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Design and Construction of a 1.5 kVA Pure Sine Wave Inverter for Office Use

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Abstract

This paper focuses on the design and construction of a 1.5 kVA pure sine wave inverter aimed at providing an efficient and reliable power conversion solution for areas with unstable power supply. The inverter converts 12V DC from deep-cycle batteries into 220V AC, offering a stable power source for sensitive electronic devices and household appliances. Using a dsPIC30F2010 microcontroller, the system manages critical operations such as Pulse Width Modulation (PWM) control and voltage synchronization. The design includes essential components like the power stage (MOSFET/IGBT), transformer, and filtering systems, integrated through a custom-designed Printed Circuit Board (PCB). Initial testing confirmed the system's stability under different load conditions, with a low battery cut-off at 10.1V and a charging cut-off at 14.7V. Performance evaluations showed high efficiency, particularly at mid-level loads, ensuring clean power output. The cooling system effectively managed heat dissipation, maintaining component temperatures within safe operating limits even under full load. The performance of this inverter was also compared with that of a 1.5 kVA modified sine wave inverter. The results show that the pure sine wave is better in terms of waveform and ability to carry loads, but in terms of cost and circuit complexity the modified sine wave is cheaper. Overall, the results demonstrate the inverter's reliability and suitability for providing uninterrupted power in regions with inconsistent electricity supply.

Keywords: *1.5 kVA pure sine wave inverter, dspic30f2010, pulse width modulation (PWM), microcontroller, transformer.*

1.0 Introduction

In recent years, the demand for efficient and reliable power inverters for continuous power supply has increased significantly worldwide. This is largely due to the persistent issue of erratic power supply, which hinders the development of many nations' economies and their industrial growth. Nigeria, despite being rich in energy resources, has a particularly unstable electricity generation and distribution infrastructure, leading to frequent outages, voltage fluctuations, and load shedding. Nigeria's electricity access rate stood at 59.5% in 2021, with 40.5% of the population having little to no access, particularly in rural and pre-urban areas [1]. These power supply problems have caused significant disruptions to businesses, households, and essential services. Even areas with access to electricity frequently experience interruptions due to breakdowns in the distribution system or overloading of the limited available supply. This has led households and businesses to seek alternative sources, such as generators, as well as solar power inverters.

Inverters are electronic devices that convert direct current (DC) to alternating current (AC) at a desired frequency and voltage through the use of appropriate switching and control units, transformers, and regulators. This conversion is essential because most household appliances and industrial equipment operate on AC power, while the sources, such as batteries and solar panels, produce DC power. Therefore, inverters play a crucial role in bridging this gap, making DC power usable for AC devices.

There are various types of inverters, each designed for specific applications and operational requirements. The primary types, categorized based on their output waveform, functionality, and application, include:

i. Square wave inverters, which are the simplest and least expensive, provide a square wave output with abrupt transitions between voltage levels and have limited applications. They are not suitable for sensitive electronic devices due to their high harmonic distortion.
ii. Modified sine wave inverters provide a stepped or chopped approximation of a sine wave, making them more efficient than square wave inverters. They are more robust and less prone to damage, suitable for most household appliances, but may produce some harmonic distortion and noise.
iii. Pure sine wave inverters, which are designed to produce a smooth sine wave output, similar to the utility power. They are ideal for sensitive electronic equipment and most appliances, but are generally more expensive and complex than the other types. [2], highlighted the importance of pure sine wave inverters in powering sensitive equipment.

Among the various types of power inverters, pure sine wave inverters have gained special importance for applications where precision and dependability are critical. They are eco-friendly, economical, dependable, and efficient. They also enhance the efficiency and ensure quiet operation of inductive loads like motors, resulting in

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low harmonic distortion, which makes them highly suitable for urban and commercial applications where noise is intolerable [3].

Typical loads in an office of consideration are as shown in Table 1.

Table 1: Typical loads in the Office

S/N	Appliances	Power Rating (W)
1	Led bulbs	20
2	Fan	18
3	Radio	10
4	laptop	65
5	Phone Charger	5
	Total	118

2.0 Methodology

The first step in designing the 1.5kVA pure sine wave inverter is to determine the power requirements. Table 2 below shows the design specification.

Table 2. Design specification

Power rating	1.5 kVA
Operating Frequency	50 Hz
Phase	Single Phase
Input Voltage	12V DC (Inverter), 220V AC (Mains supply)
Output Voltage	220V AC
Energy Source	Deep-cycle rechargeable batteries

The key components of the inverter include the control unit, power stage, transformer, and filtering system. The basic block diagram is shown in Figure 1 below.

