Power Stage Design Details of A 3kva Pure Sine Wave Inverter

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Abstract
The persistent power supply challenges in developing countries, including frequent outages and heavy dependence on generators, necessitate the development of alternative energy systems that are efficient, sustainable, and affordable. This paper presents the design of a 3kVA pure sine wave inverter focusing on the power stage, which is responsible for converting low-voltage DC from batteries into clean AC power suitable for household and business applications. The design adopts a full-bridge inverter topology utilizing high-efficiency MOSFET switches, a step-up transformer, and an LC low-pass filter to produce a 230V, 50Hz pure sine wave output. All the design calculations, component selection, and integration strategies is comprehensively developed to form a foundation for practical implementation. This paper presents a detailed guide, particularly suited for integration with renewable energy sources in this context.

Keywords: *Inverter, Low-pass Filter, Step-up transformer, Voltage regulator, MOSFET*

INTRODUCTION

Developing countries faces persistent challenges in power supply, characterized by frequent outages, voltage fluctuations, and inadequate electricity generation. Despite having national grids in these countries, many households and businesses experience inconsistent power, leading to a high reliance on fossil-fuel powered generators. These generators, while providing temporary relief, come with significant drawbacks such as high operational costs, noise pollution, and environmental degradation.

To mitigate these challenges, there is a growing shift towards alternative power solutions, particularly inverters and renewable energy systems. Inverters serve as a bridge between stored energy (typically from batteries or solar panels) and electrical appliances by converting DC power to AC power. Among the different types, pure sine wave inverters are the most efficient and reliable, producing a smooth AC output similar to grid electricity. This makes them ideal for running sensitive electronics such as computers, refrigerators, medical equipment, and communication devices without the risk of damage from harmonic distortion.

3kVA pure sine wave inverter is a practical solution for many households, small businesses, and offices, offering sufficient power to run essential appliances. Given the increasing adoption of solar energy in sub-sahara Africa due to abundant sunlight, this inverter can also be integrated into solar power systems, providing a sustainable and cost-effective alternative to fossil-fuel-based generators. The study will cover key aspects such as power stage circuit design, power electronic component selection, thermal management, and efficiency optimization. Additionally, microcontroller-based PWM control will be explored to ensure accurate waveform generation and system stability.

By developing a robust and efficient 3kVA pure sine wave inverter, this research aims to provide a reliable, cost-effective, and environmentally friendly backup power solution that aligns with the growing need for alternative energy sources. Electricity is an essential requirement for modern living, powering homes, businesses, and industries. However, in countries like Nigeria, the national grid remains unreliable, with frequent power outages and voltage fluctuations. As a result, alternative power sources such as generators and inverters have become necessary for households and businesses, (Ibrahim et al., 2020).

Among these alternatives, inverters have gained popularity due to their quiet operation, low maintenance costs, and ability to provide uninterrupted power, (Gupta et al., 2019). However, not all inverters are created equal. This study focuses on pure sine wave inverters, which are known for their ability to produce clean and stable AC power, making them ideal for sensitive electronic devices such as computers, medical equipment, and home appliances, (Zhao et al., 2020).

OVERVIEW OF INVERTER TECHNOLOGY

An inverter is an electronic device that converts direct current (DC) into alternating current (AC), making it suitable for powering household and industrial electrical appliances. Inverters are classified based on their waveform output into:

1. **SQUARE WAVE INVERTERS:** Square wave inverters are the earliest type of power inverters developed. They generate a waveform that alternates sharply between maximum positive and maximum negative values, creating a waveform that resembles a series of squares. While square wave inverters are simple and cost-effective, they have significant drawbacks. The main issue with square wave inverters is their inefficient power delivery, which can result in electrical noise and potential damage to sensitive electronic devices, (Ramesh & Patel, 2018). Most household appliances and electronics are not designed to operate on a square wave, leading to reduced performance or malfunction. As a result, square wave inverters are typically suitable only for specific applications, such as powering simple resistive loads like incandescent lights or heaters. Overall, while square wave inverters are inexpensive and easy to produce, their limitations make them less desirable for modern applications that require stable and reliable power.
2. **MODIFIED SINE WAVE:** Modified sine wave inverters represent the second generation of power inverters. They offer an affordable and straightforward solution for powering devices that require AC power. Modified sine wave inverters closely approximate a sine wave and have low harmonic distortion, which typically does not interfere with household equipment. However, there are some drawbacks: not all devices operate effectively on a modified sine wave, particularly sensitive products like computers and medical equipment, (Zhao et al., 2020) which require pure sine wave inverters. The primary disadvantage of modified sine wave inverters is that the peak voltage fluctuates with the battery voltage.
3. **PURE SINE WAVE:** Pure sine wave inverters embody the most advanced inverter technology available. The waveform generated by these inverters is identical to or even superior to the power supplied by utility companies. Generally, pure sine wave inverters are more expensive than modified sine wave inverters due to the additional circuitry required for their operation. For the purpose of this study, we will focus on pure sine wave inverters, (Zhao et al., 2020; Gupta et al., 2019).

