Chapter 3: Methodology

3.1 Conceptual Framework

The following chapter represents the research methodology, including the conceptual framework and design procedure, that was implemented in order to accomplish the objectives of the study.

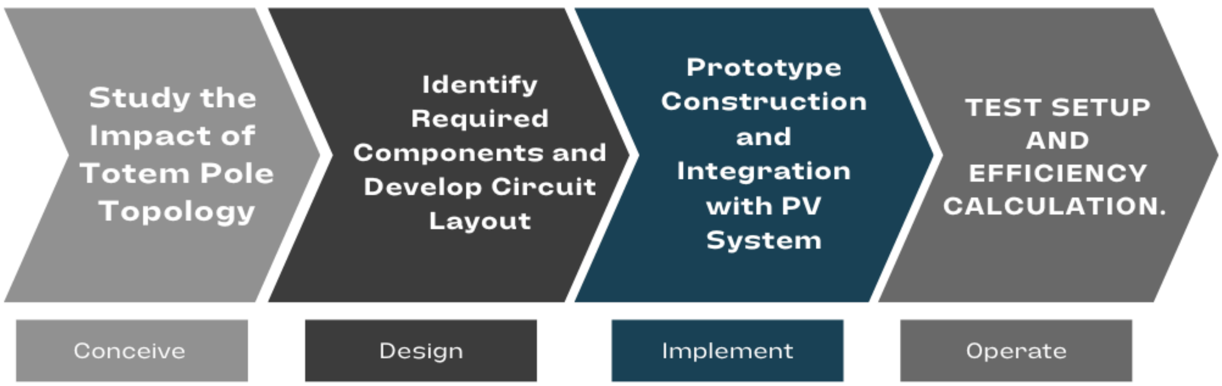

Figure 3.1 - Conceptual Framework

The conceptual framework was presented in Figure 3.1, it follows the Conceive-Design-Implement-Operate or CDIO model, indicating the relevant components in completing the capstone project.

The **Conceive** part of the study outlined how the researchers arrived at their study design considerations. The focus is on the design of the totem pole topology specifically tailored for a unidirectional inverter. This involves a thorough exploration of the theoretical foundations and design principles underlying the totem pole topology. The primary objective was to understand how this topology can be optimized to reduce switching losses and conduction losses to aim for

95 - 99% efficiency. By analyzing existing models and literature, key parameters and potential configurations are identified to form the basis of the design..

The **Design** part consists of design requirements including materials and components that are carefully selected by the researchers. Once the conceptual framework was established the next stage involves identifying the required components and developing the circuit layout. This includes selecting appropriate MOSFETs, control circuits, and passive elements for use in the inverter. The circuit layout is developed according to the design specifications to ensure it meets the desired performance criteria. This stage also involves simulations and theoretical validation of the circuit design to predict its behavior and efficiency.

In the **Implementation** part, the focus shifts to the physical construction of the inverter prototype. The circuit layout developed in the design stage was now assembled and the various components are integrated. This involved the careful assembly of the inverter ensuring that all connections are secure and that the design specifications are followed. Additionally, the inverter was integrated with existing photovoltaic (PV) system components including solar panels, solar charge controller, batteries, and boost converter, to form a complete and functional unit.

The **Operate** part involves setting up the test environment to evaluate the performance and efficiency of the inverter. This includes establishing a controlled testing setup where the inverter's functionality can be thoroughly tested. Efficiency calculations are conducted to assess how effectively the totem pole topology reduces losses and enhances overall system efficiency. Continuous monitoring is performed and any necessary adjustments are made to optimize the inverter's performance. The results of these tests provide essential feedback that would be used to refine the design further.

3.2 Design Parameters and Calculations

Designing the totem pole inverter involved defining key electrical parameters and performing calculations to meet functional, performance, and efficiency goals. The process began with an understanding of the Totem Pole Topology, known for its reduced losses and improved performance.

Detailed calculations determined specifications for components like resistors, inductors, and capacitors, ensuring alignment between theoretical designs and practical applications. These efforts established the foundation for a reliable and efficient inverter system, with the subsections detailing system requirements, component calculations, and the rationale behind each design choice.

3.2.1 System Requirements

The system requirements for the totem pole inverter were defined to ensure functionality, performance, and efficiency, guiding the selection of components and the overall design process.

The **400V DC input voltage** is a typical value for inverters using Totem Pole Topology, ensuring efficient operation by minimizing current levels and reducing conduction losses. In this project the 400V DC was derived from photovoltaic (PV) panels and achieved through a boost converter providing the high input voltage necessary for effective DC-AC conversion.

The inverter's **220V-240V AC output at 60Hz** was tailored to the requirements of the **½ HP (373W) electric motor, the** primary load. This load specification influenced the sizing of components to ensure reliable performance and sufficient power delivery.

A target efficiency of **95%-99%** minimized energy losses, achieved through the selection of advanced MOSFETs, active gate drivers, and optimized switching techniques. The **operating frequency** further influenced the sizing of passive components, such as the inductor and capacitor, to handle ripple currents while reducing switching losses.

