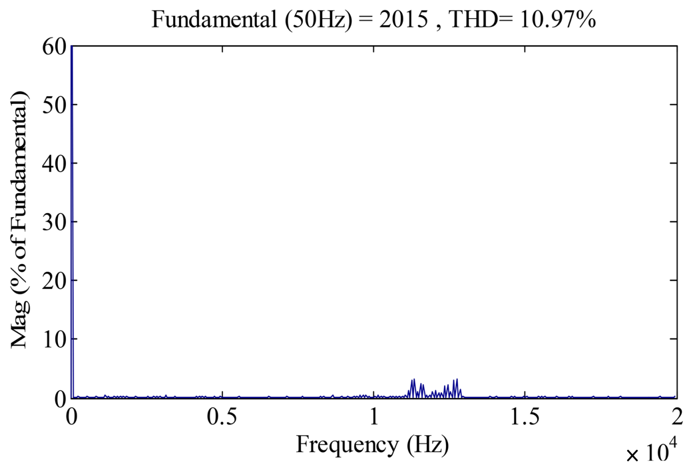

Figure 19. Frequency spectrum of 13-level inverter.

Mathematical Equation:

1) Number of levels, $m = 2N + 1$;

2) Output Voltage, $V_0 = Vm_1 + Vm_2 + \ldots + Vm_h$;

3) Number of carrier signal = (m − 1)/2;

4) Total harmonic distortion.

$$\text{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}}{V_1} \quad (1)$$

Considering this Equation (1) and analyzing the simulation by Simulink, Figure 20 represents the total harmonic distortion of different multilevel inverters in 1ф system. The output of different multilevel inverters in 1ф is shown in Figure 21 using cftool (Curve Fitting Toolbox). The Matlab code is given below for cftool analysis.

MATLAB Code:

```
X = [3 5 7 9 11 13 15];
Y = [101.02 36.12 23.71 17.49 13.57 10.97 8.75];
cftool
```

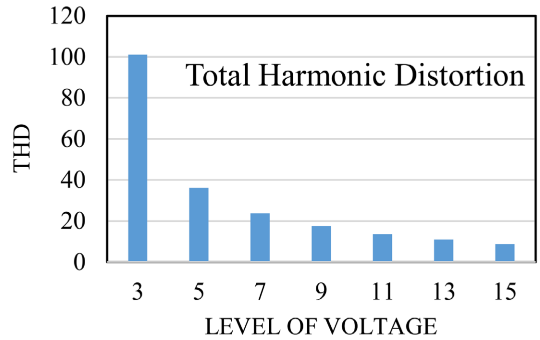

Figure 20. HD of different multilevel for 1ϕ inverter.

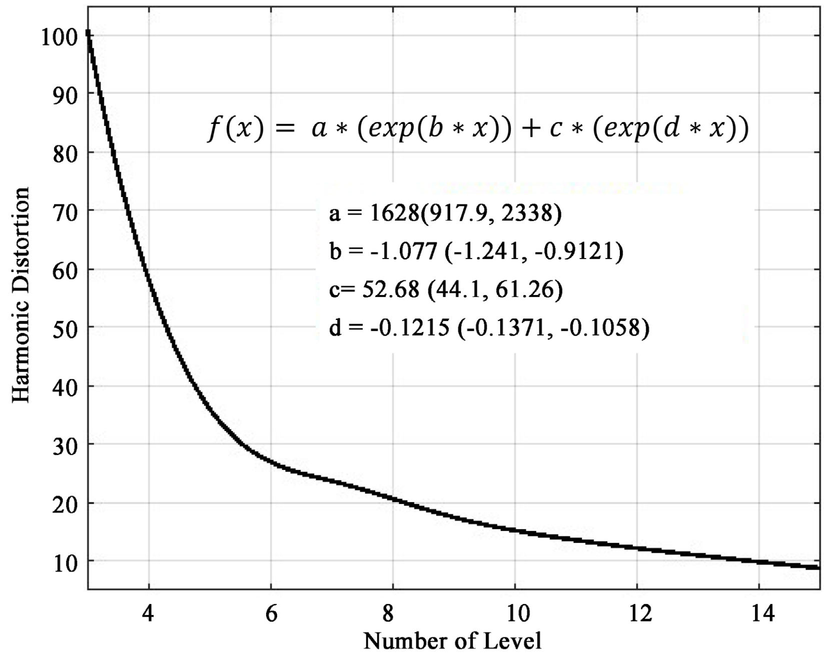

Figure 21. HD of different multi-level inverters in cftool.

Eventually, the harmonic issues can be reduced by raising an inverter's level, however doing so will result in more components and a higher cost.

5) Three-Phase Two-Level Inverter

Three-phase converters are more commonly used in comparison to single-phase half-bridge or full-bridge converters. When examining the circuit diagram of a 3-phase bridge converter [19], it becomes evident that the converter is composed of six switching devices, with two devices allocated for each phase.

When the modulating signal surpasses the carrier, pulse 1 is set to a high state (1), while pulse 2 is set to a low state (0). By utilizing a single carrier and three modulating or reference signals with a 120˚ phase shift between each other, it is possible to generate six gate pulses that drive the converter. A visual representation of the PWM switching scheme for the 3-phase bridge converter can be observed in Figure 22.

The line-to-line voltage waveform of three-phase bridge converters exhibits a similar pattern to that of the full-bridge converter. An illustration of the line-to-line output voltage waveform of the 3-phase bridge converter can be seen in **Figure 23**. Like the single-phase full-bridge converter, the line-to-line voltage of the 3-phase bridge converter exhibits approximately 88% total harmonic distortion (THD). **Figure 24** displays the frequency spectrum of the output line-to-line voltage.

6) Three-Phase Multi-Level Inverter

Three phase multilevel inverter consist of three single-phase MMC inverter or 3-phase 2-level inverter. The output phase voltage and line voltage are shown in

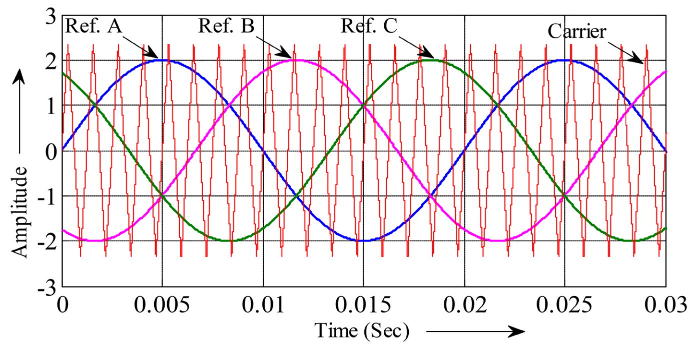

Figure 22. Modulation scheme of three-phase two-level converter.