REVIEW OF POWER STAGE DESIGN IN INVERTERS

The power stage is the backbone of an inverter, responsible for converting DC power into an AC output. The main components of the power stage include:

- DC Source: Typically batteries (lead-acid or lithium-ion) or photovoltaic (solar) panels.
- Switching Devices: Power transistors like MOSFETs or IGBTs that enable rapid switching for waveform generation, (Chen et al., 2019; Sharma et al., 2020).

- Transformer & Filters: Used for voltage conversion and waveform smoothing.

H-BRIDGE INVERTER TOPOLOGY

A widely used topology in single-phase inverter design is the H-bridge configuration, which consists of four power switches arranged in an H-pattern. Research by Gupta et al. (2019) demonstrated that H-bridge inverters reduce harmonic distortion while offering high efficiency in DC-AC conversion.

TRANSFORMER-BASED VS TRANSFORMERLESS DESIGN

The choice between a transformer-based inverter and a transformerless inverter depends on application requirements:

- Transformer-based inverters: Provide galvanic isolation, increased safety, and voltage stepping capabilities, but tend to be bulkier.
- Transformerless inverters: More compact and efficient but require additional protection circuits for safety.

A study by (Mishra & Kumar, 2021) highlighted that transformerless designs improve efficiency by up to 10%, making them suitable for renewable energy applications, but for the course of this study a transformer based inverter design will be adopted.

PULSE-WIDTH MODULATION (PWM) AND CONTROL STRATEGIES

PWM is a widely used technique for generating a smooth AC output from a DC source. Several PWM control strategies have been explored:

- Sinusoidal PWM (SPWM): Generates a sine wave output by modulating a high-frequency carrier wave. Research by (Zhao et al. 2020) showed that SPWM reduces harmonic distortion, making it a preferred choice for pure sine wave inverters.
- Space Vector PWM (SVPWM): More efficient than SPWM but complex in implementation. Studies suggest SVPWM can increase inverter efficiency by 5-7% (Ramesh & Patel, 2018).

Hysteresis Control & Fuzzy Logic Control: Advanced techniques for adaptive control, improving dynamic response and load regulation, (Sharma et al., 2020). Since SPWM remains the most practical choice for small-scale inverters, this study adopts SPWM-based control.

EFFICIENCY AND POWER LOSS OPTIMIZATION IN INVERTERS

Efficiency is a critical performance factor in inverter design. Research has identified several ways to improve inverter efficiency:

- Using high-speed switching devices: MOSFETs operate efficiently at high frequencies, reducing switching losses (Sharma et al., 2020).
- Soft-Switching Techniques (ZVS & ZCS): Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) minimize power loss by ensuring switching occurs at optimal points in the waveform (Chen et al., 2019).
- Advanced Heat Dissipation Techniques: Research has shown that proper heat sink design and cooling mechanisms improve inverter lifespan (Adeyemi & Williams, 2022).

Since MOSFETs are more efficient for low- to medium-power applications, they are chosen for this study.

INTEGRATION OF INVERTERS WITH RENEWABLE ENERGY SYSTEMS

With the growing adoption of solar energy, integrating inverters with photovoltaic (PV) systems has become a major research focus. Studies highlight three critical considerations:

1. MPPT (Maximum Power Point Tracking): Essential for extracting maximum energy from solar panels. Research by (Lee & Park 2019) showed that MPPT algorithms improve solar utilization efficiency by up to 30%.
2. Battery Management Systems (BMS): Ensures optimal battery charging and discharging cycles. A study by (Wang et al. 2021) emphasized the importance of BMS in improving battery life by 20-25%.
3. Hybrid Inverter Design: Capable of switching between grid power, battery storage, and solar energy to ensure uninterrupted power supply.

CHALLENGES AND GAPS IN EXISTING RESEARCH

Despite technological advancements, several challenges persist:

1. High cost of pure sine wave inverters, limiting accessibility in developing countries like Nigeria (Ibrahim et al., 2020).
2. Limited availability of locally manufactured inverters, resulting in high import dependency.
3. Battery inefficiencies, leading to shorter backup durations and increased maintenance costs, (Wang et al., 2021).

COMPONENT REVIEW: In order to design the inverter there was need to have a clear understanding of the major components that are needed for the design.

MOSFET DEVICE: According Koutroulis E. (2021), Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is a device that controls a current between two contacts (source and drain) using voltage control unit (gate). MOSFET are used as switch devices in the inverter/UPS output section. They are of two types which are that of the P-channel and N-channel.

A situation when the MOSFET is used as a switch, it is the n-channel The gate drive of switching signal is referenced to ground because it is placed between the load and the ground When the p-channel is required the load is connected directly to the ground and the MOSFET Switch will be connected between the load and the positive supply rail just the way it is with the PNP transistors. In a P-channel device, the conventional flow of drain current is in the negative direction so a negative gate-source voltage is applied to switch the transistor ON and when the switch goes high the MOSFET is turned OFF. The N-channel type is basically assumed in this paper for switching. The p-channel type was used at the dc converter side.