By aligning these interdependent parameters with Totem Pole Topology principles, the design achieved a balance of high performance, efficiency, and reliability, meeting the specific demands of the intended application.

Table 3.1 - Summary of Constant Values for the Design

Parameter	**Value**	**Remarks**
Input Voltage	400V DC	Derived from DC source.
Output Voltage	220V-240V AC	Suitable for motor load.
Frequency	60Hz	Standard for motor operation.
Load Power	½ HP (373W)	Electric motor.
Efficiency	95%-99%	Target performance.

These specifications define the operating parameters and guide the selection of components such as MOSFETs, inductors, and capacitors, ensuring the inverter meets both performance and reliability standards.

3.2.1.1 Other Parameter Considerations

The following design criteria were considered to further refine the inverter design ensuring optimal performance and efficiency across varying operational conditions. These parameters guided the selection of switching frequency, control methods, power factor, Total Harmonic Distortion (THD), and switching devices.

Table 3.2 - Design Criteria for Other Parameters Considerations

Specification	Requirement
Switching Frequency	The switching frequency was typically chosen to optimize efficiency and reduce component stress.
	● Ideal: 10kHz (aligned with motor control and component selection).
	● Accepted range: 5kHz-20kHz. Higher frequencies reduced filter size but might have increased switching losses.
Power Factor	The power factor should have been as close to 1 as possible to ensure efficient energy transfer and minimize reactive power.
	● Ideal: ≥ 0.95. A value closer to 1 was preferred for efficient operation, especially for motor drives.
THD (Total Harmonic Distortion)	THD should have been minimized to reduce harmonics that could interfere with other equipment and cause heating in the motor.
	● Ideal: $< 5\%$ for high-quality power delivery.

Current Ripple($\triangle I$)	Current ripple should have been minimized to avoid excessive heating, reduce stress on components, and ensure smooth motor operation.
	● Ideal: < 20% of the rated current for optimized motor performance and component lifespan.
	● Accepted range: 10%-20%. Higher values might have been acceptable in specific low-stress applications.
Control Method	The control method should have been effective in maintaining stability and performance while minimizing losses.
	● Ideal: Sine-wave PWM or space-vector PWM for smooth output and reduced harmonics.
	● Accepted: Any PWM method that ensured stable control with minimal THD.
Switching Devices	The choice of switching devices affected the efficiency, switching losses, and thermal performance.
	● Ideal: SiC MOSFETs, offering high efficiency, high-speed switching, and low conduction losses.
	● Accepted: MOSFETs with low R_DS(on) and capable of handling high voltages and currents for efficient operation.

These criteria were critical in ensuring that the inverter not only performed according to specifications but also operated reliably and efficiently under the intended operating conditions.

3.2.2 Calculation of Design Parameters

The design of the system components such as the photovoltaic panels, battery, inductor, and capacitor requires a set of essential calculations to ensure optimal performance. Below is a detailed theoretical computation for each component in base formulas, with the parameters left general.

3.2.2.1 Transient Power Requirement

To design the system, we start by calculating the transient power based on the motor load rating. The transient power calculation established the inverter's capacity to handle power surges, which were critical when starting electric motors or dealing with transient loads.

$$P_{Transient} = P_{load} \times F_{safety}$$

Where:

P_{load} : Rated power of the electric motor.

F_{safety} : Safety factor accounting for transients = 7.

This calculation helped in choosing an inverter with sufficient capacity to handle transient loads while maintaining a safety margin.

3.2.2.2 Output Current

The output current (I_0) was calculated using the relationship between the output power and the output voltage. The equation used was:

$$I_O = \frac{P_O}{V_0}$$

where P_O represented the output power, and V_0 denoted the output voltage. This calculation was essential to determine the current requirements of the system and ensured that the inverter could supply the necessary current to the motor under operational conditions.

3.2.2.3 Maximum current ripple

The maximum current ripple (ΔI_{ppmax}), was determined to evaluate the inverter's capability to handle variations in current during operation. The formula used was:

$$\Delta I_{ppmax} = \Delta I \times I_O \times \sqrt{2}$$

where ΔI referred to the current ripple factor and I_O was the output current. This analysis was critical in ensuring that the current ripple remained within acceptable limits to prevent excessive heating and to maintain system efficiency and reliability.

3.2.2.4 Inductance Value Calculation (L):

The inductance determines the energy storage and influences the current ripple in the inverter. The inductance is calculated as:

$$Inductor = L = \frac{V_{DC}}{4 \times fsw \times \Delta I_{ppmax}}$$

Where:

- V_{DC} is the DC voltage,
- fsw is the switching frequency,
- ΔI_{ppmax} is the maximum peak-to-peak current ripple.

3.2.2.5 Capacitance Value Calculation (C):

The capacitance value influences the voltage ripple and is calculated based on the switching frequency and inductance:

$$Capacitance = C = \left(\frac{10}{2 \times \pi \times fsw}\right)^2 \left(\frac{1}{L}\right)$$

Where:

fsw is the switching frequency.

L is the inductance value.

Using these base formulas, the system components (inverter, photovoltaic panels, battery, solar charge controller, inductor, and capacitor) are designed to ensure reliable and efficient operation under both steady-state and transient conditions.