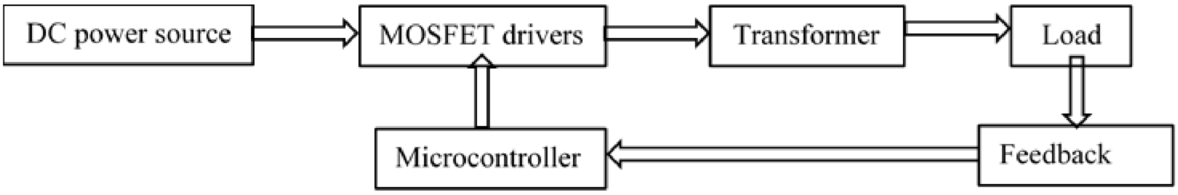

Figure 1. Block diagram of the pure sine wave inverter process

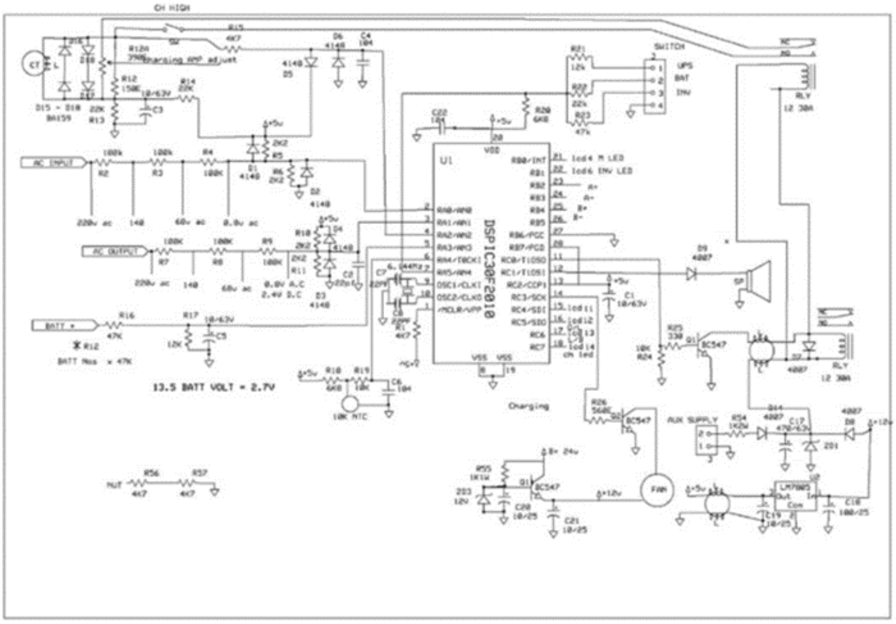

Figure 2. Control and Oscillator Circuit Diagram for Pure Sine Wave Inverter

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2.1 Control and oscillation unit

This circuit is designed to manage the charging and operation of the pure sine wave inverter system, handling the transition between mains AC power and battery backup. The circuit diagram is shown in Figure 2 below. It performs the following key functions.

i. AC Input Processing: The circuit takes input from the AC mains, rectifies it, and uses it to both charge the battery and supply power to the load when in normal mode. It monitors AC input voltage for efficient switching.

ii. Battery Charging: The circuit regulates and controls the charging of a battery through adjustable components that ensure safe charging based on the battery voltage and current limits. It includes protection mechanisms like diodes and relays to prevent overcharging and reverse current.

iii. A microcontroller (DSPIC30F2010) monitors the system, controlling key aspects like voltage levels, temperature, and switching between different operational modes (AC mains, battery, or inverter mode). The dsPIC30F2010 is a versatile 16-bit digital signal controller, specifically designed for motor control and power electronics applications. In the design of this 1.5kVA pure sine wave inverter, the dsPIC30F2010 plays a crucial role in controlling the Pulse Width Modulation (PWM), managing feedback signals, driving the MOSFETs, and handling mode switching between inverter and normal operation. The image of the DSPIC30F2010 is shown in plate 1 below.

Plate 1. DSPIC30F2010 digital signal controller

iv. AC to inverter switching: The system automatically switches between AC mains and battery backup using relays. If the mains fail, the relay shifts to inverter mode to ensure uninterrupted power to the connected load.

v. Temperature Control: A thermistor and fan circuit manage temperature, activating the fan when the system heats up to ensure proper cooling during operation.

vi. Status Indicators: LED indicators show the charging status and operational mode of the inverter, allowing for easy monitoring.

a. Generation of the pure sine wave

The production of the pure sine wave relies on Sinusoidal Pulse Width Modulation (SPWM). The dsPIC30F2010 is configured to generate SPWM by comparing a reference sine wave (the desired output) with a high-frequency triangular carrier signal. Several studies, including those by [4] and [5], have demonstrated the effectiveness of SPWM in reducing total harmonic distortion (THD) and improving overall inverter performance by controlling the width of the pulses to match the sine wave's amplitude at each point. This is one of the reasons why the dsPIC microcontroller was selected for this project, as [6], in their study, used a PIC18f2550 microcontroller to achieve a multi-level PWM rather than a sinusoidal PWM, just like [7] in their study, which is more complex than SPWM. Also, [8] used a combination of an ATMEGA328P microcontroller and an SG3524 oscillator to achieve the sinusoidal PWM to eliminate harmonic distortion.