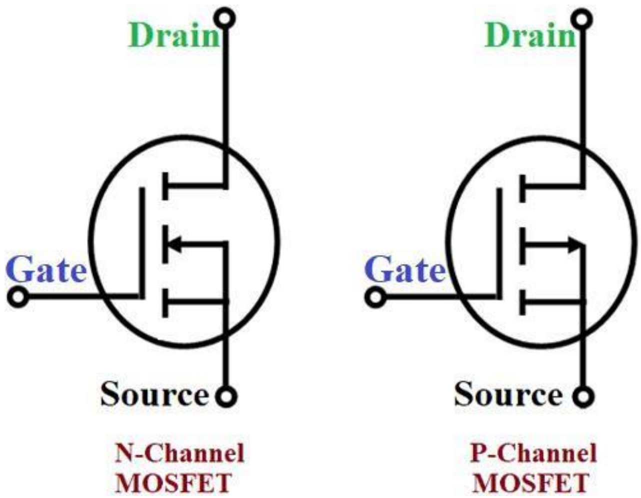


Figure 1 (N/P) channel MOSFET

PARAMETERS OF THE MOSFET

On Resistance Rds. (on): it is the resistance between the source and drain terminal when the MOSFET is fully ON.

i. Maximum Drain Current Id (max) 50A: it is the maximum current can handle from the drain to Source.
ii. Power Dissipation Pa (300W): it is the maximum power the MOSFET can handle.
iii. Drain-to-Source Breakdown Voltage: it is the maximum voltage between drain and source when the MOSFET is turned off.
iv. Thermal Resistance: it is the maximum temperature difference across the MOSFET when a unit of heat energy flows in a unit time.
v. Input Capacitance: it is the lump capacitance between the gate and drain terminals.
vi. Peak Diode Recovery: this is how fast the intrinsic diode can from off state (reverse biased to the on state, conducting).

The type of MOSFET used in this paper is the IRFP260 N-channel enhanced mode type.

RESISTOR

A resistor is a component designed primarily to limit the flow of electrical current within a circuit. Resistors can be made as fixed resistors, which have a constant resistance, or as variable resistors, which allow for manual or electrical adjustment of their resistance.

CAPACITOR

Capacitors are essential in the 3kVA Inverter design, contributing to energy storage, voltage stabilization, noise suppression, and smoothing out voltage fluctuations. Each capacitor serves a particular purpose depending on type, its capacitance and voltage rating. Their contribution to the overall system's performance ensures smooth power transitions, effective voltage regulation, stability and noise-free operation (International Capacitor Standards, 2023).

Key Roles of Capacitors in the 3kVA Inverter:

- **Energy Storage:** Capacitors help in energy storage to prevent sudden power drops during load transitions (Power Electronics Manufacturers Association, 2023).
- **Voltage Smoothing:** Stabilizing input DC voltage ensures a steady output during DC-AC conversion (Energy Storage Technologies Research Institute, 2023).
- **Noise Filtering:** Filtering out high-frequency noise ensures smooth operation in control circuits (Power Electronics Manufacturers Association, 2023).
- **High Voltage Withstanding:** Designed to withstand voltage surges during DC to AC Conversion (International Capacitor Standards, 2023).

TRANSFORMER

A transformer is a passive device that transfers electrical energy between circuits through electromagnetic induction. By generating a varying magnetic flux in its core, a transformer induces an electromotive force (EMF) in its coils, enabling energy transfer without direct electrical connections. Based on Faraday's law of induction, transformers can step up or step down AC voltage levels. For our model 3kVA inverter project, a step-up transformer is critical to converting the 24V DC from the battery to 220V AC, which powers household appliances. Transformers also provide isolation between circuits, making them integral to both power and electronic applications. Since their inception in 1885, transformers have played a crucial role in AC power transmission and distribution (Bedell, 1942).

VOLTAGE REGULATOR

A voltage regulator is designed to maintain stable voltage levels. When a consistent and reliable voltage is required, a voltage regulator is the ideal choice. It provides a fixed output voltage that remains constant despite variations in input voltage or load conditions, effectively acting as a protective buffer for components against damage. Typically, a voltage regulator features a straightforward feed-forward design and utilizes negative feedback control loops. Let's discuss the different types of voltage regulators in more detail (STMicroelectronics, 2023).

Table 1: Specification of Transformers used in the Inverter

Transformer	Application	Function in Inverter
24V – 220V Step-Up Transformer	Output to grid or load	Increases voltage for efficient energy transfer (American Transformer Company, 2023).
220V – 12V Step-Down Transformer	Control circuits	Provides safe voltages for auxiliary components (National Electric Manufacturers Association, 2023).

