REVERSE ENGINEERING ON A PWM (PULSE WIDTH MODULATION) LOW FREQUENCY HYBRID INVERTER

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CERTIFICATION

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DEDICATION

This work is dedicated to our families, friends, and mentors, whose steadfast support has been our foundation. We wish to express our profound gratitude to our supervisor, Engr. Dr. M.O. Oyedoh, for his wisdom and guidance. Our sincere thanks also go to all those whose dedication to knowledge served as a constant source of inspiration.

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ABSTRACT

This project presents a comprehensive study on the reverse engineering of a Pulse Width Modulation (PWM) Low-Frequency Hybrid Inverter used in renewable energy applications. The primary objective was to analyze, understand, and document the internal architecture, components, and operational principles of the inverter through a systematic disassembly and evaluation process. The study focused on identifying key functional sections namely, the oscillating stage, power stage, and transformer stage along with their respective roles in energy conversion and control.

The methodology involved visual inspection, electrical testing, polarity and no-load tests, and detailed circuit tracing of the printed circuit board (PCB). These procedures provided insights into component functionality, design weaknesses, and overall inverter efficiency. The inverter's performance parameters were analyzed, including output voltage, frequency stability, and energy conversion efficiency. Results showed that the PWM low-frequency inverter efficiently converts DC power to AC with high surge capacity and robust performance under varying loads, though it operates with slightly lower efficiency compared to MPPT-based systems. The study further compared PWM and MPPT inverter technologies, highlighting that while PWM inverters are simpler, cost-effective, and reliable for off-grid and backup applications, they yield lower solar energy utilization. The reverse engineering approach revealed opportunities for performance enhancement through improved component selection, integration of MPPT control, and optimized cooling mechanisms.

TABLE OF CONTENTS

Title Page i

Certification ii

Dedication iii

Acknowledgement iv

Abstract v

Abbreviations vi

Table of Figures vii

List of Tables viii

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study 1

1.2 Statement of the Problem 3

1.3 Aim and Objectives 5

1.4 Methodology 6

1.5 Scope of the Work 7

1.6 Significance of the Study 8

CHAPTER TWO: LITERATURE REVIEW

2.1 History of Reverse Engineering 10

2.1.1 Pre-Industrial and Ancient Practices 11

2.1.2 Industrial Revolution and Mechanical Engineering 12

2.2 Overview of Hybrid Inverter 13

2.2.1 Mode of Operation of Hybrid Inverter.. 15

2.2.2 Types of Hybrid Inverter.. 16

2.3 Mode of Operations for a Hybrid Inverter.. 20

2.4 Working Principle of Hybrid Inverter... 24

2.5 Core Components of a Hybrid Inverter.. 27

2.6 MPPT Charge Controller (Maximum Power Point Tracking) 33

2.7 PWM Charge Controller (Pulse Width Modulation) ……………….............................. 35

CHAPTER THREE: METHODOLOGY

3.1 Design Consideration and Analysis.. 38

3.2 Component and Stages of the Hybrid Inverter.. 40

3.2.1 Oscillating Stage.. 41

3.2.2 Power Stage... 42

3.2.3 Transformer Stage... 43

3.3 Functions of Components in the Inverter... 44

3.4 No Load Test... 47

3.5 Reverse Polarity Test.. 48

3.6 PCB Tracking... 49

3.7 Comparison of PWM Inverter and MPPT Inverter.. 50

CHAPTER FOUR: RESULTS AND ANALYSIS

4.1 Specification of the Inverter... 52

4.2 Calculation for DC Input Current... 54

4.3 Calculation for Battery Amp-Hour... 55

4.4 Calculation for Maximum Charging Power.. 56

4.5 Calculation for PV Array Current.. 57

4.6 PV String Sizing and Capability.. 58

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Summary.. 60

5.2 Conclusion... 61

5.3 Recommendation.. 62

References.. 63

TABLE OF FIGURES

Figure No.	Title / Description	Page
Figure 2.1	PWM Charge Controller	33
Figure 2.2	DC–AC Converter	34
Figure 2.3	Rectifier Charger	35
Figure 2.4	Digital Signal Processor (DSP)	36
Figure 2.5	Heat Sink	36
Figure 2.6	Transformer	37
Figure 2.7	Resistor	38
Figure 2.8	Voltage Regulator	39
Figure 2.9	MOSFET	39
Figure 2.10	Transistor	40
Figure 2.11	Capacitor	40
Figure 2.12	MPPT Controller	43
Figure 2.13	Block Diagram of MPPT Controller	44
Figure 3.1	Internal Components of the PWM Hybrid Inverter	46
Figure 3.2	No-Load Test Setup	47

LIST OF TABLES

Table No.	Title / Description	Page
Table 2.1	Comparison of AC-Coupled vs. DC-Coupled Hybrid Inverters	19
Table 2.2	Hybrid Inverter Operational Modes and Prioritization	27
Table 2.3	Comparison Between PWM and MPPT Controllers	37
Table 3.1	Comparison of PWM Inverter and MPPT Inverter	50

ABBREVIATION

Abbreviation	**Meaning**
AC	Alternating Current
Ah	Ampere-Hour
DC	Direct Current
DSP	Digital Signal Processor
DoD	Depth of Discharge
EMS	Energy Management System
FET	Field Effect Transistor
H-Bridge	Half Bridge / Full Bridge Switching Configuration
Hz	Hertz
IGBT	Insulated Gate Bipolar Transistor
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IRENA	International Renewable Energy Agency
LED	Light Emitting Diode
LF	Low Frequency
MPPT	Maximum Power Point Tracking
MOSFET	Metal-Oxide Semiconductor Field Effect Transistor
NREL	National Renewable Energy Laboratory

Abbreviation	**Meaning**
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PF	Power Factor
PV	Photovoltaic
PWM	Pulse Width Modulation
RE	Reverse Engineering
SEIA	Solar Energy Industries Association
SOC	State of Charge
SRNE	Shenzhen SRNE Solar Co., Ltd.
TOU	Time of Use
VDC	Volts Direct Current
VAC	Volts Alternating Current
Vmp	Voltage at Maximum Power
Voc	Open-Circuit Voltage
W	Watt
kW	Kilowatt
VA	Volt-Ampere
η	Efficiency Symbol (Greek Letter Eta)

RE	Reverse Engineering

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

In recent years, as communities around the world face the real impacts of dwindling fossil fuel reserves and the urgent need for more sustainable living, the demand for renewable energy systems has grown rapidly. People are now searching for energy solutions that are not only reliable and cost-effective but also environmentally friendly. Hybrid inverters, which blend the benefits of both grid-tied and off-grid systems, have become essential in making renewable energy accessible and practical for everyday use. By enabling homes and businesses to integrate solar power with conventional electricity and battery storage, hybrid inverters help families and organizations take control of their energy needs. These intelligent devices manage energy flow, maximize efficiency, and ensure a stable power supply—making life a little easier, even when conditions change.

Reverse engineering is most recognized as the procedure for taking apart someone else's product to learn how it works. However, reverse engineering is a general term that refers to a process of analysis, supported by methods and tools to investigate an existing system, its components, and their interrelationships, regardless of the implementation and ownership of the system. (Chikofsky E. *et al*, 2002). A hybrid inverter, a device that converts DC power from sources like solar panels or batteries into AC power for household use, is a key component in modern energy systems. Applied to hybrid inverters, reverse engineering involves analyzing its internal components and circuitry to understand its functionality and design. It also involves identifying design weakness, ensuring product security and improving system compatibility, or even replicating design principles for educational purpose. It also assists in troubleshooting, repair and upgrading of inverter systems. This project helps us to understand Reverse engineering, the process of analyzing a system to understand its components and operational logic, has emerged as a valuable technique in improving and securing hybrid inverter technologies.

1.2 Statement of Problem

Hybrid inverters are critical components in modern renewable energy systems. The integration of renewable energy sources into power systems has led to the widespread adoption of hybrid inverters due to their ability to manage energy from multiple sources—such as photovoltaic (PV) arrays, battery storage, and the utility grid—in an efficient and intelligent manner (Singh and Bist, 2015; Obaid *et al.,* 2020). However, most commercially available hybrid inverters are designed with proprietary architectures, protected control algorithms, and undocumented embedded systems that restrict access to their operational details (Alonso and Sanchez, 2020; Yazdani and Iravani, 2010).

Despite their importance, detailed technical information about the design, operation, and internal structure of these devices is often proprietary and not readily available to researchers, developers, and local technicians, particularly in developing regions. This lack of accessible information limits the ability to repair, modify, or improve these systems, resulting in higher costs, dependence on foreign technology, and difficulty in ensuring long-term sustainability and adaptability of renewable energy infrastructures.

This presents a significant barrier to independent research, local manufacturing, modification, maintenance, and capacity building, especially in developing regions where technical documentation and support from original equipment manufacturers (OEMs) are limited (Chikuni and Mufute, 2013). The inability to fully understand and analyze the internal workings of these devices impedes efforts to optimize their performance, ensure compatibility with local energy conditions, and reduce system costs through indigenous innovation.

Reverse engineering offers a viable pathway to bridge this knowledge gap by systematically deconstructing and analyzing hybrid inverters to reveal their hardware design, control logic, and functional principles (Alonso and Sanchez, 2020). However, there is a lack of documented research that applies reverse engineering methodologies specifically to hybrid inverters for renewable energy systems. This study aims to address this gap by conducting a comprehensive reverse engineering investigation to enhance understanding, promote local technological development, and enable cost-effective customization and maintenance of hybrid inverter systems.