3.3 Simulation Design

Simulation was an important step in designing and validating the Unidirectional Totem Pole Inverter. This section explains the process used to set up the simulation environment, analyze results, and fine-tune the inverter's performance based on the findings.

3.3.1 Simulation Process

The circuit simulation started by choosing a suitable tool like MATLAB/Simulink known for its ability to model power electronics and control systems. The following steps were followed to design the simulation:

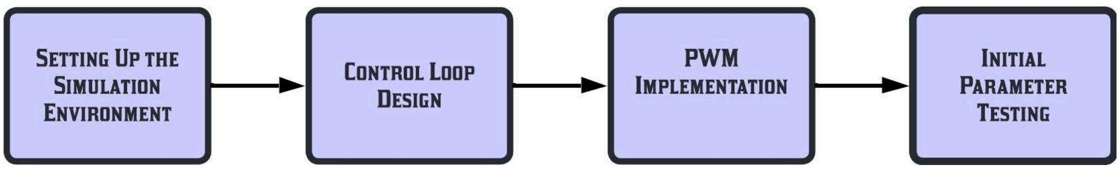

Figure 3.3 - Simulation Process Design Flow

3.3.1.1 Setting Up the Simulation Environment

The simulation environment was set up by configuring solver settings, time steps, and simulation duration to match the inverter's behavior. Models for key components such as MOSFETs, inductors, and capacitors were either imported or created using manufacturer data sheets or libraries in the software. Input and output voltage sources, load conditions, and other environmental factors were included to make the model realistic.

3.3.1.2 Control Loop Design

A control strategy was developed to ensure stable operation and meet the desired output requirements. Techniques like Proportional-Integral (PI) control were used to manage voltage, current, and frequency. Feedback loops were added to make the inverter respond to real-time performance data helping to keep it stable and efficient.

3.3.1.3 PWM Implementation

Pulse Width Modulation (PWM) signals were created to control the switching of the MOSFETs. The switching frequencies and duty cycles were set based on the inverter's requirements. The PWM logic was tested by simulating the gate signals to make sure they worked properly with the control loop.

3.3.1.4 Initial Parameter Testing

Basic design parameters like inductance, capacitance, and switching frequency were added to the simulation model. Simulations were run to check the circuit's behavior under normal conditions. Any issues such as unexpected ripples or instability were noted for further adjustments.

3.3.2 Simulation Result Analysis

After running the simulation the results were analyzed to assess the inverter's performance and find areas for improvement. This process included:

Figure 3.4 - Simulation Result Analysis Flow

3.3.2.1 Waveform Analysis

The waveforms for voltages, currents, and switching states were examined to ensure the inverter was working correctly. The output signal quality was checked to minimize distortion and meet specifications like Total Harmonic Distortion (THD).

3.3.2.2 Efficiency and Loss Analysis

The inverter's efficiency was calculated by comparing input and output power. Power losses such as conduction and switching losses in MOSFETs and resistive losses in inductors and capacitors were measured.

3.3.2.3 Parameter Adjustments

Based on the analysis design parameters were adjusted as needed. For example inductance might be increased to reduce current ripple or capacitance might be changed to minimize voltage ripple. Control loop and PWM settings were also fine-tuned to improve stability and efficiency. These changes were tested by re-running the simulation to confirm the improvements.

This step-by-step process helped identify and fix potential issues early, making the inverter design more reliable. The repeated cycles of simulation, analysis, and refinement ensured the final design met its performance goals.

3.4 Component Selection

The design and development of the Unidirectional Totem Pole Inverter involve selecting and optimizing key components to achieve efficiency, reliability, and stability in its operation. This section details the methodology and criteria used to identify and design critical components that meet the system's electrical, thermal, and operational requirements.

3.4.1 Component Design Requirements of the Unidirectional Totem Pole Inverter

In the second phase, the Component Design of the Unidirectional Totem Pole Inverter focuses shifts to selecting and designing the key components of the inverter. This includes choosing the appropriate MOSFETs for efficient switching, designing inductors capable of handling the desired current while minimizing losses, and selecting capacitors that ensure stable operation and effective filtering.

3.4.1.1 Design Criteria for MOSFET

This outlines the design criteria for selecting a specific model of SiC MOSFET for use in a Unidirectional Totem Pole Inverter. These criteria ensure that the chosen SiC MOSFET meets the necessary electrical and thermal performance requirements while balancing cost and availability considerations. Key factors such as voltage rating, current rating, on-resistance, switching speed, and reverse recovery charge are critical to the efficiency and reliability of the inverter.

- **Designed model evaluation procedure**

To evaluate the designed model, a set of criteria has been used. Each concept is then assessed and rated based on this set of criteria using the formula,

$$Weighted\ Average\ = \frac{\sum(WX)}{\sum W}$$

where $\sum(WX)$ represents the sum of the products of each data point (X) and its corresponding weight (W), and $\sum$W is the sum of all the weights. Each design was rated on a scale from 1 to 3, with 1 being the lowest and 3 being the highest, according to the criteria. The rating for each design was multiplied by its respective weight for each criterion, and the resulting product was then summed. This sum was divided by the total weight of the criteria to determine the weighted average of each design. Based on these weighted averages, the designs were categorized as either pass or fail. If the weighted average was greater than or equal to 2.5, the design passed, and the result was communicated. If the weighted average was less than 2.5, the design failed, and the iteration process continued.