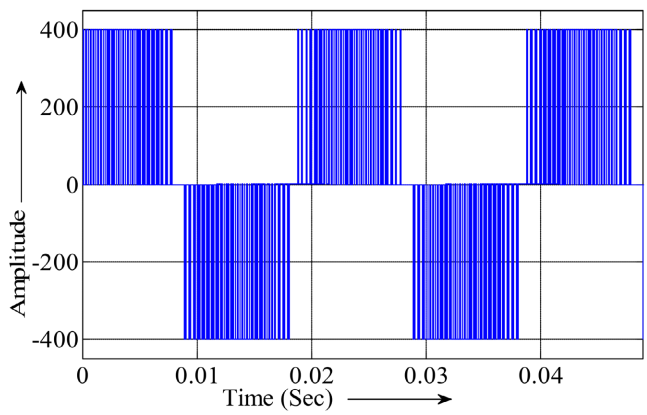

Figure 23. Output line voltage of three-phase two-level inverter.

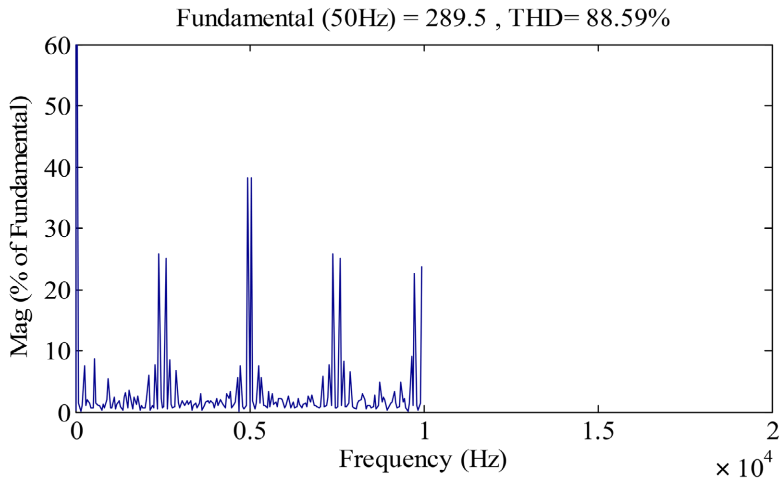

Figure 24. Frequency spectrum of three-phase two-level inverter.

Figure 25 and Figure 26, respectively. Figure 27 shows 3-phase 5-level MMC inverter. 3ϕ Line voltage, output line current and frequency spectrum of 3-phase 5-level inverter are shown in Figure 28, Figure 29 and Figure 30, respectively.

Similar to how a three-phase inverter's level can be raised to reduce harmonic difficulties, doing so will add additional components and increase the cost. From Figure 31, The Harmonic distortion for single-phase is greater than 3-phase inverter. So, for Medium and High voltage application three-phase inverter is efficient than single-phase inverter.

4. Hardware Implementation

The basic block diagram of the proposed system is depicted in Figure 32. The objective of the inverter circuit is to generate a desired output voltage of 230 V AC with a frequency of 50 Hz.

The full H-bridge inverter circuit is utilized to convert a DC voltage (12 V) into a sinusoidal AC voltage at the desired output voltage and frequency.

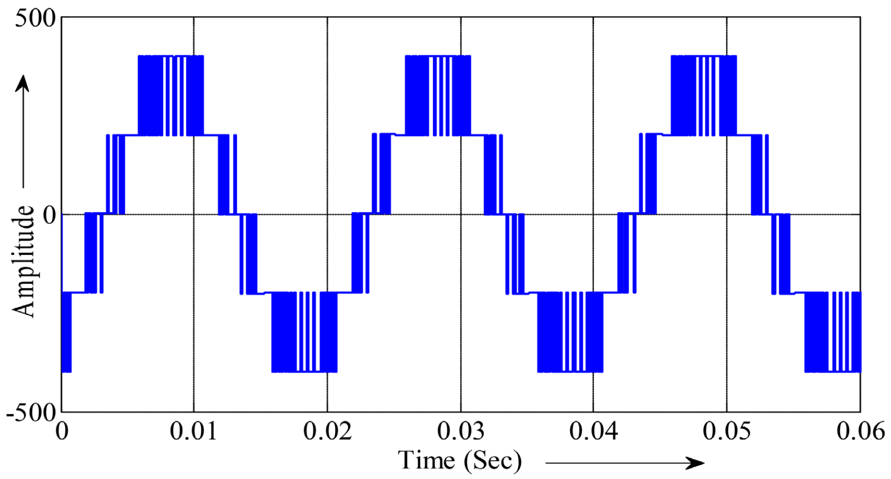

Figure 25. Output phase voltage of 3-phase 5-level inverter.

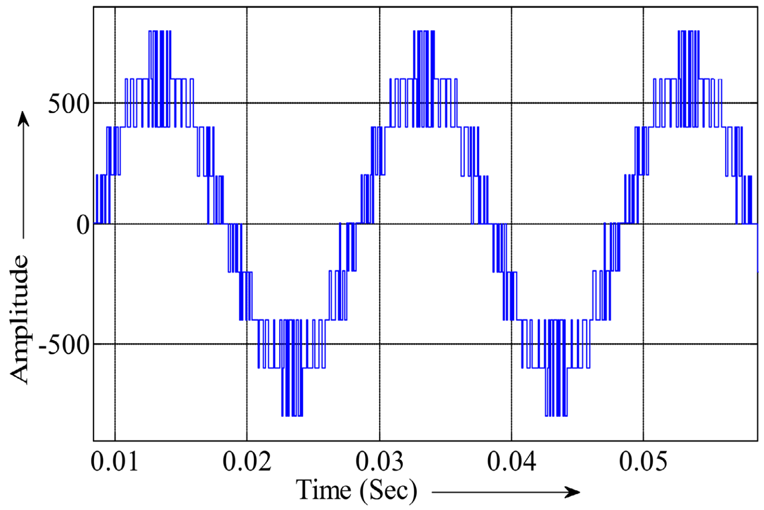

Figure 26. Line voltage of 3-phase 5-level inverter.