RELAY

A relay is an electrically operated switch that includes a set of input terminals for one or more control signals, along with a set of operating contact terminals. It can have various contact configurations, such as make contacts, break contacts, or combinations of both. Relays are commonly used to control a circuit with a low-power signal or to manage multiple circuits with a single signal. The traditional electro-mechanical relay uses an electromagnet to open or close its contacts, but other types, such as solid-state relays, utilize semiconductor properties for control without any moving parts. Relays with calibrated operating characteristics, and sometimes multiple operating coils, are used to protect electrical circuits from overloads or faults. In modern electrical power systems, these protective functions are often carried out by digital instruments still referred to as protective relays.

Figure 2: DC Relay

Figure 3: AC Relay

SG3524 – PULSE WIDTH MODULATION (PWM) CONTROLLER

The SG3524 is a PWM controller and voltage regulator IC, frequently used in switching power supplies and inverter circuits. It plays a key role in regulating voltage and enhancing the power conversion efficiency of the inverter (Texas Instruments, 2022).

Key Features:

- **PWM Control:** Maintains steady pulse-width modulation to regulate the output voltage.
- **Error Amplifier:** Error amplifiers for accurate voltage regulation (ON Semiconductor, 2023).
- **Protection Mechanisms:** Offers over-voltage, over-current, and thermal shutdown protection, ensuring reliable system performance (Fairchild Semiconductor, 2023).

Table 2: Technical Specifications of SG3524

Parameter	**Value**
Operating Voltage	8V to 40V
Output Current	Up to 100mA
Oscillator Frequency	100Hz to 400kHz
Power Dissipation	1000mW

DESIGN OF A 3KVA PURE SINE WAVE POWER INVERTER

The design of a 3kVA pure sine wave inverter requires careful consideration of several key factors, including ***power conversion efficiency, waveform quality, protection mechanisms, and integration with renewable energy sources***. Details of the step-by-step design process, covering circuit topology, component selection, control strategies, and simulation approaches used to develop a high-performance inverter suitable for small and medium energy demand conditions is laid out. The inverter is designed to convert 48V DC from a battery bank into a stable 230V AC output, capable of running household and small business appliances efficiently. The design process involves power stage development, pulse-width modulation (PWM) control, filtering techniques, and safety features to ensure reliability and durability.

BLOCK DIAGRAM OF THE INVERTER SYSTEM

The inverter system consists of several key functional blocks, each playing a vital role in power conversion and control.

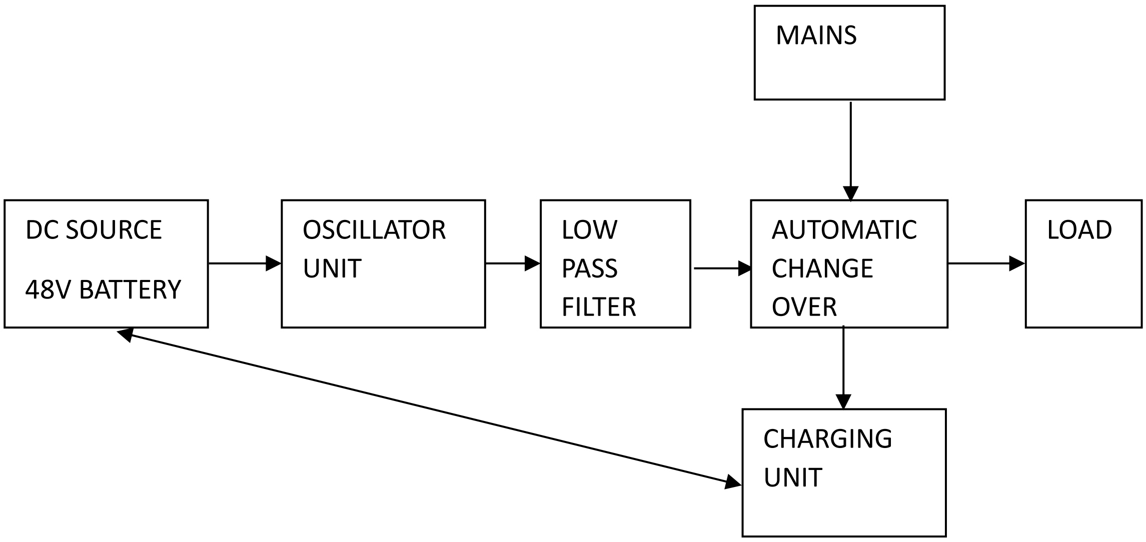
i. 48V Battery → Powers the inverter
ii. H-Bridge Inverter (MOSFETs/IGBTs) → Converts DC to AC (PWM modulated)
iii. Step-Up Transformer → Boosts AC voltage from low voltage to 230V AC
iv. LC Filter → Smooth's out the waveform to produce a pure sine wave
v. 230V AC Output → Ready for the connected load