The dsPIC30F2010 stores a sine wave lookup table in its memory, representing the reference sine wave. This sine wave is compared to the triangular carrier signal (generated by the dsPIC30F2010) to produce the necessary PWM signals. The carrier frequency for the PWM is set at 10 kHz, which is high enough to minimize audible noise and ensure efficient power conversion while keeping switching losses at acceptable levels. The width of the PWM pulses is modulated according to the amplitude of the sine wave at each point, creating a series of pulses that approximate a sine wave. After the MOSFETs switch the DC power, the output is passed through an LC low-pass filter, which smooths the modulated signal into a continuous pure sine wave. This filtering removes the high-frequency components, leaving only the fundamental sine wave.

b. Feedback Reception and Sensing

The dsPIC30F2010 receives feedback from various points in the circuit to monitor and control the inverter's performance. One important feedback signal is the battery voltage. The microcontroller constantly senses the battery voltage through its analog-to-digital converter (ADC) pins. For example, the low battery voltage is detected via pin BA3, which triggers the system to shut down the inverter when the battery voltage falls below 10.1V to prevent deep discharge. Similarly, the microcontroller senses the charging cut-off voltage of 14.7V to ensure safe charging of the battery.

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Additionally, the dsPIC30F2010 monitors the output voltage and current through the feedback circuits. The feedback data is processed in real time to adjust the PWM duty cycle, ensuring that the inverter maintains a stable output voltage under varying load conditions. This closed-loop feedback control helps to minimize harmonic distortion and ensure smooth operation.

c. Feedback and Signal Conditioning Circuit (LM324)

In this design, the LM324 is responsible for amplifying the voltage and current signals from the feedback circuits.

d. Voltage Regulation and Current Control

The dsPIC30F2010 monitors the output voltage and current through a feedback loop and adjusts the PWM duty cycle to compensate for any voltage drops or increases. This ensures that the inverter maintains a consistent 220V AC output, regardless of load fluctuations.

e. Fault Handling and Protection Features

The dsPIC30F2010 is programmed to handle various fault conditions:

i. Under-voltage and overvoltage protection: If the battery voltage drops too low (below 10.1V) or rises too high (above 14.7V), the dsPIC triggers protection mechanisms to prevent damage.
ii. Overcurrent and short-circuit protection: In case of excessive current or a short circuit, the dsPIC will quickly shut down the inverter, preventing damage to the power components.
iii. Overload protection: The microcontroller monitors the current through feedback sensors. If the load exceeds 1100VA, the dsPIC30F2010 triggers the overload protection, shutting down the system to prevent damage.
iv. Thermal protection: If the temperature sensors detect overheating, the dsPIC can activate the cooling system or shut down the system entirely to prevent thermal damage.

2.2 Power drive section

This circuit represents an IGBT drive stage controlled by a microcontroller, and it works as follows:

i. Microcontroller control: The microcontroller sends control signals to the IGBTs through optocouplers for isolation, ensuring safe switching between the control and power stages.
ii. Optocoupler isolation: Optocouplers provide electrical isolation between the microcontroller and the high-power switching components (IGBTs). This is crucial for preventing damage to the control system.
iii. IGBT power switching: The IGBTs are responsible for handling large amounts of current. Their gates are driven by the isolated control signals to switch the DC input and control the power supplied to the load.
iv. Protection and feedback: The circuit includes various protective components (diodes, resistors) and feedback mechanisms to ensure stable operation and to protect against overvoltage, overcurrent, or oscillations.
v. DC power supply and filtering: The system filters the DC input and supplies it to the IGBT power stage, ensuring smooth switching and output to the load or transformer banks.

The IGBT drive circuit is designed to manage high-power switching, with microcontroller control and isolation provided by optocouplers. The circuit diagram is shown in Figure 3 below.

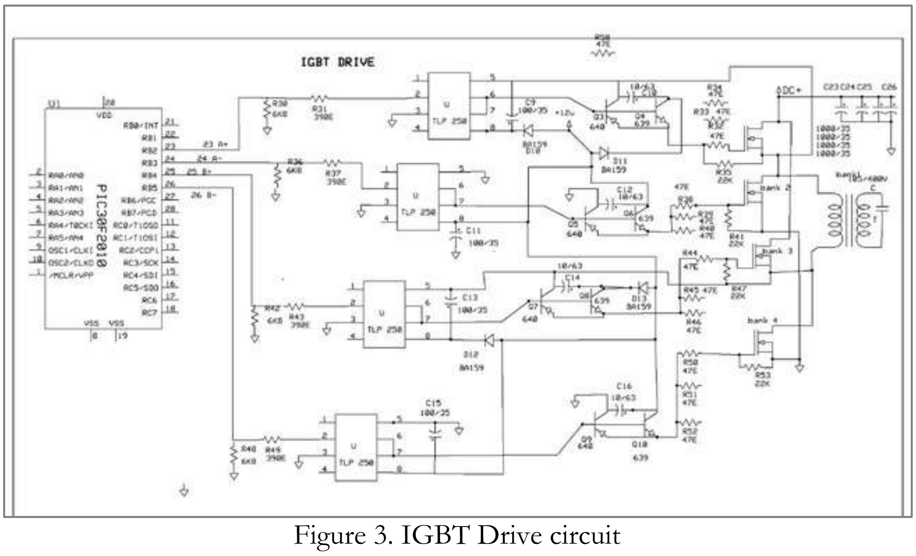

Figure 3. IGBT Drive circuit

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a. H-bridge configuration

A switching design known as an H-Bridge converter is made up of four switches arranged in an H-shaped pattern [9]. The setup controls the direction of current flow through the load, which is the primary side of the transformer. By opening and closing these switches in a specific sequence, the direction of the voltage across the load can be changed, effectively creating an AC waveform from a DC source. A typical H-bridge diagram is shown in Figure 4. The dsPIC30F2010 directly drives the MOSFETs in an H-Bridge configuration, using its dedicated PWM pins. The microcontroller controls the switching of the MOSFETs, alternating them in such a way that the high-voltage DC is converted into a stable AC output.