1.3 Aim

The aim of this project is to apply reverse engineering techniques to hybrid inverter systems in order to analyze, understand, and document their internal hardware architecture, control strategies, and functional operations.

The objectives to achieve the above aim are to;

1. To examine and document the hardware architecture of the hybrid inverter systems through detailed reverse engineering analysis.
2. To identify and analyze the embedded control algorithms and software functionalities that govern the operation of hybrid inverters.
3. To assess the functional performance of hybrid inverters by evaluating their energy conversion efficiency, grid synchronization capability, and battery management features.
4. To determine potential design weaknesses, limitations, or areas for improvement in hybrid inverter systems to enhance reliability, maintainability, and local adaptability

1.4 Scope of Work

This project focuses on the reverse engineering of an available hybrid inverter used in renewable energy applications such as solar photovoltaic (PV) power generation. This project focuses on the hardware analysis; this deals with dismembering and inspection of inverter internal components such as power electronics (IGBTs, MOSFETs), control boards, sensors, and protection circuits. Performance testing; Experimental validation of the inverter’s operational characteristics under controlled laboratory conditions and evaluation of key parameters such as conversion efficiency, voltage and current waveform quality, and system response to variable load and source conditions. Identification of design limitations; Assessment of potential weaknesses, inefficiencies, or failure points within the inverter design and suggestions for possible improvements or modifications to enhance performance, reliability, and adaptability to local energy environments.

1.5 Significance of the Study

This project on reverse engineering on a hybrid inverter holds significant relevance in addressing the need to apply reverse engineering on the hybrid inverter to generate empirical data and technical insights that are largely absent from existing literature due to proprietary nature of these devices (Alonso and Sanchez, 2020). The project will also serve as an educational resource for engineering institutions, offering practical exposure to inverter analysis and design principles that are typically inaccessible due to manufacturer-imposed restrictions. This fosters skill development in reverse engineering, circuit analysis, and renewable energy system integration among students and researchers (Chikuni and Mufute, 2013). Finally, this project helps to equip engineers and technologists with the knowledge required to troubleshoot, repair, and modify hybrid inverters without dependency on proprietary information from manufacturers. This capability is critical in promoting self-reliance and reducing operational costs in regions where technical support and replacement parts are scarce or expensive (Chikuni and Mufute, 2013).

LITREATURE REVIEW

2.1 History of Reverse Engineering

Reverse engineering is most recognized as the procedure for taking apart someone else's product to learn how it works. However, reverse engineering is a general term that refers to a process of dismembering, analysis, supported by methods and tools to investigate an existing system, its components, and their interrelationships, regardless of the implementation and ownership of the system. (Chikofsky E. *et al,* 2002). Historically, Reverse Engineering (RE) has served various functions, including duplication, compatibility enhancement, performance optimization, and security analysis. Its applications span numerous domains such as mechanical engineering, electrical and electronics engineering, software engineering, information technology and biotechnology.

In modern contexts, Reverse engineering is crucial to innovation in modern settings, especially in cases when documentation is lacking, out-of-date, or unavailable. In addition to examining how reverse engineering has changed in complexity, application, and legality, this paper charts the discipline's historical evolution. The intention is to present reverse engineering as an interdisciplinary field of study with significant implications for both industry and academics, rather than only as a technical procedure.

2.1.1 Pre Industrial and Ancient Practices

Many civilizations engaged in what is now known as reverse engineering, albeit unofficially, prior to industrial standardization. The Roman Empire dismantled and reproduced naval technology and siege equipment that it had taken from different nations. Based on reports, the Chinese military improved and replicated enemy weaponry by reverse engineering techniques during the Han era. Rather than being grounded in formal science, these early methods were mostly practical and derived from handicraft and observation. (Capra 2007).

The Renaissance period saw a more analytical approach to technological deconstruction. Leonardo da Vinci, through meticulous sketches and mechanical studies, laid the foundation for mechanical reverse engineering. His explorations, though not classified as reverse engineering at the time, introduced core concepts such as structural modeling and functional decomposition.

2.1.2 Industrial Revolution and Mechanical Engineering

As manufacturing processes grew more competitive and mechanized throughout the Industrial Revolution, reverse engineering was established. In order to support domestic industry, factories in the United States and continental Europe often reverse-engineered British devices, such as the steam and spinning jenny engines.

Reverse engineering started to blur the boundaries between innovation and intellectual property violation around this time. The quick spread of mechanical inventions brought up moral dilemmas that would eventually affect patent laws. During this time, national technical catch-up, comparative productivity, and the economics of replication were the main topics of academic study.

2.1 Overview of Hybrid Inverter

A hybrid Solar Inverter is a piece of equipment that combines the function of a battery inverter and a photovoltaic (PV) inverter into one units. Conventional inverters simply convert solar panels' direct current (DC) into alternating current (AC) for instant use; hybrid inverters are made to intelligently handle power, control energy storage systems and enable two-way energy flows between the utility grid, the PV system, and the battery bank. (Clean Energy Reviews,2024).

In contrast to conventional solar inverters, which can only feed excess electricity into the grid or supply power directly to loads, hybrid inverters integrate sophisticated bidirectional power electronics and energy management systems (EMS). This enables them to store excess energy for later use, priorities self-consumption, and seamlessly supply backup power in the event of grid outages (Solareast ESS, 2024).

The Hybrid Inverter has multiple MPPT (Maximum Power Point Tracking) which allows independent optimization of the multiple solar arrays. It has an efficiency of over 95% for both solar and battery operations. It ensures that the critical loads are powered before the non-essential loads are then powered. It is also capable of carrying out parallel operations for higher systems. (Clean Energy Reviews, 2024).

The Hybrid Inverter has different core functionality and it can be broken down below:

- **DC TO AC CONVERSION:** The DC electricity produced by solar panels is incompatible with the grid supply and common household appliances. In order to ensure safe operation, the hybrid inverter uses power electronics to convert this DC into AC and synchronizes it with grid voltage and frequency (Solareast ESS, 2024). Maximum Power Point Tracking (MPPT) is frequently used by high-quality hybrid inverters to make sure that solar panels run at their most efficient point.
- **BIDIRECTIONAL ENERGY FLOW FOR BATERY MANAGEMENT:** Hybrid inverters have the ability to convert excess AC electricity (from the grid) into DC for battery charging. They can also convert stored DC energy back into AC when needed. Its bidirectional capability is one special feature that enables complete integration of energy storage into a solar PV system (Etek Solar, 2024).
- **INTELLIGENT ENERGY MANAGEMENT SYSTEM (EMS):** An integrated EMS monitors power generation, storage levels, and consumption patterns. It determines when to directly supply loads with solar energy, when to store extra electricity using batteries, when to draw power from the battery and when to export or import data into the grid. This ensures cost savings, energy efficiency, and less reliance on the utility grid (Sunplusn Energy, 2024).
- **GRID INTERACTION AND ISLANDING CAPABILITY:** Hybrid inverters can export excess power thanks to grid-synchronization features. Additionally, they are equipped with anti-islanding protection, which safely disconnects the system from the grid during outages. By providing vital loads with power solely from solar panels and/or

batteries when in "island mode," the inverter guarantees energy continuity (SRNE Solar, 2024).

2.2.1 Mode of Operations for Hybrid Inverter

The Hybrid inverter is a complex equipment and it has different ways it can operate. The following modes of operation are usually supported by hybrid inverters (Terahive, 2024):

- **Grid-Tied Mode:** This mode functions similarly to a regular solar inverter, exporting excess energy to the utility grid and supplying loads.
- **Battery Storage Mode:** During the day, excess solar energy is stored in batteries for use at night or during periods of high demand.
- **Backup Mode:** When a grid failure is identified, it automatically switches to a battery and solar power source to continue powering critical loads.
- **Off-Grid Mode:** Completely self-sufficient operation using only solar and stored energy, without a grid connection.

2.2.2 Types of Hybrid Inverter

The Hybrid Inverter is broadly classified into different types based on their functionality and their operational characteristics:

1. **DC Coupled Hybrid Inverter:** The DC Coupled Hybrid Inverter is a device that establish a connection between solar panels and the battery storage systems. The setup stands out by its effective energy flow: batteries can be charged directly from DC power produced by the solar panels without the need for a middle man AC conversion. When the Hybrid Inverter transforms this DC power—whether it comes from the battery or the solar panels—into AC for either immediate domestic use or export to the utility grid. High-voltage Maximum Power Point Tracking (MPPT) controllers are usually used in

these systems to maximize solar energy harvesting, and they usually have integrated energy management features. (Clean Energy Reviews, 2025).

DC-coupled hybrid inverter systems are suitable for new solar and battery installations where the primary goal is high efficiency and easy integration from the start. They are the preferable solution for off-grid homes or grid-connected systems that require reliable backup power, particularly in locations prone to frequent power outages. (Clean Energy Reviews, 2025). The benefits of DC-coupled systems are significant. They provide greater efficiency because they require fewer power conversions; typically, only one DC-to-AC conversion occurs when electricity is supplied to loads or exported to the grid. (Soltaro. (n.d.))