DESIGN SPECIFICATIONS

The design of the 3kVA inverter is based on the following technical specifications: Required to operate on 230V supply voltage and 50Hz frequency which is within the 110 – 240V range that the appliance is designed to operate on. Hence,

i. Rated Power Output: 3kVA (3000W)
ii. Input Voltage: 48V DC
iii. Output Voltage: 230V AC (±5%)
iv. Output Frequency: 50Hz
v. Waveform Type: Pure sine wave
vi. Efficiency: ≥ 90%
vii. Switching Frequency: 20kHz – 50kHz (for PWM control)

Figure 4: Block diagram of a 3kva pure sine wave power inverter system



DESIGN CALCULATIONS: LOAD ANALYSIS

Target Power Output: 3000 VA (3 kVA)
Output Voltage (RMS): 230V
Power Factor (pf): 0.8 (assumed)
Real Power (P) = Apparent Power × pf = 3000 × 0.8 = 2400W
Output Current: $I_{ac} = \frac{p}{v} = \frac{2400}{230} \approx 10.43A$
Peak Current: $I_{peak} = I_{ac} \times \sqrt{2} \approx 14.75A$

DC INPUT CURRENT CALCULATION

The required DC current from the battery bank can be estimated using the formula:

$$I_{DC} = \frac{P_{out}}{\eta \times V_{DC}}$$

Where:

- I_{DC} = Required DC input current
- P_{out} = Output power (3000W)
- η = Inverter efficiency (assumed 90% or 0.9)
- V_{DC} = Input voltage (48V)

$$I_{DC} = \frac{3000}{0.9 \times 48} = \frac{3000}{43.2} \approx 69.4A$$

Thus, the inverter requires a battery bank capable of supplying at least 70A continuously.

POWER MOSFET SELECTION AND CALCULATIONS

The choice of a suitable power switching device is fundamental to the performance, efficiency, and reliability of the inverter. For the design of the 3kVA pure sine wave inverter, MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) are used due to their fast switching capabilities, ease of control, and availability of high-current, low-voltage devices suitable for low to medium power inverters.

MOSFET REQUIREMENTS FOR THE INVERTER STAGE

In a full-bridge inverter topology operating from a 48V DC input, the selected MOSFETs must be able to handle:

- High current (based on inverter power output)

- Voltage spikes and transients
- Fast switching (to generate high-frequency PWM signals)

The major design considerations for selecting the MOSFETs include:

- Drain-Source Voltage Rating (V_{DS})
- Continuous Drain Current (I_D)
- On-Resistance ($R_{DS(on)}$)
- Gate Charge (Q_g)
- Thermal resistance and power dissipation

CURRENT CALCULATION

Given:

Output Power = 3kVA
Input Voltage (DC) = 48V
Efficiency ≈ 90%
$I_{DC} \approx 69.4A$

Since the inverter uses a full-bridge with two MOSFETs conducting per cycle, each switch must be able to handle roughly half the total current at a time:

$$I_{MOSFET} \approx \frac{69.4}{2} = 34.7A$$

To provide a safety margin, a MOSFET rated ≥ 50A is preferable.

VOLTAGE RATING

To account for switching transients and back-EMF from inductive loads, the V_{DC} rating of the MOSFET should be:

$$V_{DS\,rating} \geq 1.5 \times V_{DC} = 1.5 \times 48V = 72V$$

Therefore, a MOSFET with at least 80V rating is recommended.

POWER DISSIPATION AND $R_{DS(on)}$

Power loss due to on-state resistance:

$$P_{cond} = I^2{}_{MOFET} \times R_{DS(on)}$$

If a MOSFET has $R_{DS(on)}$= 4mΩ, and it carries 35A:

$$P_{cond} = 35^2 \times 0.004 = 4.9W$$

This amount of power will be dissipated as heat and must be managed using proper heat sinking.

Lower $R_{DS(on)}$ reduces conduction losses and improves efficiency

SWITCHING LOSSES (SIMPLIFIED)

$$P_{sw} = \frac{1}{2} \times V_{DS} \times I_D \times t_{sw} \times f_{sw}$$

Where:

- $V_{DS} = 48V$
- $I_D = 35A$
- $t_{sw} = Total\ switching\ time\ (e.g., 100ns)$
- $f_{sw} = Switching\ frequency\ (e.g., 20kHz)$

Assuming:

$$P_{sw} = 0.5 \times 48 \times 35 \times 100 \times 10^{-9} \times 20000 \approx 1.68W$$

Total loss per MOSFET:

$$P_{total} = P_{cond} + P_{sw} = 4.9 + 1.68 \approx 6.6W$$

With 4 MOSFETs in the bridge, total inverter stage dissipation ≈ 26.4W

THERMAL MANAGEMENT

With estimated power losses of 5–7W per device, proper heat sinks are mandatory. If each MOSFET dissipates 6.6W and has a thermal resistance junction-to-case of 1.0°C/W, junction temperatures rise:

$$\Delta T = 6.6W \times 1.0℃/W = 6.6℃$$

With heat sink and fan cooling, junction temperature can be kept under safe limits (< 100°C). The choice of MOSFET depends on the maximum current and power dissipation. The IRFP4568 and IRF2807 are highly recommended for their high current capability, voltage margin, and efficiency, making them ideal for robust and thermally stable inverter operation.