To generate a sinusoidal waveform centered on zero voltage, it is necessary to have both positive and negative voltage across the load. This functionality can be achieved using an H-bridge inverter circuit, as illustrated in **Figure 33**. In the

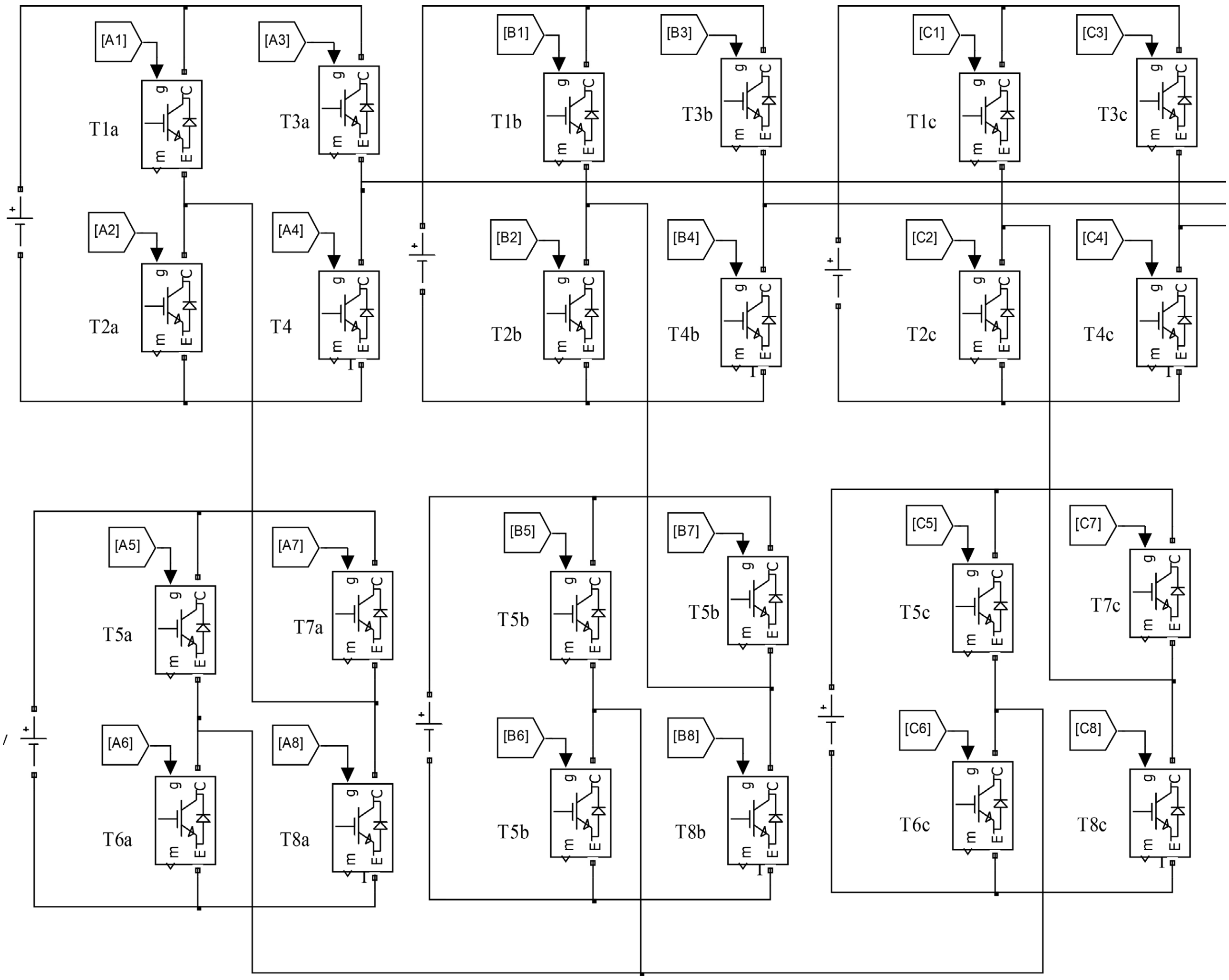

Figure 27. Circuit diagram of 3-phase 5-level inverter.

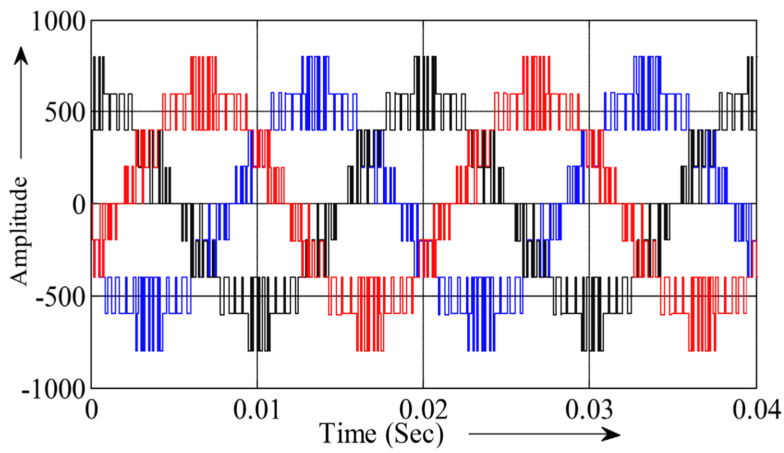

Figure 28. Three-phase line voltage.