To drive the MOSFETs, the PWM signals from the microcontroller are routed through a gate driver circuit, which amplifies the signals and ensures that the MOSFETs switch on and off reliably, minimizing losses and preventing switching errors.

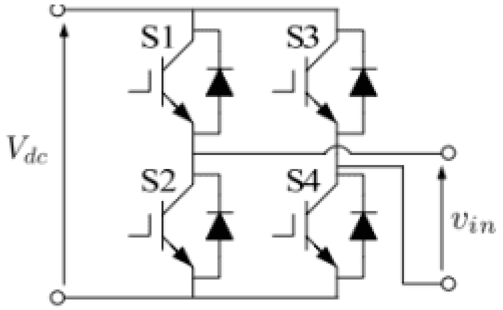


Figure 4. Typical H Bridge circuit

b. Gate Driver Circuit (TLP 250)

The TLP250 gate drivers play a critical role in driving the MOSFETs in the inverter's H-Bridge configuration. Since the dsPIC30F2010 generates low-power PWM control signals, the TLP250 gate drivers are used to boost these signals to the necessary voltage and current levels to efficiently switch the high-power MOSFETs.

Each TLP250 gate driver is connected to the gate of a corresponding MOSFET. When the dsPIC30F2010 generates the PWM signal, it is sent to the TLP250, which then boosts the signal to the appropriate voltage level (typically around 10-15V) required to turn the MOSFET on fully. The driver provides a fast and efficient way to switch the MOSFETs, ensuring minimal switching losses and accurate timing.

2.3 Transformer design

The transformer specifications are given in Table 3 below.

Table 3. Transformer Specification

Parameters	**Specification**
Input voltage	12 V
Output voltage	220 V
Power rating	1.5 kVA
Frequency, f	50 Hz
Phase	Single
Core Dimension	85mm × 52mm
Flux Density, B	1.05 Wb/m

Using transformer's equation $E = 4.44 f \emptyset m N$ (1)

Where E is the induced Emf, f is the frequency, N is the number of turns, and $\emptyset m$ is the maximum magnetic flux.

Calculations to determine the core size, number of turns, and wire gauge selection for the construction of the transformer are detailed below.

Cross-sectional area (mm^2), $A = L \times B = 85mm \times 52mm = 442mm^2$ (2)

Flux $\emptyset = BA = 1.02 \times 442 \times 10^{-6} = 450.84 \times 10^{-6}\, Wb$ (3)

Volt per turn, $E = 4.44 \times f \times \emptyset = 4.44 \times 50 \times 450.84 \times 10^{-6} = 1.0008648$ (4)

For Primary Windings; $Np = \frac{Vp}{E} = \frac{220}{1.0008648} = 219\, Turns$ (5)

For Secondary Windings; $Ns = \frac{Vs}{\varepsilon} = \frac{12}{1.0008648} = 11\,Turns$ (6)

2.4 Filtering and Output Stage

The filtering and output stage is a critical part of the inverter design as it ensures the conversion of the Pulse Width Modulation (PWM) signals into a clean sine wave output. This stage smoothens out the high-frequency components from the PWM signal and reduces harmonic distortion, which is essential for delivering stable and high-quality AC power to the load.

A 105pF, 400V capacitor is used in the filter. This capacitor works to absorb high-frequency components from the PWM signal and smooth the output waveform. The capacitor value is chosen based on the desired cut-off frequency, which is a function of the load and the PWM switching frequency. A higher voltage rating (400V) is used to ensure that the capacitor can handle the high AC voltages present in the system without breaking down.

2.5 Printed circuit board (PCB) fabrication

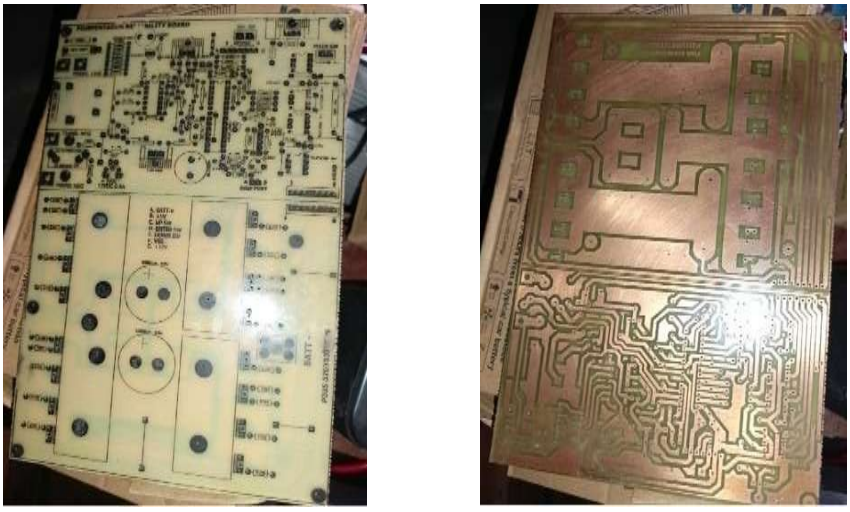
The PCBs were fabricated using a direct heat transfer method. The process includes the following;

i. Print out the PCB design on glossy paper.
ii. Measuring and cutting out the copper board to the required size, and cleaning the copper board using microcellulose thinner.
iii. Transferring of printed PCB to copper board with heat
iv. Etching of PCB by dropping in a solution of Potassium Ferrocyanide
v. Drilling holes at specified locations using a precision drilling machine