This single DC-to-AC conversion step helps to minimize energy losses (*Clean Energy Reviews*, 2025). Another advantage, as *Soltaro* (n.d.) explains, is that DC-coupled systems can lower upfront equipment costs because one hybrid inverter handles both solar power conversion and battery charging, removing the need for separate devices. In addition, *SolarEdge* (n.d.) notes that these systems make it possible to “oversize” the solar array so that any excess DC power beyond the inverter’s immediate AC output limit can be stored directly in the battery instead of going to waste. As *Clean Energy Reviews* (2025) points out, the overall setup also benefits from simpler wiring and fewer components, which reduces the likelihood of system failures.

The combination of superior efficiency, lower upfront equipment costs, and direct battery charging makes DC-coupled systems a streamlined and high-performing choice for new solar-plus-storage installations. As *Clean Energy Reviews* (2025) explains, their design is focused on preserving energy and simplifying the system from the ground up. This makes them especially appealing for greenfield projects, where the entire setup can be engineered for maximum performance from the start.

However, *Hinen Support* (2025) notes that DC-coupled systems have some drawbacks. They are less flexible for retrofitting into existing grid-tied solar setups, since upgrading often requires replacing the current solar inverter with a new hybrid model. There’s also the risk, pointed out by *Soltaro* (n.d.), that the single integrated inverter could act as a single point of failure for the entire system. In addition, *Clean Energy Reviews* (2025) highlights that more specialized DC wiring may be needed, which can make installation more complex. Finally, *Soltaro* (n.d.) adds that some DC-coupled designs have limited scalability when it comes to adding new batteries in the future.

2. **AC Coupled Hybrid Inverter:** AC-coupled hybrid inverters are designed to work seamlessly with existing solar power systems and battery storage units (*Clean Energy Reviews*, 2025). Their operation involves a multi-step energy conversion process. First, DC electricity generated by the solar panels is converted into AC by a standard grid-tied solar inverter. If this AC power is not used immediately or exported to the grid, and is instead intended for storage, it is converted back into DC to charge the battery bank via a separate battery inverter or charger (*Hinen Support*, 2025). Later, when stored energy is needed, the battery's DC power is once again converted into AC for household use or for export to the grid (*Hinen Support*, 2025).

   While these systems usually operate in grid-tied mode, they can also provide backup power during outages when a battery is connected (*Hinen Support*, 2025). One of their strongest advantages, according to *Hinen Support* (2025), is their suitability for retrofitting. AC-coupled systems make it possible to add battery storage to an existing solar installation without having to rewire the original solar array. This makes them an attractive option for homeowners with grid-tied systems who want to add backup power capabilities (*SolarEdge*, n.d.).

   Other key benefits include faster and simpler installation in retrofit scenarios, greater flexibility for expanding capacity by adding multiple batteries, and broad compatibility with a wide range of solar inverters (*Hinen Support*, 2025). They also have the advantage of being able to charge batteries not only from the PV array but also directly from the utility grid (*SolarEdge*, n.d.).

   However, AC-coupled designs also have trade-offs. They are generally less efficient due to the multiple AC/DC conversions required. For energy that is stored and later used, it must go through three stages:

- DC from the panels is converted to AC for the grid.

- AC is converted back to DC to charge the battery.
- DC from the battery is converted again to AC for use by loads.

As *Hinen Support* (2025) explains, this triple conversion leads to greater energy losses and slightly lower overall utilization compared to DC-coupled systems. Still, many homeowners accept this efficiency trade-off in exchange for the ease of integration and minimal disruption to their existing solar setup. Finally, AC-coupled systems can be more expensive because they require separate inverters for the PV array and the battery (*Hinen Support*, 2025). In some cases, compatibility with certain types of solar panels or battery storage systems may also be limited (*SolarEdge*, n.d.).

3. **Multi-mode (Bimodal) Hybrid Inverter:** Multi-mode inverters often called Bimodal Inverters are a sophisticated type of hybrid inverter that can operate both alongside the utility grid and independently when the grid is unavailable (*Clean Energy Reviews*, 2025; *SolarEdge*, n.d.). This means they can seamlessly function as both a grid-tie inverter and a stand-alone inverter, making them especially popular when paired with battery backup systems to ensure an uninterrupted power supply (*Clean Energy Reviews*, 2025).

One of their defining strengths is operational flexibility. As *Hinen Support* (2025) explains, multi-mode inverters can switch smoothly between grid-tied mode, off-grid (islanded) mode, and battery backup operation. This adaptability enables them to intelligently balance energy from solar panels, batteries, and the grid in real time, based on both demand and availability. This makes them a strong choice for users who value energy independence and reliable backup power, particularly in areas where power outages are common. They can also optimize energy costs by charging batteries during low-rate off-peak periods and discharging them during peak pricing hours.

The “bimodal” capability marks a step forward from simple power converters to full-fledged energy management hubs. Unlike standard grid-tied inverters—which shut down when the grid goes offline multi-mode inverters can create and regulate their own AC sine wave, maintaining stable voltage and frequency in an isolated network (*SolarEdge*, n.d.). Achieving this requires advanced control algorithms capable of keeping power quality high and loads balanced without the stabilizing influence of the utility grid. This feature is central to the development of distributed energy systems and localized energy resilience, paving the way for greater energy autonomy.

The benefits of multi-mode inverters include strong power resilience, energy independence, and the ability to integrate multiple power sources and operational modes (*Hinen Support*, 2025). They support bidirectional power flow, enabling batteries to be charged from both solar generation and the grid (*Soltaro*, n.d.). Many models also feature dual AC outputs, which allow critical loads to be prioritized during outages.

However, these advantages come with trade-offs. As *Hinen Support* (2025) notes, multi-mode inverters tend to have a higher initial cost than simpler inverter types. Full functionality usually requires integrated battery storage, adding to the expense and introducing ongoing maintenance needs. Installation and servicing can also be more complex due to the system's advanced design (*SolarEdge*, n.d.).

Table 2.1: Comparison of AC-Coupled vs. DC-Coupled Hybrid Inverters

Category	**AC-Coupled System**	**DC-Coupled System**
Components	Solar panels, DC inverter, charge controller, battery bank, AC inverter.	Solar panels, hybrid inverter (integrates charge controller and battery inverter).
Energy Conversion	Converts DC to AC (PV inverter), then AC to DC (battery charger), then DC to AC (battery inverter) for use.	Converts DC directly to DC for storage, then DC to AC for use.
Efficiency	Less efficient due to multiple conversions (e.g., three conversions for stored energy).	More efficient due to fewer power conversions (only one DC-AC conversion for loads).

Category	**AC-Coupled System**	**DC-Coupled System**
Cost	Typically more expensive due to additional components.	Typically less expensive due to fewer components.
Compatibility	Greater flexibility, works with various inverter types.	Less flexible for retrofitting existing systems.
Installation Complexity	Easier and quicker installation, especially for retrofits.	More complex installation for new systems; requires specialized DC wiring.
Best For	Suitable for existing solar systems seeking battery integration and backup.	Ideal for new solar + battery installations where optimal efficiency is desired.
Single Point of Failure	Less prone to single point of failure as components can work independently.	Single integrated inverter can be a single point of failure.

2.2.3 Mode of Operations for a Hybrid Inverter

Here we are going to discuss the various mode of operations employed by the Hybrid Inverter and how it is able to manage the energy flow to maximize consumptions, storage and interactions with the utility grid. The following are different modes of operations employed by the hybrid inverter in solar energy today:

1. **Grid Tied Mode:** In their default mode, hybrid inverters operate similarly to conventional grid-tied inverters—converting DC solar output into AC power for on-site use, with any surplus exported to the utility grid (*EnergySage*, 2024). A defining technical feature is the inverter's ability to precisely match the grid's voltage and frequency, ensuring safe and stable power injection (*SEIA*, 2024).

This synchronization not only prevents operational disruptions but also allows hybrid inverters to play an active role in grid stability. Many modern models include smart inverter functions, such as reactive power control, voltage regulation, and frequency support, which help stabilize the grid during fluctuating supply and demand (*NREL*, 2023). Under net metering arrangements, exported energy earns credits for the system owner (*Clean Energy Council*, 2025).

By combining grid-tied functionality with energy storage capabilities, hybrid inverters bridge the gap between distributed generation and active grid participation, making them key components in modern renewable energy infrastructure.

2. **Off Grid Mode (Islanded Operation):** In off-grid mode, a hybrid inverter fully disconnects from the utility grid and operates independently. In this setup, it draws solely on power generated by the connected solar panels and stored in batteries to meet the demands of local loads (*IRENA*, 2022). This feature is particularly vital for remote areas without grid access, or for homeowners aiming for complete energy self-sufficiency.

   When operating in islanded mode, the inverter takes on the critical role of establishing and sustaining its own local power network—often referred to as a micro grid. It must generate and maintain a stable AC voltage and frequency for all connected appliances and systems (*NREL*, 2023). Unlike grid-tied systems, where the utility grid provides inherent stability, the off-grid inverter must manage these parameters entirely on its own, balancing dynamic load changes in real time.

   Achieving this level of grid-forming control demands advanced power electronics and sophisticated control algorithms. These systems ensure consistent power quality, prevent voltage or frequency drift, and maintain reliable supply even as load conditions fluctuate (*Clean Energy Council*, 2025). Such capabilities transform the hybrid inverter from a simple power converter into a fully-fledged micro grid controller.