For reference, below is the table of criteria with its description and weight.

Table 3.3 - Design Criteria for Choosing Specific Model of SiC MOSFET

Design Criteria	Description	Weight %
Voltage Rating	The maximum drain-source voltage the SiC MOSFET can	15

(Vds)	withstand. Should exceed the system's DC input voltage to ensure safety.	
Current Rating (Id)	The maximum continuous drain current the SiC MOSFET can handle. Must be higher than the maximum current in the inverter circuit.	15
On-Resistance (Rds(on))	The resistance between drain and source when the SiC MOSFET is in the on state. Lower values reduce conduction losses, increasing efficiency.	15
Switching Speed	The rate at which the SiC MOSFET can switch on and off. Faster switching speeds reduce switching losses and improve overall efficiency.	15
Reverse Recovery Charge	The charge required to reverse the direction of current flow in the body diode. Lower reverse recovery charge reduces losses and enhances efficiency (Meneses, 2021).	15
Thermal Resistance	The ability of the SiC MOSFET to dissipate heat from the junction to the case or ambient. Lower thermal resistance aids in heat management and reliability (Wolfspeed, 2021).	5
Gate Charge (Qg)	The total charge required to turn the SiC MOSFET on and off. Lower gate charge facilitates faster switching and lowers the power required by the gate driver (Meneses, 2021).	5
Package type	The physical package of the SiC MOSFET, which affects thermal performance and ease of integration. Suitable packaging supports better heat dissipation and compact design.	5
Cost	The price of the SiC MOSFET. A balance between performance and budget constraints is essential for cost-effective design.	5
Availability	The availability of the specific SiC MOSFET model in the market. Ensuring availability reduces procurement delays and supports timely project completion.	3
Manufacturer Reliability	The reputation and reliability of the SiC MOSFET manufacturer. Reliable manufacturers provide consistent quality and technical support.	2
	Total Weight	**100**

Table 3.4 - Rating Legend

RATING:	1 - LOW	2 - MODERATE	3 - HIGH
PASS - $2.5 \leq Weighted\ Average \leq 3$		**FAIL -** $1 \leq Weighted\ Average < 2.5$	

3.4.1.2 Inductor Design

The design of the inductor for the Unidirectional Totem Pole Inverter required a detailed computation to select an appropriate inductor capable of handling the desired current while ensuring efficiency and stability. The following aspects were considered:

- **Inductance Value (L):**

  The inductance value determined the energy storage capacity and influenced the current ripple in the inverter. It was calculated based on the maximum allowable current ripple and the switching frequency of the inverter.

$$Inductor = L = \frac{V_{DC}}{4 \times fsw \times \Delta I_{ppmax}}$$

- **Current Rating**

  The inductor's current rating was based on the peak current it needed to handle without reaching saturation.

  Formula:

$$Inductance\ Current = I_{peak} = \left(I_o\right)\left(\sqrt{2}\right)$$

  Where: I_o = Average current in the circuit.

This ensured the inductor's ability to operate reliably under load conditions.

- **Thermal Management**

  Proper thermal management was implemented to maintain the inductor's operation within safe temperature limits. The design incorporated heat sinks or airflow mechanisms to manage heat dissipation effectively.

3.4.1.3 Capacitor Design

The capacitor design for the Unidirectional Totem Pole Inverter was computed to ensure stable operation and effective output filtering. The following considerations were addressed:

- **Capacitance Value (C)**

  The capacitance value influenced the voltage ripple and load current. It was calculated based on the switching frequency and inductance:

$$Capacitance = C = \left(\frac{10}{2\times\pi\times fsw}\right)^2\left(\frac{1}{L}\right)$$

  This calculation guided the selection of a capacitor with adequate energy storage and ripple handling capabilities.

- **Voltage Rating**

  The capacitor’s voltage rating was chosen to withstand the maximum voltage in the inverter circuit, ensuring reliability under peak voltage conditions.

- **ESR (Equivalent Series Resistance)**

  The Equivalent Series Resistance (ESR) was a key parameter for efficiency. Capacitors with low ESR were prioritized to minimize power losses, particularly in high-frequency applications.

- **Thermal Management**

  Thermal considerations were crucial for capacitor longevity. The design incorporated mechanisms for effective heat dissipation, such as heat sinks or airflow.

- **Type of Capacitor**

  The choice of capacitor type was based on application-specific requirements:

    - Electrolytic capacitors: Selected for their high capacitance values.
    - Ceramic capacitors: Chosen for their low ESR and high-frequency performance.

The detailed computations for the inductor and capacitor design enabled the selection of components that matched the operational requirements of the inverter. By calculating key parameters such as inductance, capacitance, current rating, voltage rating, and ESR, the design ensured efficient and reliable performance under both transient and steady-state conditions.