Plates 2 and 3 show the process of fabricating the printed circuit board and the fabricated PCB.

(a) Copper board (b) Transfer of design by heat (c) Etching

Plate 2. Fabrication of Printed Circuit Boards



(a) PCB (Front view) (b) PCB (Back view)

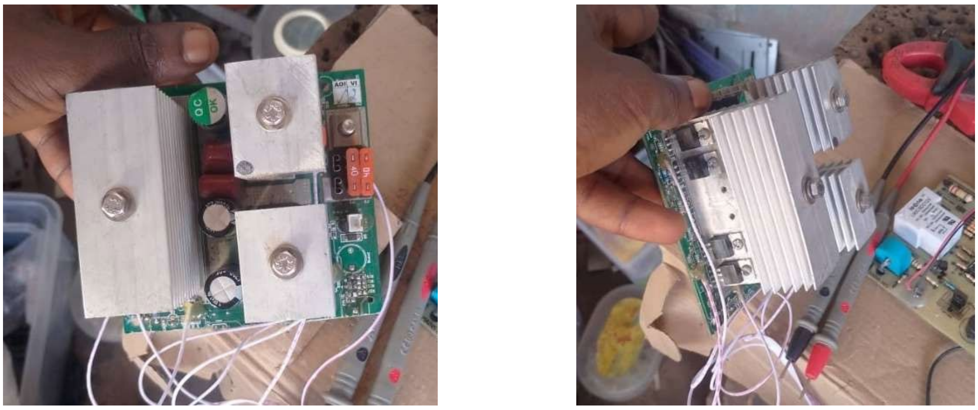
Plate 3. Fabricated PCB

2.6 Assembly of components and packaging

The assembly process followed the PCB layout design closely to ensure proper alignment of all components. Each connection was carefully soldered to provide secure and reliable electrical contact, minimizing the risk of short circuits or loose connections. Additionally, mechanical components like heat sinks and fans were mounted properly to ensure effective cooling and stability during operation.

The entire system was housed in a durable enclosure designed to protect the components from environmental factors and to withstand vibrations and mechanical stress during use. Plates 4 and 5 show the assembled oscillation and MOSFET drive board.

Plate 4. Assembled Control and Oscillation Board



(a) MOSFET Board (Top view) (b) MOSFET Board (side view)

Plate 5. Assembled MOSFET Drive Board

Finally, the various sections of the inverter were carefully assembled and mounted within an enclosure. This enclosure provides protection against environmental factors such as dust, moisture, and mechanical damage, while also allowing for proper ventilation to aid in heat dissipation. The layout was selected to ensure that critical components, such as heat sinks and fans, have adequate airflow, helping to maintain optimal operating temperatures and prevent overheating during use. Plate 6 below shows the final assembly.

(a) Inverter (top view) (b) Inverter (enclosed)

Plate 6. Inverter Enclosure and Packaging

3.0 Results and Discussion

The initial testing and debugging process was crucial to ensure that the inverter performed correctly before moving on to full-scale performance evaluation. The steps involved were as follows:

i. The inverter was powered up using a current-limited power supply to safeguard against potential damage during initial start-up. This allowed for safe verification of component connections and ensured no short circuits or faulty connections were present.

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ii. A continuity test was conducted to ensure proper electrical connections, particularly in the power stage, control circuitry, and transformer windings. This test confirmed that there were no short circuits or improper connections. Plates 7 and 8 show images of the continuity tests conducted during the project
iii. An oscilloscope was used to monitor the output waveform, verifying the generation of a stable sine wave. Any distortions or abnormalities in the waveform were identified and corrected through adjustments to the control signals. Plate 9 displays the resulting pure sine wave output, showcasing the desired sinusoidal waveform.
iv. Critical components such as MOSFETs, diodes, and transformers were monitored for temperature fluctuations during operation. Heat sinks and fans were observed to confirm they were effectively cooling the system. Thermal sensors were used to check surface temperatures and ensure the components operated within safe limits.
v. The inverter's protection features, including overcurrent, overvoltage, and short circuit protection, were triggered to verify their effectiveness. These tests ensured that the inverter would safely shut down or enter protection mode in the event of faults or overloading.
vi.