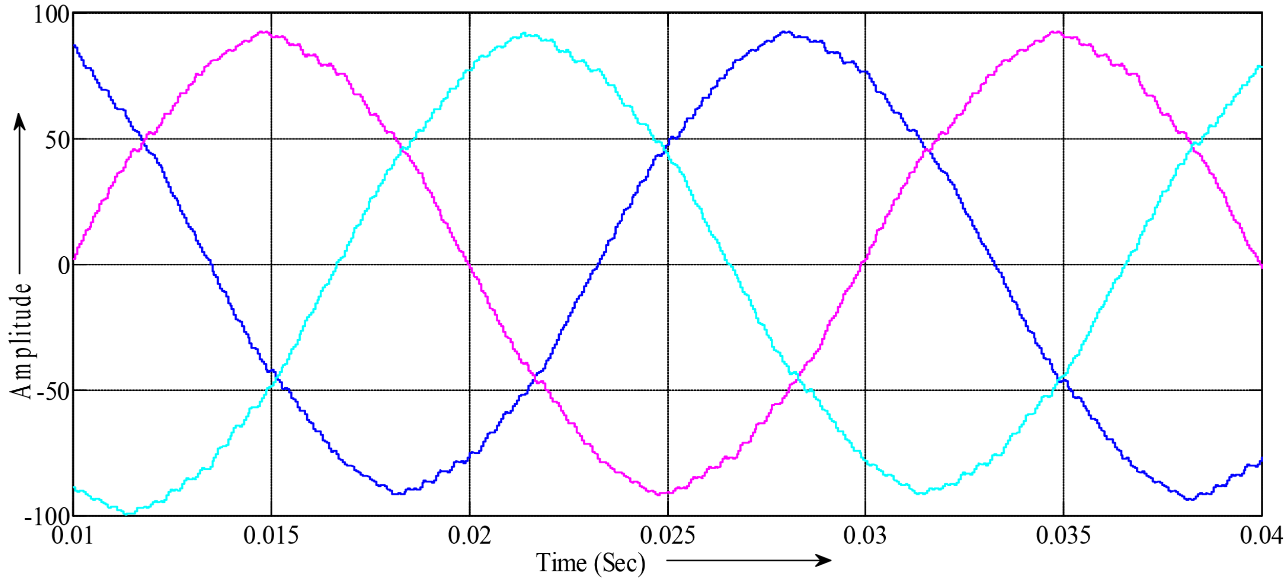

Figure 29. Output line current of 3-phase 5-level inverter.

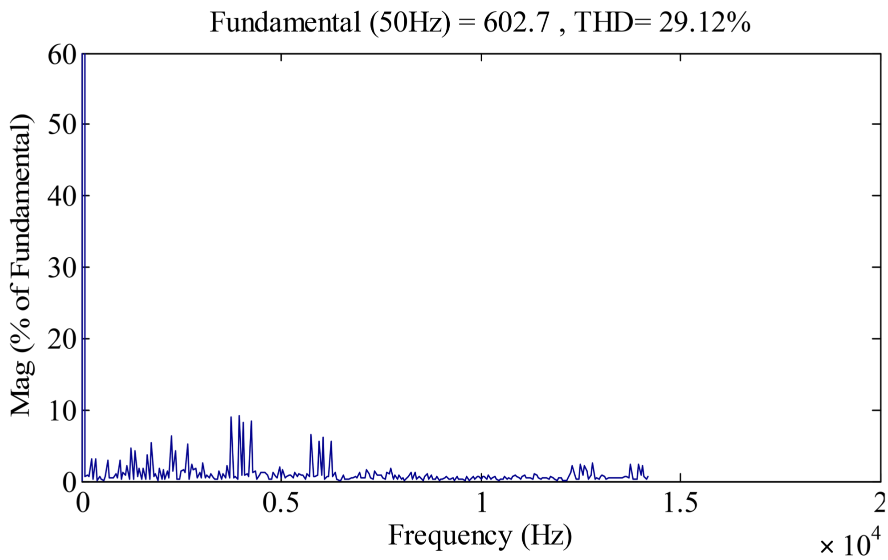

Figure 30. Frequency spectrum of 3-phase 5-level inverter.

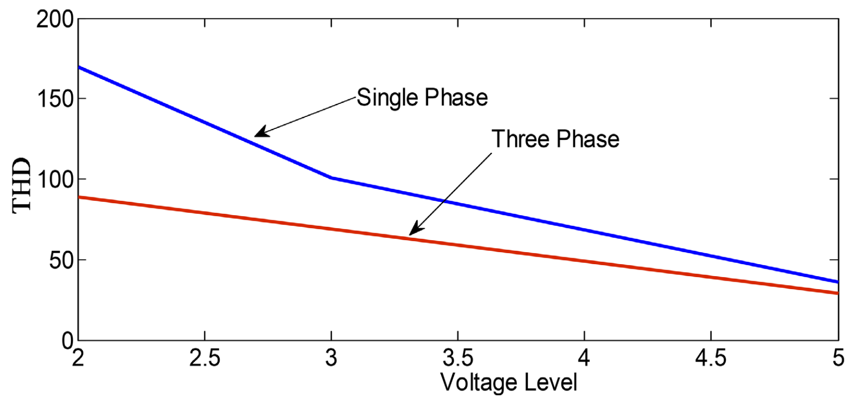

Figure 31. HD for single-phase and three-phase inverter.

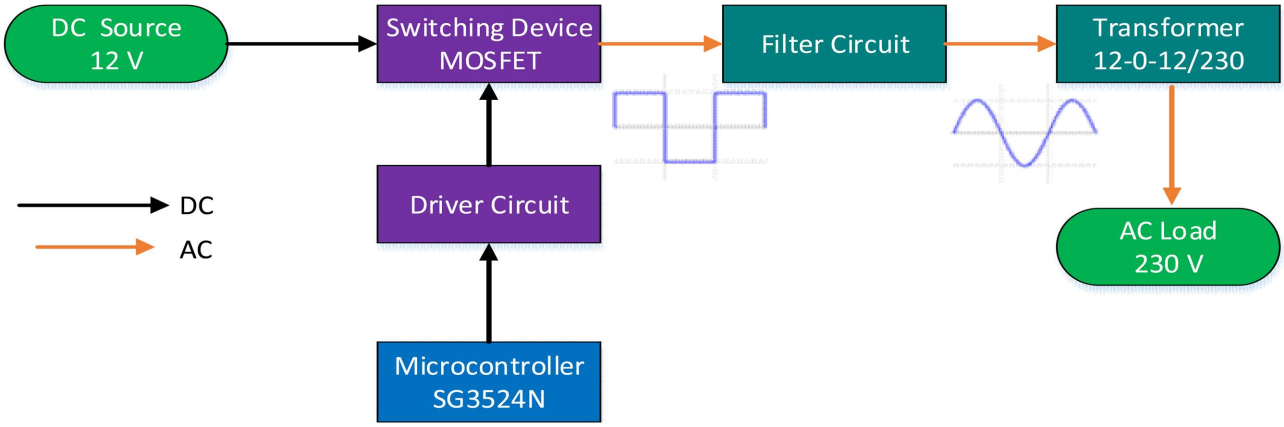

Figure 32. Block diagram of inverter circuit.