This mode is central to the growth of distributed energy systems and plays a key role in enhancing local energy resilience. As technology advances, off-grid-capable hybrid inverters are making localized, autonomous power networks increasingly practical, paving the way for communities to achieve greater energy independence (*SEIA*, 2024).

3. **Battery Backup Mode:** When an unexpected power outage occurs—or during a planned grid shutdown—a hybrid inverter automatically switches into battery backup mode (*Solar Energy Industries Association [SEIA]*, 2024). This process begins with an immediate disconnection from the utility grid, a protective function known as anti-islanding. Anti-islanding ensures that no electricity flows back into a downed grid, safeguarding utility workers and preventing potential equipment damage (*National Renewable Energy Laboratory [NREL]*, 2023).

   Once isolated, the inverter draws energy from the connected battery storage system to supply power to essential household or commercial loads. These may include critical systems such as medical equipment, refrigeration, lighting, and security systems (*Clean Energy Council*, 2025).

   One of the most impressive engineering aspects of battery backup mode is the speed of the switchover. Modern hybrid inverters achieve grid transfer times as fast as 5 milliseconds—and typically under 10 milliseconds—thanks to advanced power electronics and precise control algorithms (*IRENA*, 2022). This speed is not simply a matter of convenience; it is essential for sensitive electrical equipment that cannot withstand even brief interruptions.

   The combination of rapid transfer, system safety, and continuous power delivery highlights the hybrid inverter's dual commitment to both grid protection and uninterrupted consumer energy supply. This capability is a key reason why hybrid inverters are becoming central to energy resilience strategies worldwide (*SEIA*, 2024).

4. **Solar Priority Output Level Mode:** In solar priority mode, the hybrid inverter is programmed to maximize the use of solar energy for powering AC loads first

(*EnergySage*, 2024). Whenever the solar array produces more power than is currently needed, the surplus energy is automatically diverted to charge the battery bank.

If solar generation drops below demand—for instance, on cloudy or rainy days—the system draws from the battery to maintain supply. Only when both the solar input and battery reserves are insufficient will the system tap into the utility grid for electricity.

This mode offers significant cost savings in regions with abundant sunlight and high electricity tariffs, as it reduces dependency on grid-supplied power while making full use of available renewable energy (*EnergySage*, 2024). It also contributes to greater energy independence, a benefit valued by households and businesses aiming to cut operational costs and minimize carbon footprints.

5. **Battery Priority Output Level Mode:** In battery priority mode, the hybrid inverter is configured to draw power from the battery first to run AC loads (*EnergySage*, 2024). Solar energy generated during the day is primarily directed toward charging the battery, ensuring it remains the main power source.

   If the battery's charge drops below a set threshold—or if neither solar nor battery power can meet demand—the system automatically switches to utility grid power. Once the battery is recharged to a predefined level (for example, 52 V for a 48 V battery bank), the inverter switches back to running on battery power.

   This operating mode is particularly advantageous for energy-independent users or those living in areas with frequent power outages, as it delivers a reliable, uninterrupted electricity supply without heavy reliance on the grid (*EnergySage*, 2024).

6. **Mains Priority Output Level Mode:** In mains priority mode, the utility grid is set as the primary source for supplying AC loads (*EnergySage*, 2024). Solar energy generated is directed mainly toward charging the battery. Solar power will only supplement the mains

supply if grid power is insufficient or if the battery is fully charged and the available solar generation can directly power the loads.

If solar output is inadequate, the mains will continue to provide the primary energy supply without interruption. This configuration is particularly suitable in locations where grid electricity is stable and cheaper than solar-generated power, enabling solar energy to be stored for use during outages or peak-demand periods (*EnergySage*, 2024).

The configurable priority strategies of hybrid inverters emphasize their complex control methods that enable them to perform dynamic energy exchange and enhanced demand-side management (EnergySage, 2024). Rather than just converting power, these systems actively manage energy flows, allowing users to optimize usage based on economic factors such as time-of-use (TOU) electricity prices.

For example, the inverter can be designed to charge batteries during off-peak hours, when electricity prices are lower, and discharge them during peak periods, reducing overall energy expenses (EnergySage, 2024). This functionality converts consumers from passive users of electricity to active participants in the energy market, providing them more control over their consumption patterns and the capacity to interact strategically with the grid.

2.3 Working Principle of Hybrid Inverter

A hybrid solar inverter combines the characteristics of a typical inverter, charge controller, and battery management system into a single intelligent machine. It optimizes energy utilization from several sources solar panels, batteries, and the electrical grid via smart monitoring and control. When connected to a power supply, the hybrid inverter starts a system start-up and self-diagnosis operation. During this stage, the inverter ensures that important components such as the DC input terminals, DC/DC converter, inverter bridge, energy storage battery, and control circuits are free of faults or irregularities. Once all internal testing is complete, the system enters a standby mode, waiting for operational commands or sufficient solar input to commence power conversion (Gupta and Kumar, 2021).

Once the MPPT circuit has provided maximum DC power, the inverter's DC-AC conversion stage takes over. The inverter uses Pulse Width Modulation (PWM) technology to generate a pure sine wave AC output from a DC input. The PWM approach uses fast switching of semiconductor devices (typically IGBTs or MOSFETs) to shape the output waveform. The inverter synchronizes its output voltage, frequency, and phase with the grid or load to ensure stable operation. The digital signal processor (DSP) manages this process by continuously monitoring grid parameters to ensure exact synchronization (Hossain *et al*., 2017; Masters, 2013).

Hybrid inverters are distinguished by their capacity to control battery energy. During seasons of abundant sunlight and low load demand, excess solar power is stored in energy storage batteries. In contrast, during a grid failure, nighttime, or low irradiance, the inverter seamlessly shifts to battery discharge mode to power the linked loads. The inverter also uses effective charging algorithms, such as multi-stage charging (bulk, absorption, and float), to extend battery life and prevent overcharging or deep draining (Anern, n.d.). This technique allows hybrid inverters to allocate energy optimally across solar, grid, and storage sources. Hybrid inverters include microcontroller-based intelligent scheduling functions that control power flow between the grid, solar array, and batteries. In grid-connected mode, the inverter adjusts its power output to match grid circumstances, returning surplus energy to the grid whenever possible. In the event of a grid breakdown, it instantly switches to off-grid mode within milliseconds, assuring continuous power supply to key loads.

Furthermore, hybrid inverters can participate in peak shaving and valley filling operations, which include removing energy from the grid during off-peak hours and delivering it during peak demand periods, decreasing system stress and electricity prices (Singh and Kaushik, 2020).
Throughout operation, the inverter continuously monitors system parameters like voltage, current, temperature, and battery state. Protection mechanisms include overvoltage and under voltage protection, overcurrent and short-circuit protection, over-temperature protection, and overcharge/deep-discharge prevention. If an irregularity is identified, the system isolates the damaged circuit and activates an alert or shutdown sequence to protect both the equipment and the linked loads. Data logging, remote monitoring, and fault diagnosis are all features of advanced models that use IoT interfaces (Hossain *et al*., 2017).

Table 2.2: Hybrid Inverter Operational Modes and Prioritization

Mode	Primary Function	Power Source Usage	Key Characteristics/Applications
Grid-Tied	Grid synchronization & power export.	Solar to home/grid.	Normal operation, net metering, reduces utility bills.
Off-Grid (Islanded)	Autonomous power supply.	Solar & battery to home.	Remote locations, complete energy independence, self-sufficient systems.
Battery Backup	Uninterrupted power during outages.	Battery to home.	Powers critical loads during blackouts, ensures power resiliency.
Solar Priority	Maximize solar self-consumption.	Solar first, then battery, then grid.	High electricity costs, abundant sunlight, eco-conscious users.
Battery Priority	Maximize battery usage.	Battery first, then solar, then grid.	Frequent outages, independent living, high-quality power supply.
Mains Priority	Maximize grid reliance.	Grid first, then solar/battery.	Stable grid, lower grid rates, solar as backup.

2.4 Core Components of Hybrid Inverter

A Hybrid Inverter is an intelligent device that is capable of solar plus storage. It integrates both functionality from both grid tied and off grid inverters that helps to manage energy flow from the solar panels, battery storage, the grid and the load in the house. The following are key components in the hybrid inverter:

Pulse Width Modulation (PWM) Charge Controller

Figure 2.1 PWM Charge Controller

This component regulates the charging of the battery bank from the solar panels. Instead of optimizing for maximum power, a PWM controller acts as a smart switch, connecting the solar array directly to the battery. It then rapidly switches the connection on and off, effectively reducing the average voltage from the panels to match the charging voltage required by the batteries (Anern, n.d.).

Unlike an MPPT controller, which adjusts the electrical operating point to extract the maximum available power, a PWM controller essentially "drops" the excess panel voltage as heat to align with the battery voltage (Tikkiwal et al., 2021). This results in lower overall energy harvest, especially in non-ideal conditions (e.g., cool, sunny days when panel voltage is high), but offers a cost-effective and reliable solution for smaller systems or warmer climates.

DC to AC Inverter (Converter)

Figure 2.2 DC-AC Converter

This is the core component that converts direct current (DC) electricity from the batteries (and potentially solar panels) into the alternating current (AC) electricity used by household appliances (Khare, 2019).

The conversion process itself often uses PWM techniques at a high frequency to synthesize a clean AC sine wave using power semiconductors like IGBTs (Texas Instruments, n.d.). The DC-to-AC inverter stage is distinct from the PWM charging stage.