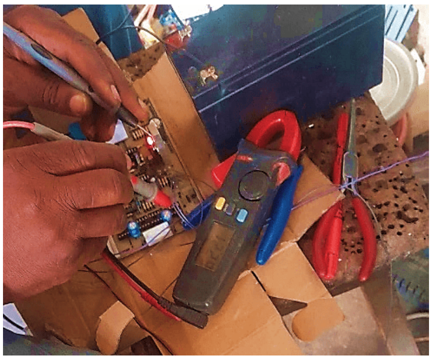

Plate 7. Checking the output of the gate drivers

Plate 8. Continuity test

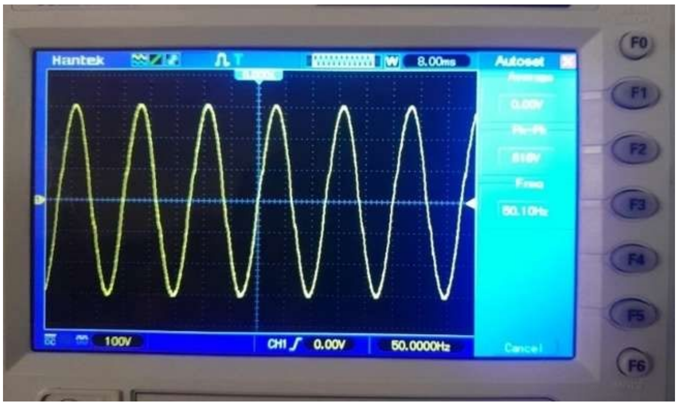

Plate 9. Output sinusoidal waveform

a. Testing under various loads

The inverter was tested under different load conditions to evaluate its performance. The following table summarizes the results of the load testing, showing the power input, output voltage and current, power output, and efficiency.

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i. Resistive load testing

Light bulbs were connected to the output of the inverter. The output voltage and current were monitored. Table 4 below shows the result of the test, while Plate 10 shows the test setup.

Table 4. Resistive Load Test

Load (VA)	Power Input (W)	Output Voltage (V)	Output Current (A)	Power Output (W)	Efficiency (%)	Noise
0	13.77	220	0.00	0	0	None
250	199.80	220	0.867	190.74	95.5	None
500	280.90	220	1.211	266.42	94.8	None
750	395.20	220	1.688	371.36	94.0	None
1000 overload	445.05	000	0.00	000.00	00.0	None

Plate 10 Resistive load testing with light bulbs

i. Reactive load testing

In order to evaluate the inverter's performance with reactive loads, two standing fans were tested. Digital multimeters were connected to both the input and output of the inverter to measure the power supplied and the power consumed by the load. A digital oscilloscope was also connected to the output to check for any changes or distortions in waveform quality when inductive loads were applied. Table 5 below presents the test results, while Plate 11 shows the test setup.

Table 5. Reactive load test

Load (Fan)	Speed Position	Power Input (W)	Output Voltage (V)	Output Current (A)	Power Output (W)	Efficiency (%)	Humming Noise
94W	Off	27.96	220	0.000	00.00	00.0	None
	Position 1	65.87	220	0.295	64.90	98.5	None
	Position 2	72.44	220	0.324	71.28	98.4	None
	Position 3	74.23	220	0.332	73.04	98.4	None
150W	Off	27.94	220	0.000	0.00	00.0	None
	Position 1	181.95	220	0.789	173.58	95.4	None
	Position 2	138.96	220	0.607	133.54	96.1	None
	Position 3	165.45	220	0.713	156.86	94.8	None

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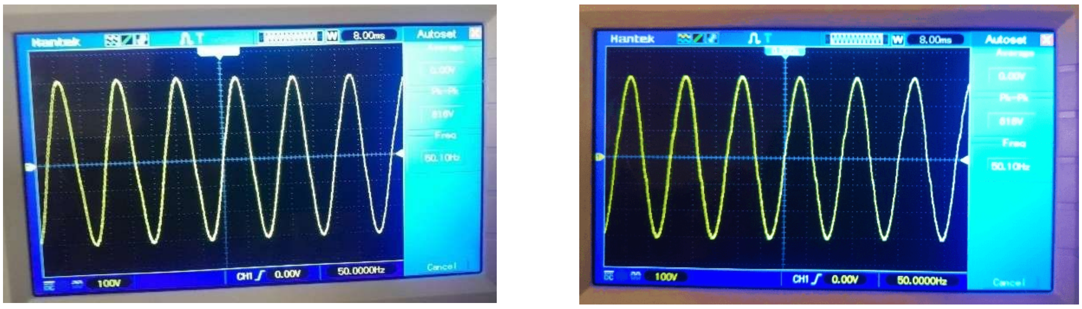
Plate 11. Reactive load testing with an industrial standing fan

ii. Load transitions

The inverter's ability to handle sudden changes in load was tested by quickly switching between different load levels. The goal was to observe how the inverter managed these transitions and whether any voltage spikes or dips occurred. The impact of the 150-watt fan load on the pure sine wave inverter was assessed using an oscilloscope. Plate 12 below illustrates the changes in waveform quality under different operational conditions: no load, speed 1, speed 2, and speed 3.