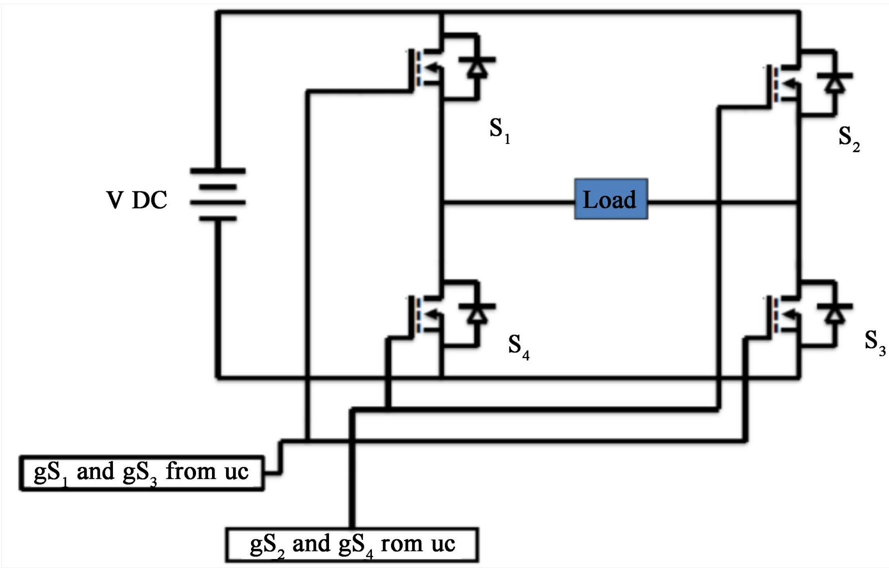

Figure 33. The full H-bridge single-phase inverter.

standard H-bridge configuration, switches S1, S3, S2, and S4 are arranged accordingly. During one half of the cycle, both gating signals GS1 and GS3 are simultaneously switched. In Figure 33, mount the microcontroller SG3524 on a holder. The capacitors (4.7 μF) must be rated at least 15 V. Preset RT can be used for adjusting the inverter's operating frequency. Transistors in the driver stage require a heat sink. A transformer is 12-0-12 V primary, 230 V secondary and 300 VA. The filter circuit is a low-pass type.

While during the other half, both GS2 and GS4 are switched simultaneously. The only difference lies in the phase relationship between GS1 and GS3, which leads GS2 and GS4 by half a cycle or 180 degrees of the switching signal. However, the output of the circuit does not exhibit a sinusoidal waveform and is periodic in nature. To address this, the SG3524 microcontroller, which is a voltage-mode PWM controller, is employed. This microcontroller generates the necessary sinusoidal PWM signals to drive and switch the H-bridge MOSFET transistors.

The prototype design of the inverter circuit consisting of various components like micro-controller, MOSFET's (used as a switch), heat sink, etc. and the connection diagram of the inverter of different measuring instruments are shown in Figure 34 and Figure 35, respectively. A resistive load (like 100 W Bulb) is used in Figure 36 to show the experimental results of the output waveform for the

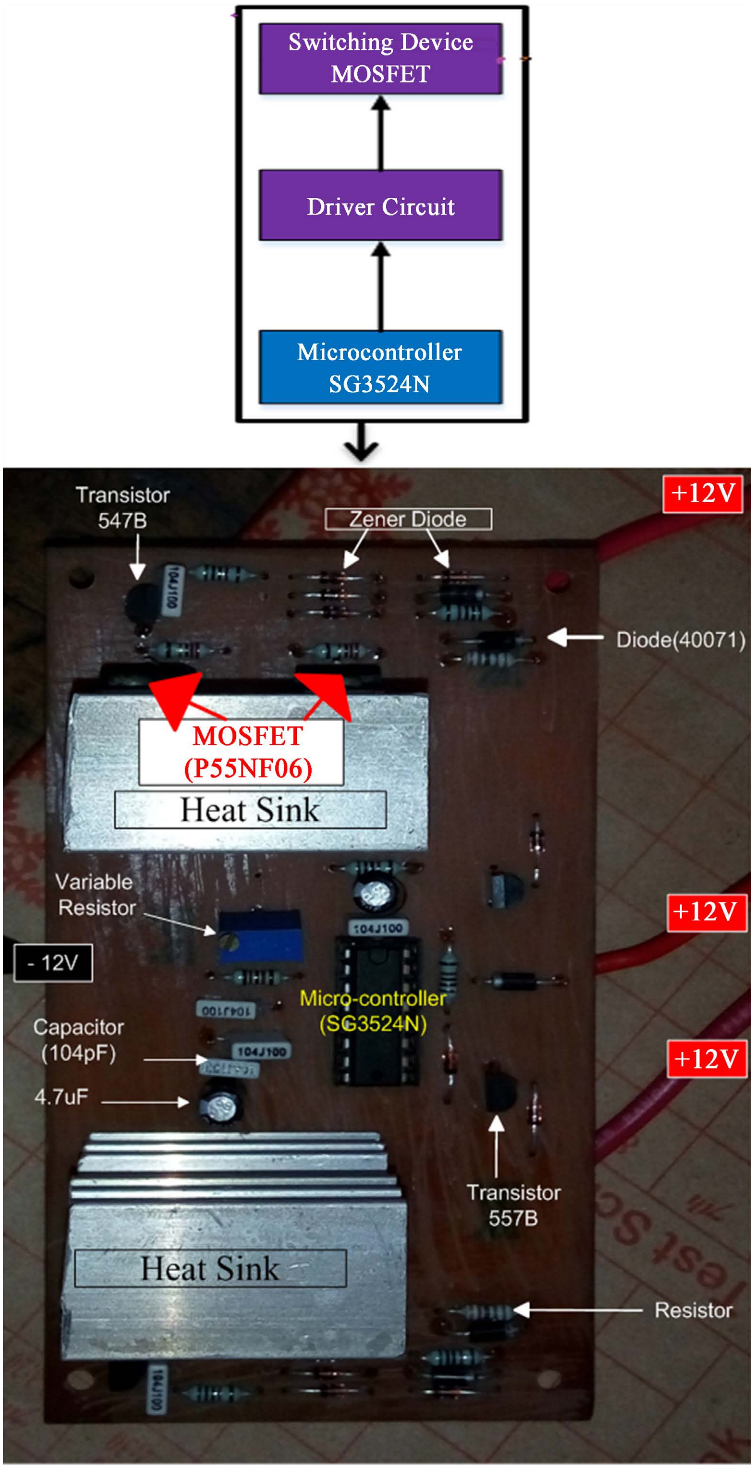

Figure 34. Inverter circuit.