DESIGN OF THE OSCILLATORY UNIT

The oscillatory unit is responsible for generating the control signals required to produce a pure sine wave output. It creates a 50Hz reference sine waveform and modulates it using high-frequency triangular or saw-tooth waves to generate Sinusoidal Pulse Width Modulation (SPWM). This modulation technique controls the switching of the inverter's power stage (H-Bridge) to approximate a sine wave.

OSCILLATOR FREQUENCY CALCULATION

Using SG3524 formula:

$$f = \frac{1.44}{(R1 + 2R2) \times C_t}$$

If:

- R1 = 10kΩ
- R2 = 56kΩ
- C_t = 0.22µF

Then:

$$f = \frac{1.44}{(10k + 112k) \times 0.22\mu\text{F}} \approx 52.76Hz$$

SELECTION OF THE BRIDGE RECTIFIER

The rectification circuit used in this design is a full-wave bridge rectifier which comprises of four diodes. This is shown in figure 5 below:

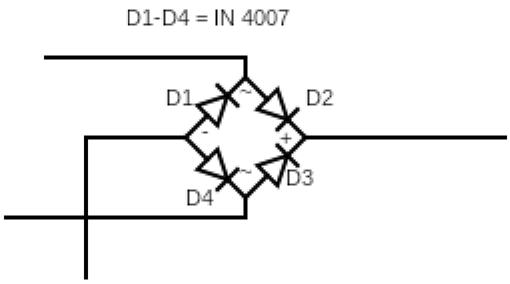


Figure 5: The Bridge Rectifier

The four-diode full-wave bridge rectifier is preferred over the two-diode center-tapped full-wave rectifier and the single-diode half-wave rectifier due to its key advantages, including:

- Better transformer utilization,
- Higher average output voltage,
- No need for a center-tapped transformer, simplifying the design.

Diode Selection Criteria

The choice of diodes was based on the following considerations:

i. Forward Current Rating: This is the maximum current the diode can conduct in the forward-biased condition without failing. The diode must be selected such that the actual current passing through it during operation is well below this maximum forward current rating to ensure reliability.

ii. Peak Inverse Voltage (PIV): PIV is the maximum reverse voltage a diode can withstand without breakdown. The peak inverse voltage is the maximum reverse voltage that a diode can withstand without destroying the junction. If the reverse voltage across a diode exceeds this value, the reverse current increases sharply and breaks down the junction due to excessive heat. Peak inverse voltage is extremely important when diode is used as a rectifier. In rectifiers, it has to be ensured that reverse voltage across the diode does not exceed its PIV during the negative half cycle of input ac voltage. Hence, PIV consideration is generally the deciding factor in diode rectifier circuit. The peak inverse voltage of a rectifier diode lies between 10V and 10kV depending upon the type of diode

$$V_{peak} = \sqrt{2}V_{rms}$$

Where V_{rms} the transformer's output voltage using the maximum output voltage (that is 240VAC) we have that V_{rms} = 240V.

$$\therefore V_{peak} = \sqrt{2} \times 240 = 339.4V$$

For a bridge rectifier, the peak voltage equals the peak inverse voltage. Therefore, the calculated PIV is 339.4V

Thus, the IN4007 diode was chosen for the rectifier since it satisfies the above stated requirements according to its design specifications.

Voltage drop across diodes = (2 x 0.7) = 1.4V

Voltage supplied= 339,4 - 1.4 = 338V.

Where 0.7 is the forward conducting voltage of silicon diode.

TRANSFORMER DESIGN CONSIDERATIONS

The choice of transformer was based on the following:

i. The input voltage range
ii. The output voltage range
iii. The power rating of the transformer in KVA
iv. Operating frequency of power supply
v. The number of turns and the diameter of the transformer coil

The input voltage range from the H-bridge supply is from 16~24VDC single phase supply. The output voltage range of the transformer is from 220~240V AC to the changeover (switch) circuit. The rating of the transformer or the power rating of the transformer is 3KVA. This indicates that the capacity of the circuit is 3KVA. Total current of the circuit is given by:

Current demand by voltage regulators + current demand by microprocessor + current demand by indicator unit (LED)

Where the current demand by voltage regulator = 8mA × 2 = 16mA

Current demand by microprocessor = 3.6mA

Current demand by indicator unit = 20mA

$$\therefore Total\ current\ of\ the\ circuit, I_L = 16mA + 3.6mA + 20mA = 39.6mA$$

$$E_2 = \frac{E_1 \times E_2}{N_1}$$

$N_2 = 160\ turns, N_1 = 8\ turns$

Given that: $E_1 = 12V,\ E_2 = \frac{12\times160}{8} = 240V$

Where:
E_1 = Input voltage
E_2 = Output voltage
N_1 = Primary Turn
N_2 = Secondary Turn