Bidirectional Battery Charger/Converter (Rectifier Charger)

Figure 2.3 Rectifier Charger

This enables the inverter to charge the batteries from the AC grid. It converts grid AC power into DC power at the correct voltage and current for battery charging (Khan et al., 2018).

This rectifier function is crucial for a hybrid system, allowing the batteries to be charged from the grid when solar power is insufficient, such as at night or during cloudy weather (Boutaghane et al., 2025).

Digital Signal Processor (DSP)

Figure 2.4 DSP

The "brain" of the system is the Digital System Processor (DSP). It controls the bidirectional converter, the inverter's output, the PWM charging cycles, and safety features like disconnecting the grid. It controls how solar panels' DC is converted to AC for domestic use. (Agrawal et. al, 2025).

Since a PWM system does not require the use of complex algorithms to determine the maximum power point, its control logic is typically less complicated than that of an MPPT system. Its duty cycle modulation focusses on preserving the proper battery charging voltage.

Heat Sink

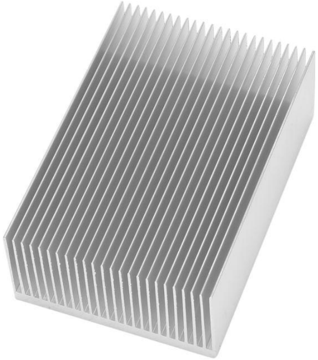

Figure 2.5 Heat Sink

It helps in dissipating the heat produced by the power stage of the hybrid inverter during PWM charging procedure as well as DC to AC conversion.

Because PWM controllers are less effective than MPPT controllers, a larger percentage of solar energy is transformed into heat, particularly when there is a significant voltage difference between the panel and the battery. For PWM-based systems, this makes proper fan cooling and heat sinking especially crucial (Texas Instruments, n.d.).

Transformer

Figure 2.6 Transformer

A transformer is a static device with no moving elements that transfers electrical power between circuits while varying the voltage and current while keeping the frequency constant usually between the range of 50 to 60Hz.

A step-down transformer is one that reduces voltage from primary to secondary by having fewer secondary winding turns than primary winding turns. A step-up transformer is one with more secondary winding turns than primary winding turns and boosts voltage from primary to secondary. The mutual induction theory underlies the operation of an electrical transformer. (Shubuham.L. et al)

Resistor

Figure 2.7 Resistor

A resistor is an electrical component that limits or regulates the flow of electrical current in an electronic circuit. Resistors can also be used to provide a specific voltage for an active device such as a transistor. All other factors being equal, in a direct-current (DC) circuit, the current through a resistor is inversely proportional to its resistance, and directly proportional to the voltage across it. This is the well-known Ohm's Law. In alternating-current (AC) circuits, this rule also applies as long as the resistor does not contain inductance or capacitance.

Resistors can be fabricated in a variety of ways. The most common type in electronic devices and systems is the carbon-composition resistor. Fine granulated carbon (graphite) is mixed with clay and hardened. The resistance depends on the proportion of carbon to clay; the higher this ratio, the lower the resistance. (Shubuham.L. et al)

Voltage Regulator IC 7812

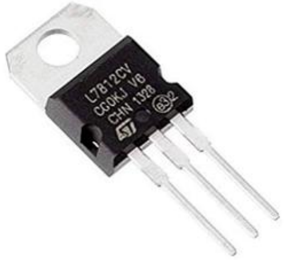

Figure 2.8 Voltage Regulator

7812 is a famous IC which is being widely used in 12V voltage regulator circuits. Truly speaking it is a complete standalone voltage regulator. We only need to use two capacitors, one on the input and second one on the output of 7812 in order to achieve clean voltage output and even these capacitors are optional to use. To achieve 12V 1A current, 7812 should be mounted on a good heat sink plate. Thanks to the transistor like shape of 7812 which makes it easy to mount on a heat sink plate. 7812 has built in over heat and short circuit protection which makes it a good choice for making power supplies. (Shubuham.L. et al)

MOSFET

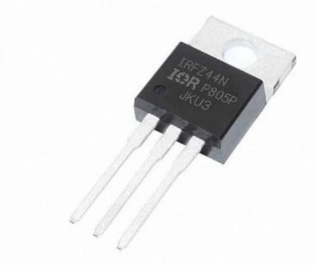

Figure 2.9 The MOSFET

MOSFET (metal-oxide semiconductor field-effect transistor) is a special type of field-effect transistor (FET) that works by electronically varying the width of a channel along which charge carriers (electrons or holes) flow. The wider the channel, the better the device conducts. The charge carriers enter the channel at the source, and exit via the drain. The width of the channel is controlled by the voltage on an electrode called the gate, which is located physically between the source and the drain and is insulated from the channel by an extremely thin layer of metal oxide.

The MOSFET has certain advantages over the conventional junction FET, or JFET. Because the gate is insulated electrically from the channel, no current flows between the gate and the channel, no matter what the gate voltage (as long as it does not become so great that it causes physical breakdown of the metallic oxide layer). Thus, the MOSFET has practically infinite impedance. This makes MOSFETs useful for power amplifiers. The devices are also well suited to high-speed switching applications. Some integrated circuits (ICs) contain tiny MOSFETs and are used in computers. (Shubuham.L. et al)

Transistor

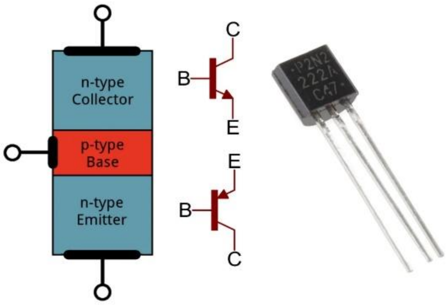

Figure 2.10 The Transistor

A transistor is a semiconductor device used to amplify or switch electronic signals and electrical power. It is composed of semiconductor material with at least three terminals for connection to an external circuit. A voltage or current applied to one pair of the transistor's terminals changes the current through another pair of terminals. Because the controlled (output) power can be higher than the controlling (input) power, a transistor can amplify a signal. Today, some transistors are packaged individually, but many more are found embedded in integrated circuits.

The essential usefulness of a transistor comes from its ability to use a small signal applied between one pair of its terminals to control a much larger signal at another pair of terminals. This property is called gain. It can produce a stronger output signal, a voltage or current, which is proportional to a weaker input signal; that is, it can act as an amplifier. Alternatively, the transistor can be used to turn current on or off in a circuit as an electrically controlled switch, where the amount of current is determined by other circuit elements. (Shubuham.L. et al)

Capacitor

Figure 2.11 The Capacitor

A capacitor is a tool consisting of two conductive plates, each of which hosts an opposite charge. These plates are separated by a dielectric or other form of insulator, which helps them maintain an electric charge. There are several types of insulators used in capacitors. Examples include ceramic, polyester, tantalum air, and polystyrene. Other common capacitor insulators include air, paper, and plastic. Each effectively prevents the plates from touching each other. A capacitor is often used to store analogue signals and digital data. Another type of capacitor is used in the telecommunications equipment industry.

This type of capacitor is able to adjust the frequency and tuning of telecommunications equipment and is often referred to a variable capacitor. A capacitor is also ideal for storing an electron. A capacitor cannot, however, make electrons. A capacitor measures in voltage, which differs on each of the two interior plates. Both plates of the capacitor are charged, but the current flows in opposite directions. A capacitor contains 1.5 volts, which is the same voltage found in a common AA battery. As voltage is used in a capacitor, one of the two plates becomes filled with a steady flow of current. At the same time, the current flows away from the other plate. To understand the flow of voltage in a capacitor, it is helpful to look at naturally occurring examples. Lightning, for example, is similar to a capacitor. The cloud represents one of the plates and the ground represents the other. The lightning is the charging factor moving between the ground and the cloud. (Shubuham.L. et al)

2.5 Charge Controller

A charge controller, commonly referred to as a solar charge regulator, is a vital electrical component in photovoltaic (PV) and hybrid inverter systems. It regulates the voltage and current from the solar panels to the battery bank, preventing overcharging, over discharge, and battery damage. Essentially, it serves as a link between the solar array and the storage system, enabling secure and efficient energy transfer.

The basic function of a charge controller is to keep the battery voltage within a safe range. When solar panels create power, the voltage varies according to the intensity of the sunshine. The charge controller regulates this energy before it reaches the battery. According to Masters (2013), the charge controller "prevents excessive battery charging by limiting the rate of current flow into the battery and disconnecting the charging source when the voltage reaches the set level." This ensures that the battery's lifespan is increased while maintaining optimal performance.

When sunlight touches the solar panels, it generates direct current (DC). The charge controller monitors this flow and modifies it based on the battery's state of charge (SOC). We have three phase which are:

Bulk Charging Phase: When the battery is severely drained, the controller permits the maximum current to charge quickly.

Absorption Phase: As the battery nears full charge, the controller decreases current to avoid overcharging.

Float Phase: The controller keeps the battery fully charged by giving only enough current to offset self-discharge losses.

These charging stages ensure that the battery performs efficiently while also preventing gassing and thermal runaway (Kalogirou, 2014).

We have two basic types of Charge controllers which are the MPPT (Maximum Power Point Tracking Charge Controller and the PWM (Pulse Width Modulation) Charge controller.