3.4.2 Module Selection for the Unidirectional Totem Pole Inverter

The third phase, Module Selection for the Unidirectional Totem Pole Inverter involves a detailed design of the inverter's control and power management modules. This includes selecting suitable microcontrollers such as Arduino, ESP32, PSoC, or XMC, for control operations and selecting Gate Drivers to efficiently manage MOSFET switching.

Table 3.5 - Design Criteria for the Selection of Microcontroller

Design Criteria	Description	Arduino Uno	ESP32	XMC	PSoC	Weight %
Processing Power	The capability to handle complex calculations and control algorithms efficiently.					20
Clock Speed	Determines the speed of processing tasks.					15
RAM	Determines the capability to handle runtime data.					10
Flash Memory	Storage for code and libraries.					10
I/O Pins	Number of input/output pins available for interfacing with peripherals.					5
Analog-to-Digital Converter	Converts analog signals to digital.					5
Digital-to-Analog Converter	Converts digital signals to analog.					5
PWM Outputs	Pulse Width Modulation outputs for motor control and other applications.					5
Communication Interfaces	Availability of UART, SPI, I2C, CAN, and other communication protocols.					5
Power Consumption	Important for energy efficiency in inverter applications.					5

Real-Time Operating System (RTOS)	Support for multitasking and real-time operations.					5
Ease of Programming	Availability of development tools and community support.					5
Cost	Budget constraints for the project.					2
Wi-Fi-Bluetooth	Built-in wireless communication capabilities.					3
					Total Weight	**100**

To select the most suitable microcontroller for the Unidirectional Totem Pole Inverter the following evaluation procedure was followed:

First, each microcontroller is rated on a scale of 1 to 3 for each design criterion with 1 being the lowest and 3 being the highest based on performance and specifications. Then the weight percentage for each criterion is assigned based on its importance to the overall performance and design requirements of the inverter ensuring that the total weight of all criteria sums to 100%.

Next, for each microcontroller the rating is multiplied by the corresponding weight percentage for each criterion to get the weighted score. This weighted score is calculated using the formula:

$$Weighted\ Average\ = \frac{\Sigma(WX)}{\Sigma W}$$

where W is the weight and X is the rating.

After calculating the weighted score for each criterion, the total weighted score for each microcontroller is computed by summing all the weighted scores. Finally, the total weighted scores of all microcontrollers are compared, and the microcontroller with the highest total weighted score is selected for the inverter design.

- **Design Model Evaluation Procedure for Selecting SiC MOSFET Gate Driver**

  To select the most suitable SiC MOSFET gate driver for the Unidirectional Totem Pole Inverter, a comprehensive evaluation procedure is employed. This procedure involves rating each gate driver based on specific design criteria, applying weight percentages to these criteria, and calculating the total weighted score for each gate driver.

Table 3.6 - For Selecting SiC MOSFET Gate Driver for the Unidirectional Totem Pole Inverter

Parameter	Description	Weight %
Voltage Rating	Must match or exceed the maximum voltage rating of the SiC MOSFET.	20
Current Rating	Ensures the gate driver can supply adequate current for fast switching of the SiC MOSFET.	15
Switching Speed	Faster switching reduces switching losses and allows for high-frequency operation.	15
Isolation Capability	Provides safety and noise immunity, especially in high-voltage applications.	10
On-Resistance	Lower on-resistance reduces power losses in the gate driver.	10
Protection Features	Includes over-voltage, under-voltage, and over-temperature protections to ensure reliable operation.	10
Power Dissipation	Adequate thermal management is required to maintain performance and reliability.	10
Cost	Balance between performance requirements and budget	5

	constraints.	
Integration	Compatibility with the specific inverter design to ensure optimal performance.	5
	Total Weight	**100**

The evaluation process began by assigning ratings to each gate driver on a scale of 1 to 3 for each design criterion, with 1 being the lowest and 3 being the highest based on their performance and specifications. The weight percentage for each criterion is assigned based on its importance to the overall performance and design requirements of the inverter, ensuring that the total weight is summed to 100%.

For each gate driver, the rating for each criterion is multiplied by the corresponding weight percentage to obtain the weighted score. The weighted score is calculated using the formula:

$$Weighted\ Average\ = \frac{\sum(WX)}{\sum W}$$

where W is the weight and X is the rating.

Once the weighted scores for all criteria were calculated, the total weighted score for each gate driver was computed by summing these weighted scores. The gate driver with the highest total weighted score was selected for the inverter design.

3.5 PCB Design and Layout

Designing and laying out a Printed Circuit Board (PCB) is an important part of creating electronic systems. It involves drafting a schematic and turning it into a physical layout while following practical guidelines to ensure good performance, ease of manufacturing, and reliability. This section explains the steps for creating the schematic and designing the PCB layout.