DETERMINATION OF NUMBER OF TURNS

Since the voltage per turns has been gotten, the exact number of turns in both primary and secondary winding can be calculated.
Recall, E/t = 2.2361
Making t the subject of the formula

$$t = \frac{E}{2.2361}$$

Where:
t = number of turns
E_1 = applied voltage
E_2 = Output voltage
E/t= voltage/turns
The calculation for the number of turns of the winding is shown below

FOR PRIMARY WINDING

$$E_1 = primary\ voltage\ 48\ Vac$$

$$\therefore \frac{48}{no\ of\ turns} = 2.2361$$

$$\therefore No\ of\ turns = \frac{48}{2.2361} = 21.47 turns$$

$$T_1 = 21.47\ turns$$

Targeted efficiency = 90%
Percentage loss = 10%

$\therefore Compensating\ for\ loss\ by\ adding\ 10\%\ of\ winding\ to\ total\ number\ of\ windings$

10% of 21.47 = $\frac{10}{100}$\`$\times 21.47 = 2.147\ \ turns$
Total primary turn = 21.47 + 2.147 = 23.617 turns

FOR SECONDARY WINDINGS

$$E_2 = secondary\ voltage = 240\ Vac$$

$$\frac{E}{t} = 2.2361$$

$$t = \frac{E}{2.2361} = \frac{240}{2.2361} = 107.3\ turns$$

$$\therefore T_2 = 107.3\ turns$$

Similarly, 10% of $107.3 = \frac{10}{100} \times 107.3$

$$\therefore Total\ secondary\ turns = 107.3 + 10.73 = 118\ turns$$

Therefore, the turn ratio $K = \frac{T_2}{T_1}$

OR $K = \frac{N_2}{N_1} = \frac{118}{23.617} = 4.99\ \approx 5.0$

EFFICIENCY OF THE TRANSFORMER

Efficiency = $\frac{output\ power}{input\ power} \times 100 = (1 - \frac{output\ power}{input\ power}) \times 100$

For power factor of 0.8

Input power = $3000 \times 0.8 = 2400 watts$

Therefore, Efficiency = 1-(88.09/2400)$\times$ 100 = 96.23%

It has an improved efficiency for this design which is good for the system.

SYSTEM ARCHITECTURE

The implementation of the inverter system is divided into logical hardware blocks that correspond with the major subsystems in the power stage. These are:

- DC Input Supply (Battery Bank)
- Inverter Bridge Stage (MOSFET H-Bridge)
- Control Unit (PWM Generation and Regulation)
- Driver Circuitry (Gate Signal Interface)
- Output Transformer and Filtering Stage
- Protection Mechanisms
- Feedback and Regulation Systems

The interconnection of these components ensures coordinated conversion from 48V DC to 230V AC at 50Hz, with sinusoidal output suitable for household and business appliances.

Implementation of Key Subsystems: DC Input Supply

The system is powered by a 48V DC battery bank, configured from four 12V batteries in series. The batteries are selected to meet the required current capacity for a 3kVA load, ensuring long-term energy storage, voltage stability, and support for surge demands.

The battery terminals are connected to the inverter's power input through:

- High-current cables (to minimize voltage drop)
- Inline DC fuse (80A) for overcurrent protection
- DC contactor or relay for disconnect logic
- Reverse polarity diode or MOSFET protection

H-Bridge Inverter Module

The heart of the power conversion stage is a full H-bridge composed of four high-current N-channel MOSFETs (e.g., IRFP260 or IRF2807). These are mounted on a heat-sinked PCB or chassis and wired to allow alternating current paths through the output transformer's primary winding. Switching is performed using PWM signals, with two diagonal MOSFET pairs conducting alternately to form a bipolar square wave modulated by the SPWM signal. To prevent shoot-through, dead time is introduced in the driver logic.

Control and Modulation System: SPWM Generation

The control system is implemented using either:

- A dedicated PWM controller IC such as SG3524
- Or a microcontroller (e.g., Arduino, STM32) programmed to generate Sinusoidal Pulse Width Modulated (SPWM) signals.

SPWM is chosen for its simplicity and effectiveness in approximating a sine wave output. The controller generates two complementary PWM signals that modulate the H-bridge to simulate an AC waveform.

- Reference Signal: A sinusoidal waveform generated internally or from an analog input
- Carrier Signal: A high-frequency triangular waveform (~20-50kHz)

- Modulation: The intersection of the reference and carrier determines the PWM width

The output waveform is a high-frequency AC signal with varying pulse widths corresponding to the sine wave envelope.