2.6 MPPT Charge Controller (Maximum Power Point Tracking)

The MPPT is a power electronic device used to improve the efficiency of the solar panel. They are capable of extracting a much higher percentage of the available power from the solar panel, compared to PWM controllers. It is an electronic tracking controller that looks at the output of the panels and compares it to the battery voltage. It then figures out what the best power that the panel can put out to charge the battery. It takes and converts it to the best voltage to get maximum AMPS into the battery (Deepika.S. et al, 2021)

Figure 2.12 MPPT Controller

How does the MPPT Controller work?

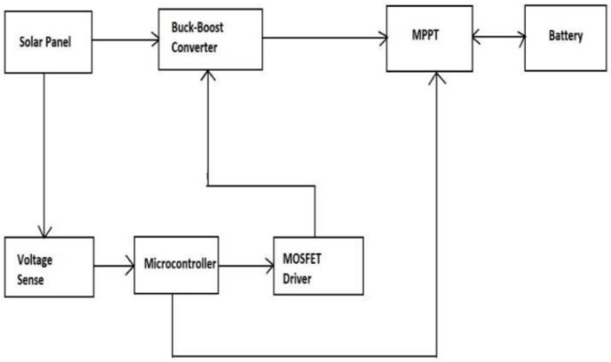

Figure 2.13 Block Diagram of the workings of the MPPT controller

This is where maximum power point tracking, also known as optimization, is useful. Let's say your battery is 12V. The battery receives 10.8 amps at 12 volts after an MPPT reduces the 17.6V at 7.4 amps. Everyone is happy now that you still have nearly 130 watts. A higher voltage must be supplied to the battery in order to force the amps in, even though 11.3 amps at 11.5 volts is the ideal power conversion. This is an oversimplified explanation; in reality, the MPPT charge controller's output may fluctuate continuously to ensure that the battery receives the maximum amount of amps. (Deepika.S. et al, 2021)

The advantages of the MPPT charge controller are outlined below:

1. They offer an increase in efficiency of up to 30% (Tulika Majaw et al., 2018).
2. MPPT charge controllers are used to correct the variations in the I-V characteristics of the PV cell.

It has these shortcomings though:

1. MPPT charge controllers are more expensive.
2. Generally, they are larger in size.

2.7 PWM Charge Controller (Pulse Width Modulation)

A PWM charge controller controls the average current flowing into the battery by using pulses. When the battery level is low, the pulse is turned on for a higher percentage of the time than it is off (high duty cycle). When the battery approaches full voltage however, the average current is reduced. The purpose of this is to allow the battery to be fully charged with less stress applied to it.

Tulika Majaw et al (2018) gives these benefits for the PWM charge controller.

1. Reduces battery heating and gassing.
2. Maximum high average battery capacities.
3. Equalization of battery cells.
4. Automatic adjustment for battery aging.

Its disadvantages though are:

1. PWM controllers possess limited capacity for system growth.
2. They cannot be used effectively with 60A panels.

Table 2.3: Comparison between PWM (Pulse Width Modulation) Controller and MPPT (Maximum Power Point Tracking) Controller

Feature	**PWM (Pulse Width Modulation) Controller**	**MPPT (Max. Power Point Tracking) Controller**
Basic Function	Connects solar array directly	Acts as a "smart DC-DC

	to battery, switching on/off to regulate voltage.	converter" to find the optimal power point.
Efficiency	Lower (typically 70-80%). Energy above battery voltage is lost as heat.	Higher (typically 93-97%). Harvests significantly more energy.
Cost	Lower component cost, making the inverter more affordable.	Higher component cost, increasing the inverter's price.
System Voltage	Solar array voltage must closely match battery voltage.	Solar array can have a higher voltage than the battery bank.
Best For	Smaller systems, warm climates, cost-sensitive applications.	Larger systems, areas with cloudy/cool weather, maximizing Rate of Investments

CHAPTER THREE

METHODOLOGY

3.1 Design Consideration and Analysis

In this Chapter, we are looking at the internal components of the hybrid inverter and their functions, drawbacks and compare it with other product and see how these drawbacks can be worked on to further increase the efficiency of the hybrid inverter.

There are some test and important facts to take into consideration that before disassembling the inverter:

- **Inspection:** Before electrical testing, perform a visual check to ensure that the unit is safe for power up. The visual inspection comprises of proper check of loose terminals, poor solder joint or damaged insulation part.
- **Polarity Test**: There are some hybrid inverters that do not have polarity displacement protection and this makes other inverters more expensive than others. We make use of a Multimeters to check for polarity test. We put the multimeter on Transistor reading, the value kept rising even when the polarity was reversed. Thus, the inverter does not have polarity displacement protection.
- **Cable Sizing:** Cable sizing is very important for every electrical installation. The right cable should be used because it can lead to tripping off, overstressing or burn out the hybrid inverter system.
- **No Load Test:** This test is carried out to check the basic functionality of the hybrid inverter before we disassemble it for reverse engineering processes. We measure the AC output voltage and the frequency of the hybrid inverter.
- **DC Test:** We perform a DC test to verify the hybrid inverter response to solar and battery input conditions. We make use of a multimeter to measure the DC voltage and current to confirm if they are within specified operating range.
- **Load Test:** We carry out load test to check for the hybrid inverter efficiency, voltage regulation and thermal performance under various kinds of loads. These loads may be resistive and inductive.

3.2 Components and Photographic image of the Hybrid Inverter

The Hybrid Inverter that was purchased for this project was a PWM (Pulse Width Modulation) Low Frequency Inverter. It comprises of three stages which are the:

1. Oscillating Stage
2. Power Stage
3. Transformer Stage

3.2.1 Oscillating Stage

The oscillating stage functions as the inverter's signal generating and control part. It transforms the steady 24 V DC input into a pulsating square-wave or modified sine-wave signal with a predetermined frequency (often 50 Hz). During deconstruction, this level was discovered to contain PWM control ICs, crystal oscillators, driver transistors, and logic circuits. The oscillation frequency in this inverter was controlled by a control chip (possibly UC3843 or comparable), which was backed up by timing resistors and capacitors.

It Generates pulse width switching pulses (PWM signals) that drive the gate of MOSFETs during the power stage. It simulates an AC waveform by maintaining an output frequency of approximately 50 Hz and controlling the duty cycle. It Provides phase-shifted signals to different MOSFET pairs for push-pull or H-bridge operation. It stabilizes voltage by incorporating feedback control from the output stage.

3.2.2 Power Stage

This part switches and amplifies the low-voltage PWM signal to produce a high-current AC waveform. The power stage of the P2.5 inverter was designed with high-current N-channel MOSFETs (IRFP150N type) placed in a push-pull configuration, which switched the DC input across the transformer's primary winding. It functions as a DC-AC converter, driving the transformer primary with alternating current. It amplifies the oscillator's control pulses to handle high currents (up to 60 A).

3.2.3 Transformer Stage

The transformer stage is where the output energy is converted and isolated. The device converts the MOSFET bridge's low AC voltage (about 24 V AC) to the needed 220 V AC output and provides galvanic isolation between the battery and AC load. The P2.5, use a ferrite-core or laminated iron transformer that operates directly at 50/60 Hz.

It Increases the voltage from low-level AC to grid-compatible 220 V AC. It isolates the DC input and AC output for safety. It filters and smoothes the PWM output to produce a quasi-sine waveform.

The PWM low frequency inverter is made up of different components which are:

- Heat Sinks
- Capacitors (Polarized and Non Polarized types)
- Mosfets (H- Bridge)
- Cooling Fans
- PWM Microcontroller
- Voltage Regulator
- Diodes
- Resistors
- Relays
- Fuse (Circuit Breaker)
- Transistor
- Transformer
- Buzzer
- LED

3.3 Functions of the Components in the Inverter

Heat Sinks: It absorb and dissipate heat generated by power components (like MOSFETs, diodes, or voltage regulators) to prevent overheating. It also keeps the MOSFETs and IGBTs within safe operating temperatures during high current switching.

Capacitors: We have the polarized and un-polarized type. The polarized type helps store and smooth DC voltage; used in DC bus filtering and energy storage after rectification and the un-polarized type is used for noise suppression and signal coupling in control circuits.

Mosfets (H Bridge): It act as high-speed electronic switches to convert DC into AC by alternating current direction in the load. Four MOSFETs form an H-bridge, controlled by PWM signals to create alternating output voltage.

Cooling Fans: It Enhance air circulation to remove excess heat from components and heat sinks. It ensures continuous operation without thermal shutdown.

PWM Microcontroller: It generates precise Pulse-Width Modulation (PWM) signals to control MOSFET switching. It serves as the “brain” of the inverter, managing voltage regulation, switching sequence, and protection functions.

Voltage Regulator: It maintains stable supply voltage for the control circuit and microcontroller. It steps down and regulates the DC voltage (e.g., from 24 V to 5 V or 12 V) for logic circuits.

Diodes: It Limit current, divide voltage, and bias transistors or MOSFET gates. It Control gate drive current, sense voltage, and form part of feedback or protection circuits.

Fuses (Circuit Breaker): It protects against overcurrent and short-circuit conditions by breaking the circuit. It Prevents damage to components and wiring during faults in the inverter.

Relay: It switch between mains supply and inverter output.

Transistor: It is often used in gate driver circuits or signal amplification for PWM control.

Transformer: It converts DC (after H-bridge) to high-voltage AC (e.g., 12 V - 230 V).