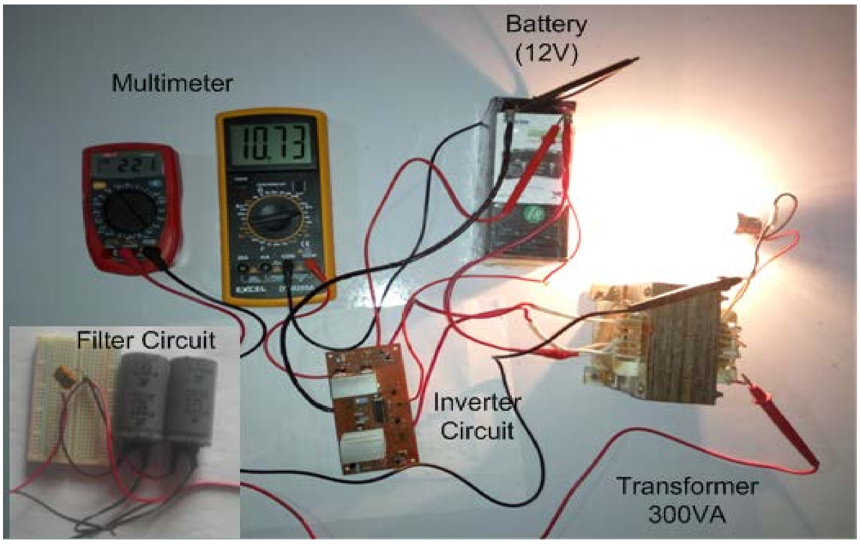

Figure 35. Hardware setup.

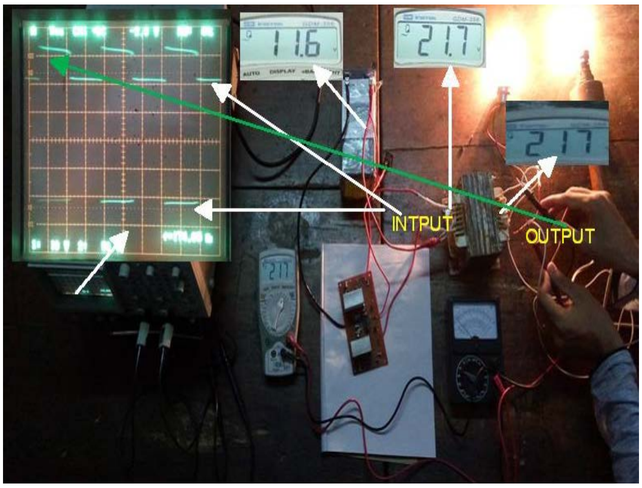

Figure 36. Observation of hardware setup with 100 W load.

single-phase full-bridge inverter. Two waveforms are displayed in a suitable scale of CRO without filter and with LC filter to get AC waveforms of 50 Hz, shown in Figure 37 and Figure 38, respectively. The simulation results of the waveform of the full H-bridge single-phase inverter and the experimental results of output waveforms of the inverter to ensure the output waveform results are compared and practically verified. The inverter tested for various AC loads which are shown in Table 1 that also describes in Figure 39.

5. Analysis of Switching Device

The output waveform of single-phase three-level inverter using MOSFET and IGBT are shown in Figure 40 and Figure 41, respectively. Where harmonic distortion for MOSFET (104%) is greater than IGBT (101%). Figure 42 and Figure 43 shows the output of resistive load using the switching device IGBT and MOSFET, respectively. For Inductive load, output is like as same as resistive load

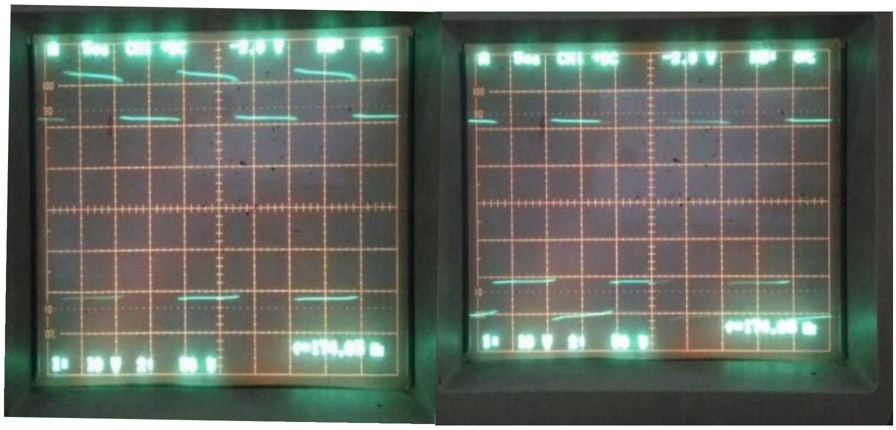

Figure 37. Output wave shape without filter.

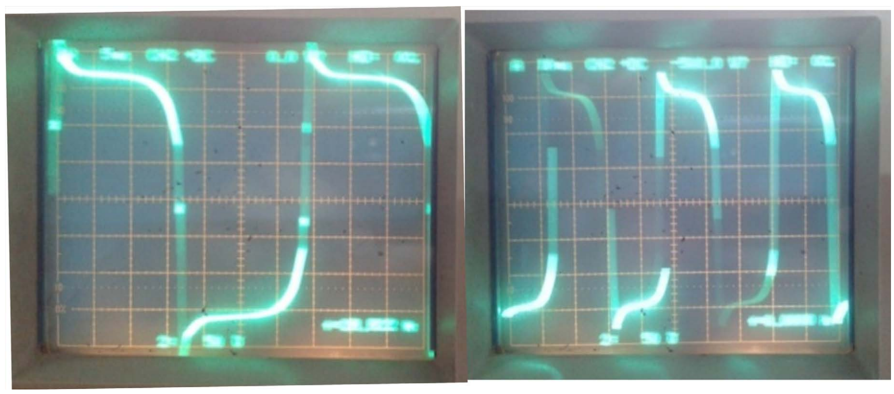

Figure 38. Output wave shape using filter

Table 1. Observation of output voltage with variation of load.