(a) On no load (b) Fan speed 1



(c) Fan speed 2 (d) Fan speed 3

Plate 12. waveform quality of the output under different operating conditions

The waveform quality was consistently monitored and found to align with the design specifications for a pure sine wave output.

b. Overload protection testing

The overload protection feature of the inverter was tested to ensure that the system could effectively detect and respond to load conditions exceeding the inverter's rated capacity. The following results were observed:

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1. Overload trigger point: The inverter's overload protection was activated when the load exceeded 1100VA. At this point, the system immediately shut down to prevent damage to the inverter and connected components. This trigger point is set below the inverter's maximum capacity of 1.5kVA, ensuring early detection and prevention of stress on the power components.
2. System response: Once the overload was detected, the inverter indicated with an LED and buzzing sound, followed by cutting power to the connected load to prevent overheating or component failure. This protection mechanism successfully safeguarded the inverter from damage due to excessive power demand.
3. Post-shutdown recovery: After the overload event, the system monitors to check if the load has been disconnected from the output before it resets to resume normal operation. This ensures that any overload condition is addressed before the inverter is brought back online, reducing the risk of recurring overload scenarios.

c. Discussion of Results

This section summarizes and interprets the findings from the previous tests.

1. Heat management and thermal performance: This thermal management system was activated when the internal temperature rose, thereby preventing overheating and ensuring safe operating conditions. When the temperature drops back within safe limits, the cooling system deactivates to conserve energy, thus enhancing the overall efficiency of the inverter.
2. Inverter efficiency: In the resistive load test (Table 3), the inverter showed a steady efficiency decline as the load increased. At a 250 VA load, the inverter achieved an efficiency of 95.5%, which slightly decreased to 94.8% at 500 VA and further to 94.0% at 750 VA. This gradual decrease in efficiency with increasing load is expected, as higher resistive loads often lead to greater internal losses. However, even at 750 VA, the efficiency remained relatively high, indicating that the inverter performs well under resistive loads. At a load of 1000 VA, the inverter experienced an overload condition, resulting in a complete drop in output voltage and efficiency. This behavior demonstrates the inverter's protective mechanisms, likely designed to prevent damage under excessive loads. In the reactive load test (Table 4), the inverter maintained high efficiency across varying speed levels. For the 94W fan, efficiency levels remained around 98.4% to 98.5%, and with the 150W fan, efficiency ranged from 94.8% to 96.1%. The overall results from both the resistive and reactive load tests indicate that the inverter achieves high efficiency under most operating conditions within its rated load.
3. Load handling: During resistive and reactive load tests, the inverter sustained steady voltage output as the load increased without waveform distortion or excessive power loss.
4. Noise levels: During the tests with both resistive and reactive loads, no audible noise was detected. This silent operation reflects stable switching and effective design choices.
5. Comparison with other inverter technologies

[10], In his report, he constructed and conducted comparable tests on his 1.5 kVA modified sine wave inverter. These tests were performed under the same conditions, including identical battery capacity, environmental factors, load, and measuring equipment used in the tests on the pure sine wave inverter.

The results and observations from both the resistive and reactive load tests on the 1.5 kVA modified sine wave inverter are provided in Tables 6 and 7 below.

Table 6. Resistive load test for a 1.5 kVA modified sine wave inverter

Load (VA)	**Power Input (W)**	**Output Voltage (V)**	**Output Current (A)**	**Power Output (W)**	**Efficiency (%)**
0	13.70	233	0.0	000.00	00.0
250	224.0	219	0.87	190.50	85.0
500	297.0	194	1.28	248.32	83.6
750	389.5	168	1.89	317.52	81.5
1000	334.0	136	1.97	267.92	80.2

Table 7. Reactive load test for a 1.5 kVA modified sine wave inverter

Load (Fan)	**Speed Position**	**Power Input (W)**	**Output Voltage (V)**	**Output Current (A)**	**Power Output (W)**	**Efficiency (%)**	**Humming Noise**
94W	Off	15.96	220	0.071	15.62	97.9	Mild
	Position 1	62.32	214	0.272	58.21	93.4	Moderate
	Position 2	66.01	211	0.290	61.19	92.7	High
	Position 3	67.59	203	0.308	62.52	92.5	High

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Load (Fan)	Speed Position	Power Input (W)	Output Voltage (V)	Output Current (A)	Power Output (W)	Efficiency (%)	Humming Noise
150W	Off	004.71	220	0.021	004.62	98.1	Mild
	Position 1	198.20	206	0.839	172.83	87.2	High
	Position 2	170.51	211	0.720	151.92	89.1	Intense
	Position 3	191.41	213	0.789	168.06	87.8	Intense

The impact of the 150-watt fan load on the modified sine wave inverter was carefully monitored using an oscilloscope to assess its effect on waveform quality and overall inverter performance. As the fan was tested across different speed settings, the oscilloscope captured variations in the output waveform, allowing for a detailed analysis of any distortion introduced by the inductive load. This monitoring process helped evaluate the inverter's ability to maintain stable output under reactive conditions, revealing insights into how the modified sine wave responded to fluctuations in power demand caused by the fan's changing speeds. This evaluation provided a comprehensive understanding of the modified sine wave inverter's limitations when powering inductive loads, particularly in terms of waveform integrity and voltage stability. Plate 13 below displays the waveform quality under different conditions: no load, speed 1, speed 2, and speed 3.