Buzzer: It provides audible alerts for fault, low-battery, or overload conditions.

LED: It indicates operational status (power on, charging, fault, overload, etc.).

Below are photographic images of the internal and external components of the hybrid inverter:

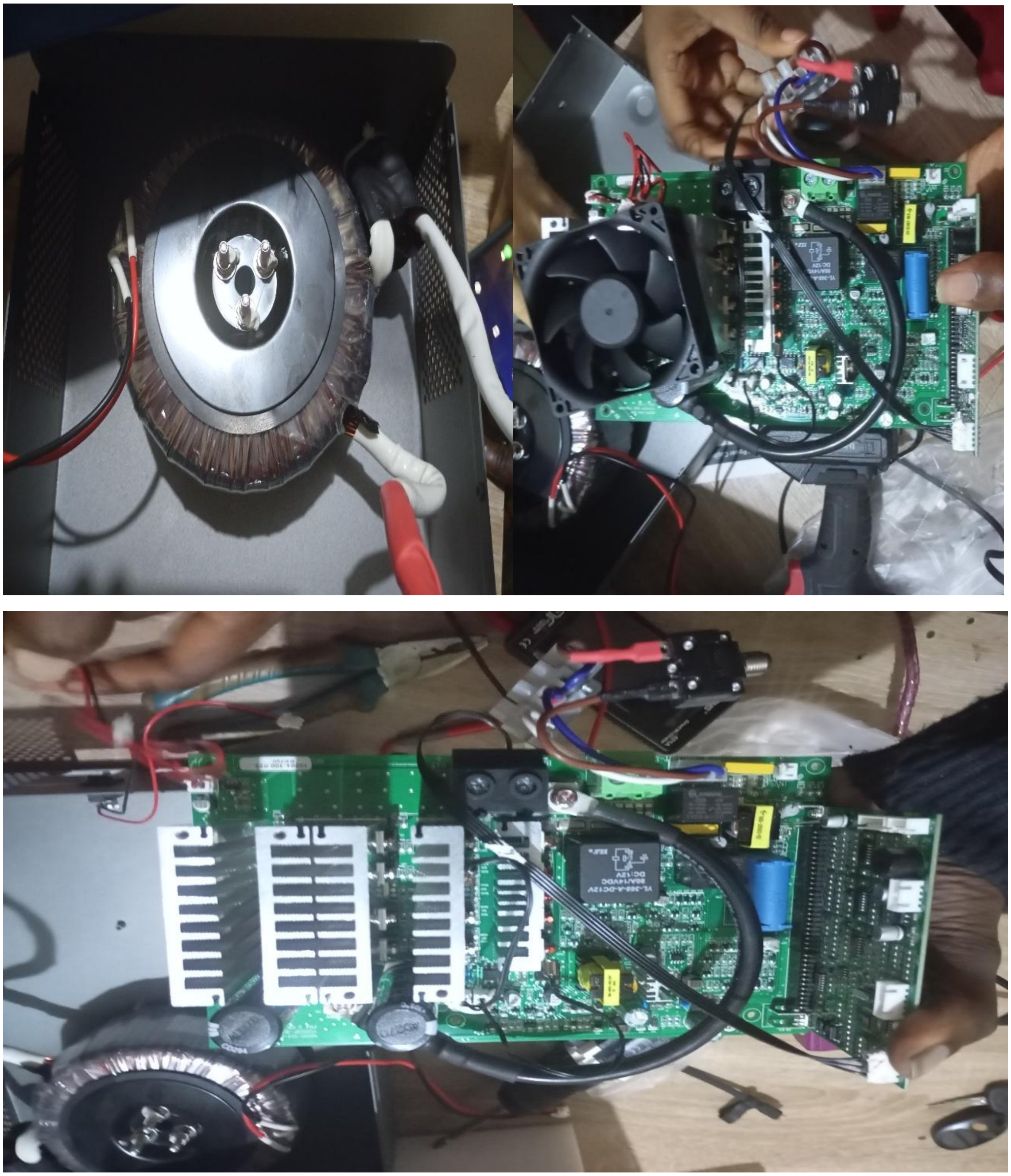

Figure 3.1 Internal Components of the PWM Hybrid Inverter

3.4 No Load Test

For this Inverter, we carried out a No load test where we used two 12 Volts battery connected in series to give us 24 Volts in total. The measured value of the battery in the multimeter was 24.84 Volts. We made use of the multimeter for this test. Below was the measured value:

Output Voltage: 220 V

Frequency: 49.99Hz

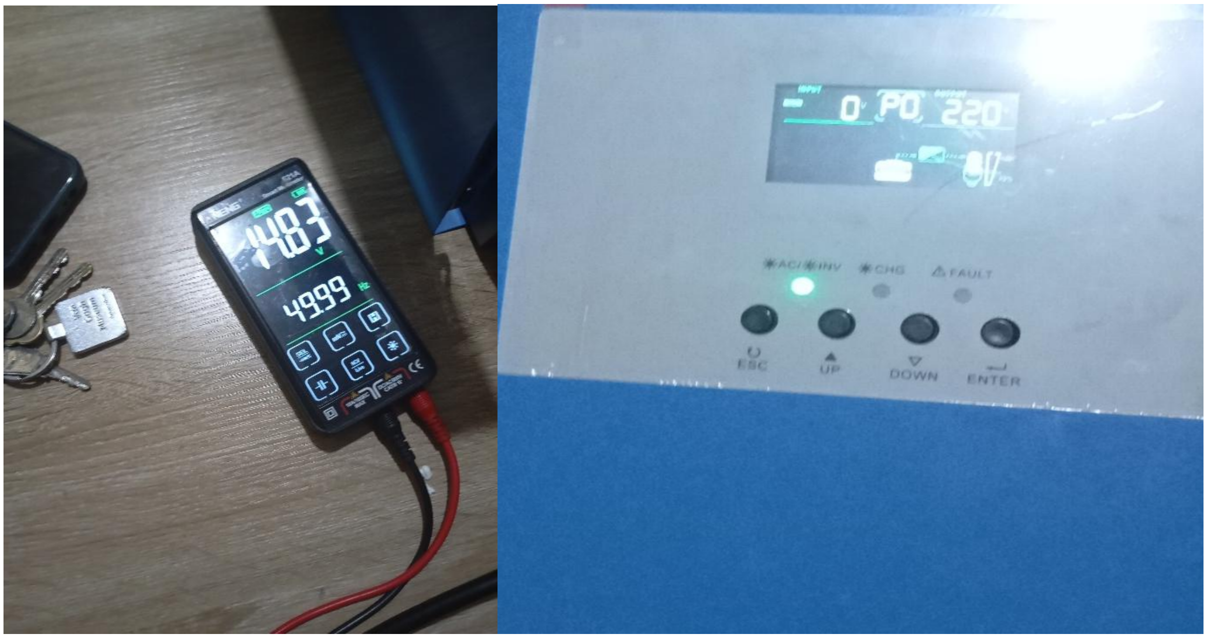

Figure 3.2 No – Load Test

3.5 Reverse Polarity Test

Here, we carried a reverse polarity test on the hybrid inverter, we set our multimeter on transistor reading, the transistor value kept on increasing and did not drop even when the polarity was reversed. This indicates that the inverter does not have polarity displacement protection.

3.7 PCB Tracking

Here, we traced all the copper conductive track or pathways for electronic signals for all the components to ensure that none of the tracking was burnt out. After going through most of the track, we found out that all the tracks were functional and none was burnt out.

3.8 Comparison of the PWM Inverter with MPPT types of Inverter

Table 3.1 Comparison of the PWM Inverter and MPPT Inverter

Feature	Our PWM LF Inverter (Model P2.5)	Typical MPPT Hybrid Inverter (e.g., Victron or Growatt 3 kW)
Rated Power	2500 VA (~2000 W)	3000 W (≈ 3 kVA)
Battery System	24 V DC	24 V DC / 48 V DC
PV Input Range (Vmp)	30 – 80 VDC	120 – 450 VDC (Vmp window)
Max PV Voc	110 VDC	500 – 600 VDC
Charger Type	PWM (on/off switching ≈ battery voltage)	MPPT (DC-DC converter adjusts to maximum power point)
Charging Efficiency	≈ 75 – 85 % (typical)	≈ 97 – 99 % (typical)
Energy Harvest from PV	Lower, especially when PV Vmp ≫ battery voltage	Higher, optimized under variable irradiance
Weight / Design	Heavy (transformer-based, low frequency)	Light (high-frequency switching, no large transformer)
Surge Capability	Excellent (2–3× rated load)	Moderate (1.2–1.5× rated load)
Ideal Application	Off-grid homes, motor loads, robust environments	Solar PV systems seeking maximum harvest & efficiency
Maintenance	Simpler but less efficient	More complex but efficient

		and flexible

CHAPTER 4
RESULTS AND ANALYSIS

4.1 Specification of the Inverter

Model: P2.5

Capacity: 2500VA

DC Input: 24VDC

AC Input: 220VAC, 50/60Hz

Solar Charge Mode: PWM-24

Rated Current: 60A

Best Vmp (Voltage at Maximum Power) Range: 30-40VDC

Operating Voltage Range: 30-105VDC

Maximum Solar Voltage (VOC): 105VDC

4.4.1 Calculation for DC Input Current

For this inverter, we will assume that it will supply 2500VA at a power factor of 0.8.

$$Output\ Power\ (KW) = Power(KVA)\ \times Cos\o \ldots\ldots \quad (4.1)$$

Where:

Power (KVA) = 2500VA

Cos ø = 0.8

$$Output\ Power\ (KW) = 2500 \times 0.8 = 2000W = 2.0KW$$

Now, we need to get the input power of the hybrid inverter. So we will assume an efficiency of 80%

$$DC\ Input\ Power = \frac{Output\ Power}{\eta} \ldots\ldots \quad (4.2)$$

Where;

Output Power = 2500W

Efficiency (η) = 0.80

$$DC\ Input\ power = \frac{2000}{0.80} = 2500W$$

$$DC\ Input\ Current = \frac{DC\ Input\ Power}{DC\ Voltage} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.3)$$

Where;

DC Input Power = 2500W
DC Voltage: 24V

So;

$$DC\ Input\ Current = \frac{2500}{24} = 104.16A$$

Thus, at full rated load (2500W) and an efficiency of 80%, the inverter draws a current of 104.16A from a 24V battery.