3.5.1 Schematic Design Preparation

The schematic design serves as the starting point for the PCB. The process was broken down into simple steps:

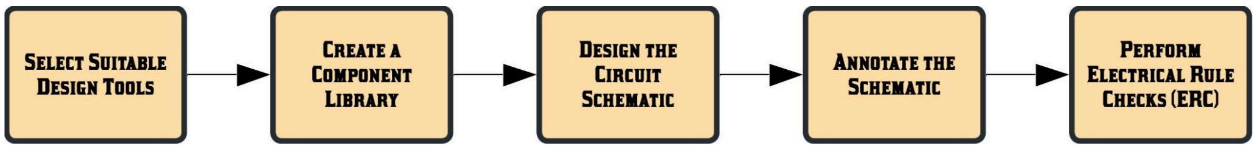

Figure 3.5 - Schematic Design Flow

3.5.1.1 Choosing a PCB Design Tool

The first task was selecting a PCB design software like EasyEDA, Altium Designer, KiCAD, or Proteus. The choice depended on the project's needs and complexity. These tools provided access to component libraries and features for basic simulation and analysis.

3.5.1.2 Setting Up a Component Library

A collection of components was created or downloaded including symbols and footprints. Each component's specifications and dimensions were checked against the manufacturer's datasheet to ensure they were correct.

3.5.1.3 Drawing the Circuit Schematic

Components were added to the schematic editor and arranged in a logical way to make the design clear and organized. Connections were made using wires, nets, and labels, helping to represent the circuit in a straightforward manner.

3.5.1.4 Labeling Components

Unique identifiers were given to each component to make it easy to reference them during the layout process. These labels were compared with the bill of materials (BOM) to make sure they matched.

3.5.1.5 Running Electrical Rule Checks (ERC)

Built-in tools for electrical rule checks were used to find issues like missing connections or conflicting signals. Any problems detected were fixed to complete an accurate schematic.

3.5.2 PCB Layout Guidelines

After finishing the schematic the next step was turning it into a PCB layout. The process was completed in several steps:

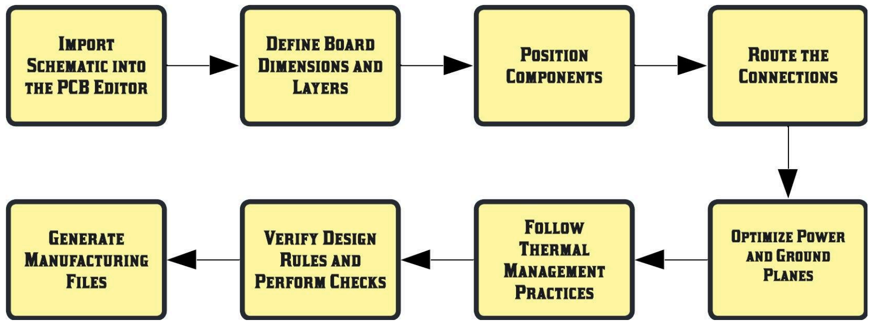

Figure 3.6 - PCB Layout Guidelines Chart

3.5.2.1 Importing the Schematic

The schematic was imported into the PCB editor bringing in all the components and their connections accurately.

3.5.2.2 Defining Board Size and Layers

The size and shape of the PCB were decided based on the project's physical requirements. The number of layers needed whether single-layer, double-layer, or multi-layer was determined by the circuit's complexity.

3.5.2.3 Placing Components

Components were arranged on the board based on their function and connection requirements. Sensitive or high-speed parts were placed closer together to reduce noise and signal issues.

3.5.2.4 Routing the Connections

Traces were drawn to connect the components while following design rules for width, spacing, and impedance. Vias and extra layers were used when necessary to simplify complex routing.

3.5.2.5 Adding Power and Ground Planes

Dedicated areas for power and ground were included to improve stability and reduce electrical noise. Wider traces were used for high-current paths and small loop areas were designed to reduce interference.

3.5.2.6 Managing Heat

Components that produced a lot of heat were given thermal reliefs or heat sinks. Adequate spacing was maintained between components to allow proper heat dissipation and airflow.

3.5.2.7 Checking the Layout

The design was checked using design rule checks (DRC) to identify problems such as spacing or trace-width violations. Adjustments were made as needed to match manufacturing requirements.

3.5.2.8 Preparing Manufacturing Files

Files required for production, like Gerber files and drill files were created and reviewed to ensure the design was ready for fabrication.

This straightforward process ensured that the PCB was practical, easy to manufacture, and prepared for testing and further development.

3.6 Assembly Process

The assembly process is a critical phase in the development of any system, as it transforms individual components into a fully functional unit. For the Totem Pole Topology Inverter the assembly process involved several detailed steps starting with the design of schematics and culminating in the final testing and validation of the integrated system. Each stage focused on ensuring that all components were assembled in accordance with design specifications, optimizing performance, and ensuring the system's reliability and efficiency. The process was carried out in a systematic and iterative manner to minimize errors and maximize functionality, ensuring the successful integration of all parts.

3.6.1 Prototyping Steps

Prototyping was an essential part of the assembly process as it allowed for the creation of a functional version of the Totem Pole Topology Inverter. This phase involved the design, assembly, and testing of a prototype that would demonstrate the functionality of the inverter before full-scale production. The prototyping steps were carefully planned to ensure that each component was correctly implemented and tested under real-world conditions. This phase was crucial for refining the design, troubleshooting potential issues and verifying that the inverter met all performance and efficiency requirements. Each step of the prototyping process was designed to ensure that the final product would be reliable and optimized for long-term use.