(a) On no load (b) Fan speed 1

(c) Fan speed 2 (d) Fan speed 3

Plate 13. waveform output quality for the modified sine wave inverter

During the testing, the modified sine wave inverter exhibited notable waveform distortion at each speed level, particularly under reactive load conditions. In contrast, the pure sine wave inverter consistently maintained a smooth, undistorted waveform across all speeds, demonstrating its superior handling of inductive loads like fans. The efficiency results further highlight the differences between the two inverter types. The modified sine wave inverter showed a significant efficiency drop under both resistive and reactive loads. In the resistive load test (Table 5), efficiency decreased from 85.0% at a 250 VA load to 80.2% at 1000 VA, illustrating a clear decline as the load increased. For reactive loads, as detailed in Table 6, the efficiency of the modified sine wave inverter also varied widely, reaching as low as 87.2% at higher fan speeds. By comparison, the pure sine wave inverter consistently maintained higher efficiency levels, even with reactive loads.

Voltage stability was another point of comparison. The modified sine wave inverter's output voltage fluctuated significantly, dropping to as low as 136V at higher resistive loads, while the pure sine wave inverter maintained a stable output around the 220V mark. This fluctuation in voltage can lead to poor performance and potential damage to appliances reliant on steady voltage.

The modified sine wave inverter also emitted an audible hum that intensified with increased motor speed. As shown in Table 6, the noise was especially pronounced at higher fan speeds, creating a less favorable environment for applications where silent operation is essential.

Based on these observations, pure sine wave inverters demonstrate significant advantages over modified sine wave inverters. They offer improved efficiency, minimal noise, stable voltage output, better load-handling capabilities, more effective protective features, and greater long-term reliability.

d. Cost analysis and bill of engineering measurement and evaluation

The project was designed with cost-effectiveness in mind, without sacrificing performance. Table 8 below shows the bill of engineering measurement and evaluation for the project.

Table 8. Bill of engineering measurement and evaluation

Component	**Quantity**	**Unit Cost (₦)**	**Total Cost (₦)**
dsPIC30F2010	1	18,000	18,000
TLP250 Gate Driver	4	2,000	8,000
MOSFETs (IRF640)	8	1600	12,800
LM324 IC	2	250	500
Capacitors	15		5,000
Resistors	40		5,000
Transformer (1.5kVA)	1	35,000	35,000
Diodes	10		800
Relay (12V, 30A)	2	2,500	5,000
LEDs and Buzzer			2,600
Heat Sink	3		7,000
Cooling Fan (12V)	1	1,500	1,500
Enclosure (Metallic)	1	7,500	8,000
Wiring and Connectors		2,500	2,500
12V Battery (100Ah)	1	150,000	150,000
Printed Circuit Board	1	10,000	10,000
Soldering Materials			5,400
Fuses (15A)	4	200	800
NTC Thermistor	1	1,000	1,000
MISCELLANEOUS			15,000
TOTAL			**300,000**

In order to provide additional context and serve as a benchmark, the BEME for a 1.5 kVA modified sine wave inverter developed by [10] is also presented in Table 9 below. This data serves as a reference to highlight the cost considerations of a modified sine wave design, which was analyzed during the course of this project.

Table 9. Bill of engineering measurement and evaluation for the modified sine wave inverter by [10]

Component	**Quantity**	**Unit Cost (₦)**	**Total Cost (₦)**
SG3524 PWM Controller IC	1	10,000	10,000
PC817 Optocoupler	2	300	600
MOSFETs (IRF260)	6	1200	7,200
Inductor	2	2,500	5,000
Capacitors	8		1,000
Resistors	35		4,500
Transformer (12V to 220V)	1	26,000	26,000
Diodes	8		900
Relay (12V, 30A)	3	2,500	7,500
LEDs and Buzzer			1,500
Heat Sink	2		3,800
Cooling Fan (12V)	1	1,500	1,500
Enclosure (Metallic)	1	7,000	7,000
Wiring and Connectors		2,500	2,500
12V Battery (100Ah)	1	150,000	150,000
Printed Circuit Board	1	5,000	5,000
Soldering Materials			5,000
Miscellaneous			6,000
Total			**245,000**

4.0 Conclusion

The inverter exhibited high efficiency, particularly under mid-load conditions, with minimal power loss during the conversion process. Its cooling system, featuring heat sinks and fans, proved effective in maintaining safe operating temperatures even during extended full-load operation, preventing overheating and ensuring long-term reliability. The inverter efficiently handled both resistive and reactive loads, maintaining a stable output voltage and current throughout the tests. Unlike modified sine wave inverters, which struggled to provide consistent 220V output under varying loads, the pure sine wave inverter showed no such instability. Lastly, it operated silently, even under full load and varying motor speeds.

Although the inverter showed good efficiency under mid-range loads, there is potential for further improvement in efficiency under full-load conditions. Optimizing the circuit design to minimize power losses at higher loads could lead to even better overall energy efficiency. Also, incorporating smart monitoring and control systems, such as IoT-based solutions, would allow real-time tracking of key parameters like voltage, temperature, and load conditions. This feature would be particularly beneficial for high-end or industrial applications where continuous monitoring is essential. Finally, expanding the inverter's power capacity to accommodate 3 kVA or 5 kVA would broaden its range of applications.

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