4.4.2 Calculation for Battery Amps – Hours

We need to calculate the battery amps – hours to achieve desired run time. The selection of the right battery is required. For Battery sizing, we always account for the Depth of Discharge (DoD). For Example, for Lead – Acid Battery, we allow a 50% DoD and for Lithium Battery, we allow a DoD of about 80-90%.

The formula for calculating the required battery in Ah is given below;

$$Required\ Battery\ (Ah) = \frac{\mathrm{Pin} \times \mathrm{thr}}{DC\ Voltage} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

Where;

Runtime (thr) = 1hrs

Power input (Pin) = 2500W

$$Required\ Battery\ (Ah) = \frac{2500 \times 1}{24} = 104.16 \approx 104Ah$$

So, dependent on the kind of battery being used, we will have to apply the DoD on the Required Battery in amps – hours. The formula for this is given below;

$$Required\ Battery\ Bank\ Capacity(Ah) = \frac{Unadjusted\ Ah}{DoD} \text{ .... (4.5)}$$

Which is:

Unadjusted Ah = 104Ah

DoD = 0.50

$$Required\ Battery\ Bank\ Capacity\ (Ah) = \frac{104}{0.50} = 208Ah$$

Base on the battery capacity, lets subject it to a load of 1000W and see how long the battery will last. We will be using a 24 V system;

$$Total\ Battery\ Power = 208 \times 24 = 4992Wh$$

So we will account for the inverter efficiency, we will use 80%

$$Usable\ Energy = 4992 \times 0.80 = 3993.6 \approx 3994Wh$$

So, we will account for Depth of Discharge. We will use DoD as 50%

$$Usable\ Energy\ (at\ 50\%\ DoD) = 3994 \times 0.50 = 1997Wh$$

We will then calculate the runtime where we will divide the usable energy by the load in Watts.

$$Runtime = \frac{1997}{1000} = 1.997 \approx 2hrs$$

Thus, the battery will last for 2 hours if subjected to a 1000W load.

4.4.3 Calculation for Maximum Charging Power from the Internal Charger

The Formula for calculating maximum charging power is given as:

$$Charger\ Output\ Power\ (\text{Pchg}) = Voltage\ (Battery) \times Current\ (Charger) \text{........... (4.6)}$$

Where:

Voltage (Battery) = 24V

Current (Charger) = 60A

So,

$$Charger\ Output\ Power\ (Pchg) = 24 \times 60 = 1440W$$

4.4.4 Calculation for PV Array Current

The Charger is PWM. The PV array must provide voltage near voltage battery for effective charging. The label on the inverter gives a Vmp range of 30 – 40V. We will choose a typical Vmp for a 24V system. Many 24 V systems use panel strings with Vmp of 36-40 V (e.g., two 12-V panels in series). We will calculate Vmp = 36 V.

$$PV\ Current\ at\ Vmp, I = \frac{Charger\ Output\ Power\ (Pchg)}{Maximum\ Power\ Voltage\ (Vmp)} \text{................................... (4.7)}$$

Where:

Charger Output Power (Pchg) = 1440W

Maximum Power Voltage (Vmp) = 36 V

$$PV\ Current\ at\ Vmp, I = \frac{1440}{36} = 40A$$

To achieve full 60 A charging at 24 V using PWM, the PV array needs supply approximately 40 A at 36 V. Because PWM essentially restricts the PV to near-battery voltage (without a diode/drop), MPPT would allow larger PV voltages and convert them to higher current more efficiently — but your unit uses PWM.

4.4.5 PV String Sizing

The maximum solar voltage was 105V. So, we must ensure that the voltage of the open circuit voltage does not exceed 105 V. The number of panels you can put in series depends on the on the panel Voc.

Here, we are going to use a 36 Cell Small panel where the Voc is approximately 22V.

$$Maximum\ Series\ Panel = \frac{105}{22} = 4.7727 \approx 5\ Panels$$

$$Solar\ Voltage = 22 \times 5 = 110V$$

The value above exceeds 105V. so we will make use of 4 which will give us 88V. Hence, we will make use a 4 series panel.

4.4.6 PV Array Capability

From the Inverter data we are given:

Rated PV current = 60A

Best Vmp = 30-40V

Max PV Vov = 105V

Using Vmp = 35V

$$PV\ Power\ Limit = Vmp \times Rated\ PV\ current \ldots\ldots (4.8)$$

$$PV\ Power\ Limit = 60 \times 35 = 2100W$$

So, the inverter's PWM charge controller can handle about 2.1 kW of solar input well matched to the 2.0 kW AC output.

From these calculations with PF = 0.8 and efficiency = 0.8, your 2.5 kVA PWM inverter can deliver around 2.0 kW AC. To support this load, the inverter requires around 104 A DC from the 24 V battery. To operate for one hour, a 208 Ah (lead-acid, 50% DoD) is required. The PV side can handle up to 2.1 kW and has a maximum voltage of 105 V. Energy losses from PWM regulation diminish solar efficiency by about 25% when compared to MPPT systems. Under identical settings, a 24 V MPPT inverter outperforms the PWM model by around 20-25% in terms of long-term performance and energy yield.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Summary

This project focused on the design, analysis, and reverse engineering of a Pulse Width Modulation (PWM) Low-Frequency Inverter, which converts direct current (DC) from a battery source to alternating current (AC) suited for home and industrial applications. The study was separated into three functional sections: oscillation stage, power stage, and transformer stage. The oscillating stage used a microprocessor to provide PWM control signals, resulting in a consistent switching pattern. The power stage, which consisted of MOSFETs grouped in an H-bridge design, amplified the DC signal and converted it to pulsed AC. The transformer stage then increased the low-voltage AC to the appropriate mains voltage (e.g., 220V AC).

The inverter's control logic was developed to achieve efficient power conversion while minimizing distortion and increasing dependability. During testing, the inverter successfully generated a near-sinusoidal AC output waveform, demonstrating efficient switching control and voltage regulation. Supporting components such as heat sinks, diodes, capacitors, and a voltage regulator provided stability, protection, and constant performance under varied load situations.

Overall, the project met its key goals of designing and understanding the functional functioning of a PWM-controlled inverter system, evaluating its performance, and identifying practical improvements for future development.

5.2 Conclusion

The PWM (Pulse Width Modulation) low-frequency inverter has shown to be a successful and dependable device for converting DC power into AC power while providing improved control, efficiency, and performance. Reverse engineering and study revealed that the inverter's architecture has three major stages: the oscillation stage, the power stage, and the transformer stage, each of which is critical to the entire operation. The oscillation stage creates the PWM signal that controls the switching sequence of the MOSFETs in the H-bridge circuit, allowing for accurate voltage and frequency control. The power stage converts this low-level signal into a high-current output capable of driving loads, while the transformer stage isolates and transforms the voltage, resulting in a safe and stable AC output.

The inverter's low-frequency design ensures reliable operation, large surge capacity, and compatibility with inductive loads such as motors and compressors. It is, however, larger and less efficient than high-frequency inverters due to the size of the transformer and accompanying magnetic losses. Despite this, the PWM approach considerably improves waveform quality, lowers harmonics, and increases overall system efficiency and stability. To summarize, the PWM low-frequency inverter successfully strikes a compromise between control flexibility, durability, and power reliability, making it ideal for off-grid, renewable energy, and backup power applications.

5.3 Recommendation

- **Improve Efficiency through Component Optimization:** Use MOSFETs or IGBTs with lower switching losses and faster recovery diodes to enhance overall conversion efficiency.
- **Integrate MPPT Technology:** Combining PWM control with MPPT (Maximum Power Point Tracking) could optimize solar energy utilization, especially in photovoltaic systems.
- **Enhance Cooling and Protection Systems:** Effective heat sinks, cooling fans, and thermal sensors should be included to prevent overheating and prolong component lifespan.
- **Employ Digital Control Systems:** Upgrading to microcontroller- or DSP-based control will allow real-time monitoring, fault detection, and adaptive modulation strategies.
- **Reduce Transformer Size and Losses:** Consider using ferrite core materials or higher switching frequencies (where possible) to minimize core losses and overall system weight.
- **Conduct Regular Maintenance and Testing:** Periodic inspection of components such as capacitors, relays, and fuses ensures reliable and long-term performance.
- **Compliance with Standards:** Ensure the inverter design complies with IEC, IEEE, or local grid standards to maintain safety, reliability, and interoperability.

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