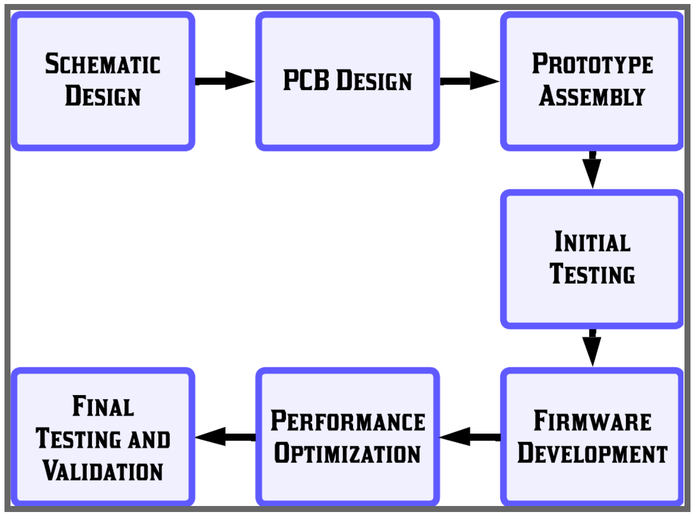

Figure 3.7 - Development Process

3.6.1.1 Schematic Design

The process of assembling the components on the printed circuit board (PCB) for the Totem Pole Topology Inverter started with the completion of the schematic design phase. This phase included creating schematics that showed the electrical connections and component placements needed for the inverter.

3.6.1.2 PCB Design

After the schematic design, the PCB layout was developed to arrange the components efficiently and reduce signal interference.

3.6.1.3 Prototype Assembly

Once the PCB design was finalized and manufactured, the prototype assembly began. The process started with organizing all the components needed for the assembly including passive elements like resistors, inductor and capacitors as well as active components like MOSFETs, gate drivers, and integrated circuits.

The assembly process continued with the placement of smaller passive components which were soldered onto the board using manual soldering or automated equipment depending on the complexity. Then the active components were positioned and soldered with attention given to their orientation and connection to avoid errors during operation.

3.6.1.4 Initial Testing

After all the components were mounted and soldered the PCB was inspected visually to find any soldering defects or misalignments. Additional checks including continuity tests were done to confirm proper electrical connections across the board.

3.6.1.5 Firmware Development

This step ensured the PCB assembly was ready for firmware integration. The firmware development process involved creating and uploading software to control the inverter's operations. This included defining the control logic, setting operational parameters, and implementing algorithms for managing power flow and efficiency. The firmware was then tested on the assembled prototype to ensure compatibility and correct functioning before moving to the next phase.

3.6.1.6 Performance Optimization

Performance optimization involved refining both the firmware and hardware to enhance the inverter's efficiency and performance. This included fine-tuning control parameters in the firmware, such as switching frequencies and operational thresholds, as well as adjusting hardware components to minimize power losses and improve thermal management. These adjustments were iteratively tested and validated to ensure the desired outcomes were achieved.

3.6.1.7 Final Testing and Validation

The final stage involved thorough testing and validation processes to verify that the inverter met the defined efficiency and performance standards. These tests included functional testing to ensure all operations performed as intended, stress testing to evaluate the system's durability under various conditions, and efficiency analysis to confirm it achieved the desired performance metrics. Any identified issues were addressed, and the system was retested to ensure reliability and overall functionality before final approval.

3.6.2 Integration with System Components

Once the inverter prototype was completed, the integration with other system components was the next crucial phase. This step involved connecting the inverter to other key elements such as the PV panels, solar charge controller, battery, and boost converter to form a cohesive energy system. The goal was to ensure that all components worked together seamlessly to optimize energy conversion, storage, and distribution. Detailed planning, careful assembly, and thorough testing were essential to ensure the compatibility and performance of the integrated system. This phase marked the transition from individual prototypes to a fully functional energy system, ready for real-world application and performance validation.

3.6.2.1 Component Procurement

The integration process began by procuring the essential components required for the system. This included PV panels, a solar charge controller, battery, and boost converter. Each component was carefully chosen based on its compatibility with other parts and its ability to provide optimal performance within the system. The specifications were cross-checked to ensure that each component would work cohesively together. The selection was also based on the results from **3.2.2 Calculation of Design Parameters**, which provided the necessary parameters for selecting components that would align with the system's performance requirements. The following criteria were used for the selection of each component:

Table 3.7 - Criteria for Off-the-shelves Components Procurement

Component	Criteria
PV Panels	● **Power Output**: Must match the inverter's input voltage and power requirements ● **Efficiency**: High conversion efficiency to maximize energy generation. ● **Durability**: Resistant to weather conditions and degradation.