Output Power Watt	Battery Voltage (DC) Volt	Output Voltage (AC) Volt
0	12.36	246.4
25	12.05	235
40	11.89	225
60	10.73	221
100	11.60	217

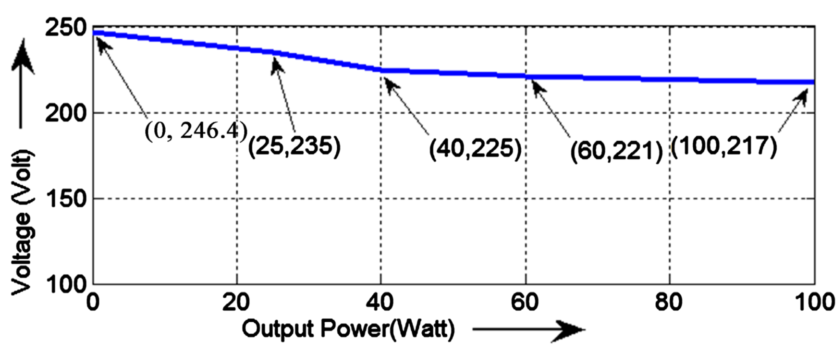

Figure 39. Output power (load) vs. output voltage curve.

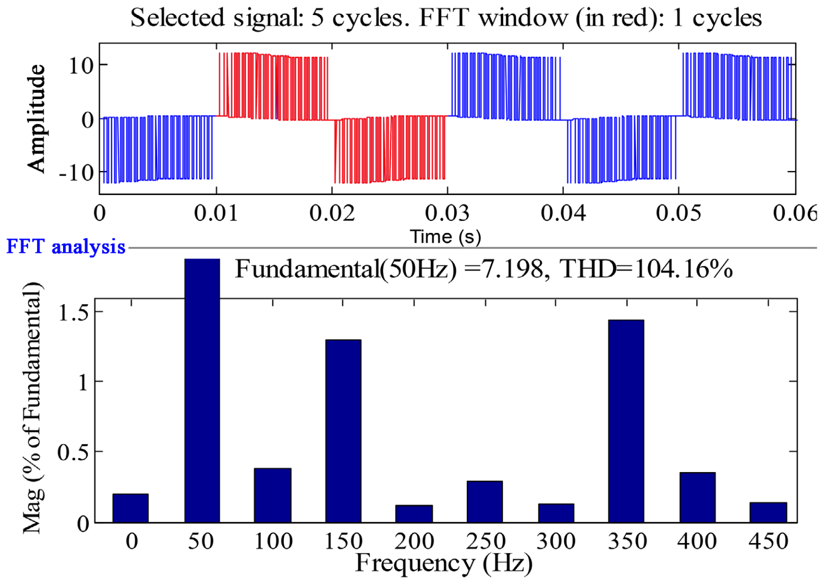

Figure 40. Output voltage and THD of inverter using MOSFET.

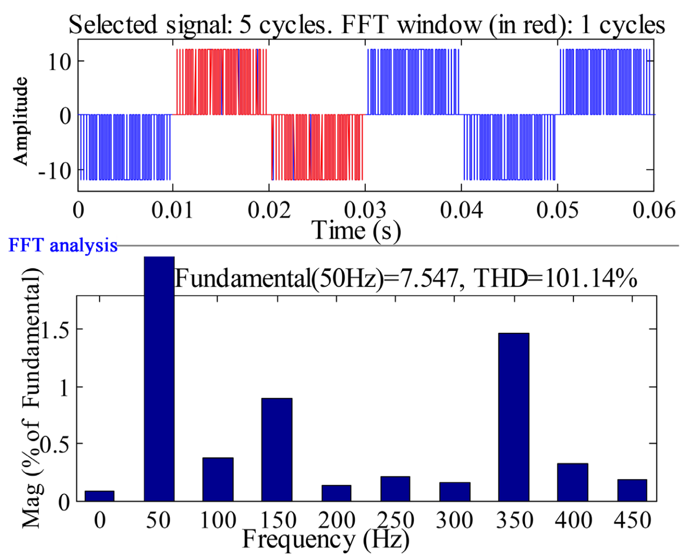

Figure 41. Output voltage and THD of inverter using IGBT.

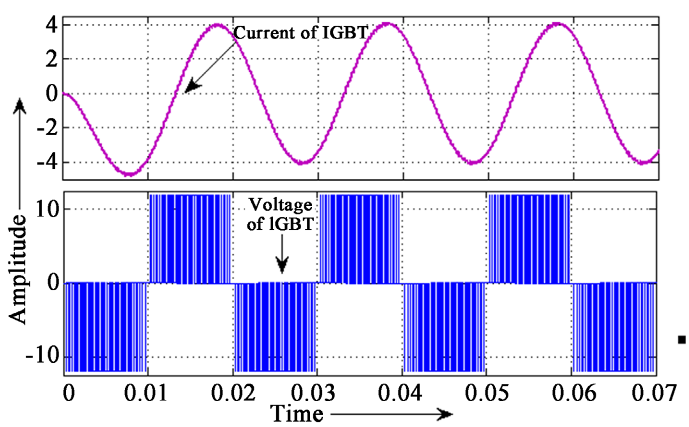

Figure 42. Output wave shapes of IGBT.

which is shown in Figure 44 but signal is distorted and there is a voltage variation for MOSFET observed in Figure 45. Figure 46 highlights that IGBT technology is suitable for frequencies ranging from 0 to 25 kHz, while MOSFET technology is more appropriate for frequencies between 250 and 1000 kHz. However, when it comes to selecting a switching device within the frequency range of 25 to 250 kHz, this comparative study becomes particularly significant. These findings underscore the importance of carefully considering the selection of the switching device based on the desired frequency range and the corresponding losses associated with rated current.