Driver Circuitry

To effectively switch the MOSFETs at high frequency and voltage levels, an IR2110 or equivalent high-low side gate driver is used. Each driver module receives the PWM signals from the control unit and:

- Amplifies them to appropriate gate drive levels (10–15V)
- Provides galvanic isolation between control and power sections
- Introduces programmable dead-time to prevent shoot-through conditions

Each half of the bridge (Q1-Q2 and Q3-Q4) is driven by an independent gate driver with proper bootstrap capacitors and gate resistors for noise suppression and clean transitions.

Step-Up Transformer and Output Filtering

The output of the H-bridge is fed into the primary side of a step-up transformer rated at 3kVA, with an input winding suitable for 48V AC and an output winding delivering 230V AC.

- Core Type: Toroidal or EI core with laminated steel
- Insulation: Thermally rated enameled copper wire
- Turn Ratio: Approximately 1:4.6 based on earlier calculations

After the transformer, the signal still carries switching noise, which is suppressed using an LC low-pass filter:

- Inductor: Around 2–3mH, rated for 15A
- Capacitor: 10–15μF polypropylene film capacitor

This results in a clean, near-sinusoidal waveform with low Total Harmonic Distortion (THD), ideal for powering sensitive loads.

Feedback and Regulation System

For stable and regulated operation, voltage and current feedback are implemented as follows:

- Voltage Divider: Steps down the AC output voltage to a measurable level for the controller
- Current Sensor: Shunt resistor or Hall effect sensor on output or battery line
- Feedback Loop: Integrated into the PWM generation system for automatic duty cycle adjustment

The system can implement safety cutoffs such as:

- Low battery voltage cutoff
- Overload shutdown
- Over temperature protection

Protection and Reliability Measures

To ensure safe operation and component longevity, the following protective measures are integrated:

- Surge Suppressors at transformer and AC output terminals
- Freewheeling Diodes across MOSFETs to protect against back-EMF
- Heat Sinks and Cooling Fans on all power devices, regulated by temperature sensors
- Inrush Current Limiters to prevent transformer saturation at startup
- Fuses/Breakers at all critical current paths
- EMI Filter at the output to reduce conducted and radiated noise

Implementation Workflow

The following steps define a logical hardware implementation workflow for building this inverter:

1. Design: Split into high-voltage (power) and low-voltage (control) sections.
2. Component Mounting: Start with passive components, then active, then power switches.
3. Subsystem Testing:
   - Test control unit and PWM generation
   - Test driver signals using oscilloscope
   - Apply DC power to H-bridge with dummy load
4. Transformer and Filter Integration
5. Load Test with Bulb/Resistive Load
6. Final Validation under Varying Load Conditions

Functional Evaluation of the Power Stage Design

The power stage of the inverter, which is the core of this paper, was meticulously designed to convert 48V DC into a clean 230V AC output using a full-bridge inverter topology controlled by a Sinusoidal Pulse Width Modulation (SPWM) scheme. Based on theoretical and design evaluations, the system is expected to perform the following functions effectively:

- Efficient DC to AC Conversion: With an estimated conversion efficiency of over 90%, the inverter should deliver up to 2400W of real power from a 3000VA apparent power rating at a power factor of 0.8.
- Pure Sine Wave Output: The adoption of SPWM ensures low harmonic distortion, making the output waveform suitable for sensitive electronic equipment such as computers, televisions, and medical devices.
- Thermal Stability: Power losses in the MOSFETs and transformer were carefully calculated and minimized using proper component selection and thermal management strategies. Heatsinks and fan-based cooling will ensure temperature regulation during prolonged operation.
- Voltage Regulation and Protection: Integration of feedback loops using voltage dividers and current sensing (as discussed in Chapter 4) enables dynamic regulation and protection against conditions like overvoltage, overcurrent, and thermal overload.
- Scalability: The modularity of the power stage allows for future upgrades in power rating or integration into hybrid systems incorporating solar energy sources or grid interface.

Table 3: Expected system performance

Parameter	Expected Value
Output Voltage	230V AC ± 5%
Output Frequency	50Hz ± 0.5Hz
Total Harmonic Distortion	< 5% (SPWM + LC Filter)
Power Output	3kVA (3000VA)
Real Power	2400W (with 0.8 pf)
Efficiency	≥ 90%
Output Waveform Type	Pure Sine Wave
Response Time	< 100ms (theoretical)

Expected System Performance

Even though the system was not physically built or simulated, the implementation plan and component parameters suggest that the designed inverter would achieve the following performance characteristics. These expected values are derived from industry-standard benchmarks and published results for similar inverter designs, as well as from the detailed calculations and design considerations presented earlier.

Contribution to Local Energy Challenges

The proposed inverter design is highly relevant to the power sector, where frequent blackouts, high generator dependency, and rising fuel costs demand more sustainable solutions. The proposed inverter offers:

- Affordability: Designed using locally available components, making it cost-effective compared to imported units.
- Renewable Integration: Can be connected with solar panels and charge controllers to form a solar hybrid inverter.
- Environmentally Friendly: Operates silently and without emissions, unlike fossil-fuel generators.
- Energy Independence: Provides households and small businesses with autonomous energy backup systems.

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