6. Conclusion

In this paper, we conducted simulation experiments using MATLAB/Simulink

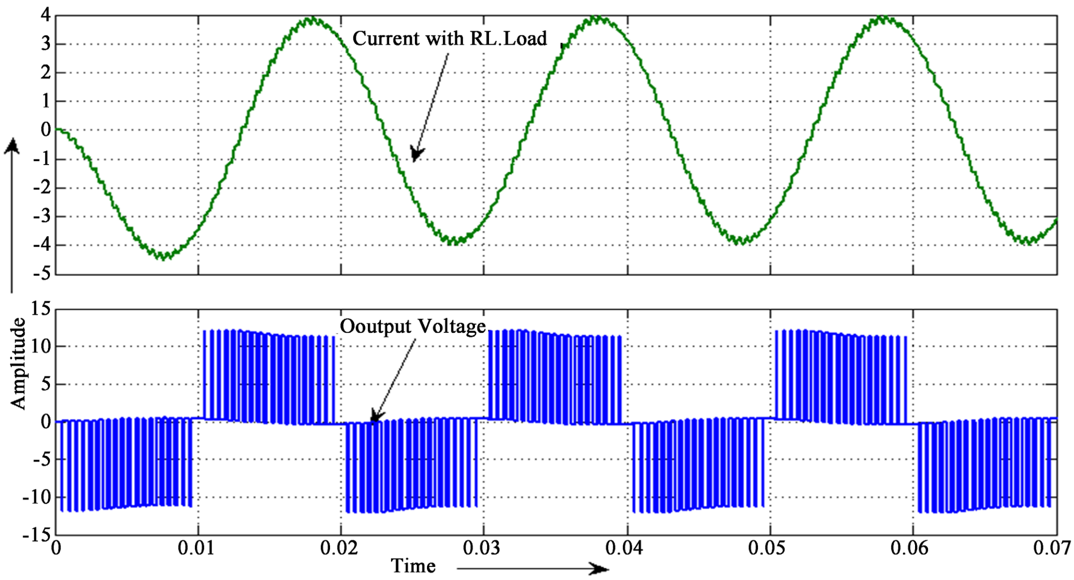

Figure 43. Output wave shapes of MOSFET.

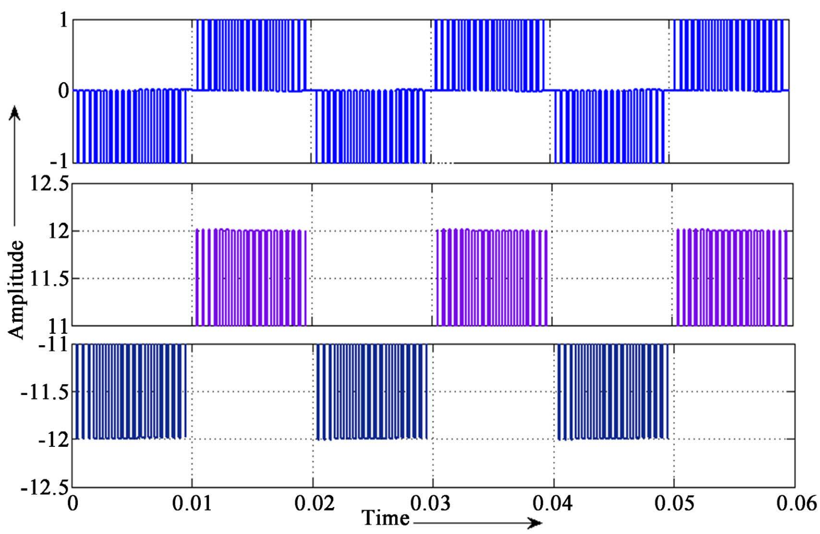

Figure 44. Close-view of IGBT output with R-L load.

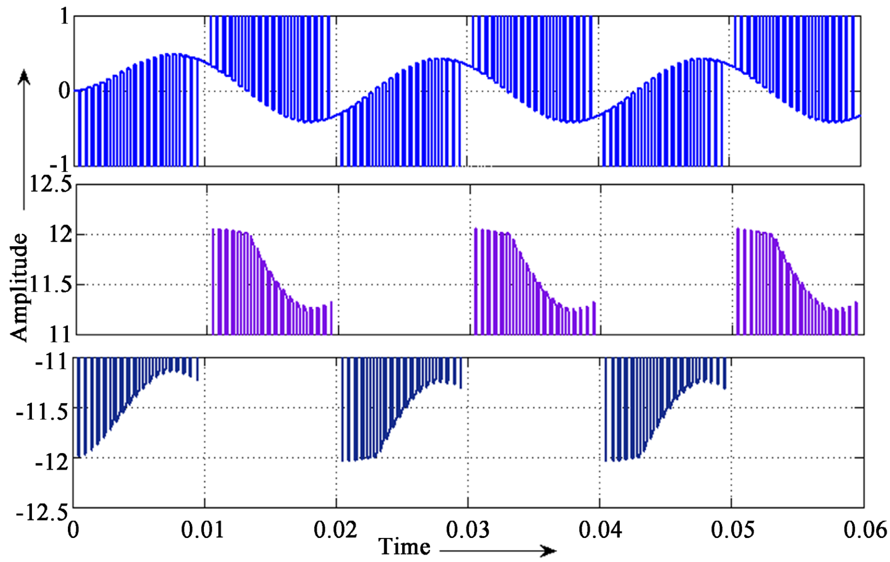

Figure 45. Close-view of MOSFET output with R-L load.

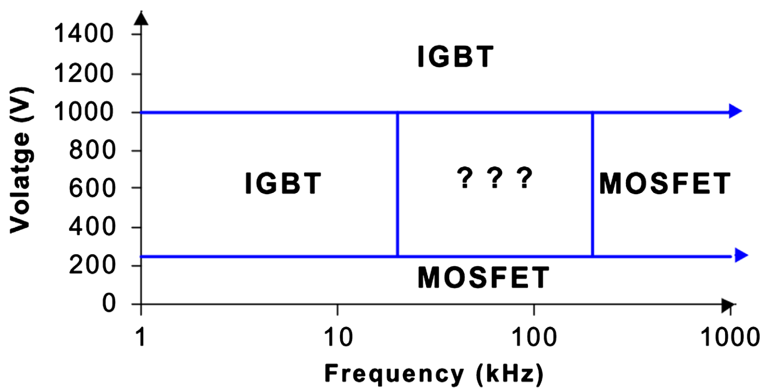

Figure 46. Switching frequency and voltage level considerations [20].

software and compared the results with experimental data obtained from practical implementation using the LAB Module. By analyzing the simulation results of IGBT and MOSFET technologies, considering output voltages and calculating the total harmonic distortion (THD), it is observed that increasing the level reduced THD. Additionally, employing a 3-phase inverter further reduced THD, and using IGBT technology resulted in even lower THD. Thus, it can be concluded that these factors contribute to improved performance in terms of harmonic distortion reduction. The primary objective of our research was to design a control circuit for a single-phase inverter, which we successfully implemented using the SG3524 microcontroller. This paper illustrates the evaluation of inverter performance under various AC load conditions in **Figure 39**, specifically at 25W, 40W, 60W, and 100W. Moreover, this research paves the way to use a three-phase modular converter for dual-purpose applications in DC and AC microgrids in [21], for vehicle mobile power in [22] and for electrical energy harvesting from the foot stress on foot overbridge using piezoelectric tile in [23].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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