	• **Voltage and Current**: Compatible with the solar charge controller and the system's voltage configuration
Solar Charge Controller	• **Input Voltage Range**: Must be compatible with the voltage output of the PV panels. • **Charging Algorithm**: Supports maximum power point tracking (MPPT) for optimal energy conversion. • **Current Capacity**: Sufficient to handle the current produced by the PV panels. • **Efficiency**: High conversion efficiency with minimal energy loss.
Battery	• **Capacity**: Must provide sufficient storage for the energy produced by the PV panels to meet demand. • **Voltage and Chemistry**: Compatible with the charge controller and inverter. • **Cycle Life**: Long lifespan to minimize the need for replacements. • **Efficiency**: High charge/discharge efficiency to ensure minimal energy loss.
Boost Converter	• **Input/Output Voltage Range**: Must be able to step up the voltage from the battery to match the inverter's input requirements. • **Efficiency**: High efficiency for minimal energy loss. • **Power Rating**: Sufficient to handle the required load without overheating. • **Size and Integration**: Compact and easy to integrate into the system without causing excessive power loss or heat generation.

3.6.2.1a Voltage Calculation for Series Connection

The total voltage output of the photovoltaic array was determined by the number of panels connected in series. This calculation was crucial for matching the PV array's voltage to the operating range of the solar charge controller and inverter.

Formula:

$$V_{mp} = V_{panel} \times N_{series}$$

This guided the selection of PV panel configurations to ensure compatibility with the system's voltage requirements.

3.6.2.1b Current Calculation for Parallel Connection:

The total current output of the photovoltaic array was determined by the number of panels connected in parallel, influencing the current-handling capacity of the charge controller.

Formula:

$$I_{mp} = I_{panel} \times N_{parallel}$$

This calculation ensured the solar charge controller could handle the array's maximum current output.

3.6.2.1c Total Power Output

The total power output of the photovoltaic array determined the system's ability to meet energy demands and influenced the sizing of the battery and inverter.

Formula:

$$P = V_{mp} \times I_{mp}$$

This calculation was used to validate the system's power capacity relative to the load demand.

3.6.2.1d Usable Energy:

The usable energy of the battery was a key parameter for ensuring the system could meet energy demands without over-discharging the battery, which could reduce its lifespan.

Formula:

$$E_{usable} = E_{total} \times DOD$$

This calculation aided in selecting a battery with adequate capacity to store energy for continuous operation.

3.6.2.1e Battery Life under Continuous Load:

The battery life calculation estimated how long the battery could sustain a given load, helping to size the battery appropriately for the intended application.

Formula:

$$Battery\ Life = \frac{E_{usable}}{P_{load}}$$

This ensured the battery could support the system's operation for the required duration.

3.6.2.2 System Layout Design

Following the procurement phase the system layout design was initiated. During this phase, a detailed schematic of how the components would be integrated was developed. The design ensured that the PV panels, charge controller, battery, boost converter, and inverter would interact seamlessly. Consideration was given to the placement of each component, wiring routes, and the optimal connection methods to minimize energy losses and ensure safe and efficient system operation.

3.6.2.3 Electrical Connections

With the layout design complete the next step involved establishing the necessary electrical connections. The PV panels were connected to the Solar Charge Controller to ensure proper charging of the battery. The charge controller was then linked to the battery enabling it to store the electricity generated by the panels. Each connection was carefully made to avoid short circuits ensuring reliable and safe operation of the system.

3.6.2.4 Boost Converter Integration

The Boost Converter was then integrated into the system to regulate the voltage output from the PV panels or battery to the inverter. This step was critical to ensure that the voltage was stepped up to the appropriate level for the inverter to function effectively. The converter was connected between the battery and the inverter to ensure that power was delivered at the correct voltage maintaining the stability of the entire system.

3.6.2.5 Inverter Integration

The Totem Pole Inverter responsible for converting DC power to AC was connected to the output of the boost converter. This integration was crucial for enabling the system to provide usable AC electricity. The inverter’s connection was set up to ensure that it could receive a steady and regulated input from the boost converter enabling the inverter to produce clean, stable

AC power for external use.

3.6.2.6 Communication Setup

Communication systems were then set up to enable monitoring and control of all the components within the system. This allowed for real-time data exchange between the PV panels, charge controller, battery, boost converter, and inverter. The setup ensured that the system could be easily monitored for performance with the ability to troubleshoot or adjust settings remotely if needed. This step was essential for maintaining the system's efficiency and providing operational flexibility.

3.6.2.7 System Testing

Once all components were connected and communication was established, system testing was performed. The system was powered on and each component was tested to verify that it was functioning as expected. The test involved checking the voltage levels the efficiency of energy transfer and the proper operation of the inverter. Any issues were noted and troubleshooting was carried out to ensure that all connections and components were working correctly.

3.6.2.8 Performance Validation

The final step in the integration process was performance validation. The system's overall efficiency was measured to ensure it fell within the target range of 95% to 99%. This step was essential to confirm that the integration process had been successful and that the system was operating at peak performance. After validation the system was considered fully operational, meeting the required standards and ready for use.

3.7 Testing Procedures

The testing procedures for the unidirectional totem pole inverter are designed to ensure the system's functionality, safety, efficiency, and reliability under various operating conditions. This section provides a comprehensive overview of the methodologies used to evaluate the inverter, starting from basic functional tests to advanced performance assessments. The procedures are divided into three main phases: Initial Testing, Intermediate Testing, and Final Testing, each with specific objectives and detailed sub-processes. These tests collectively validate the design and readiness of the inverter for practical deployment while adhering to industry standards for performance and safety.

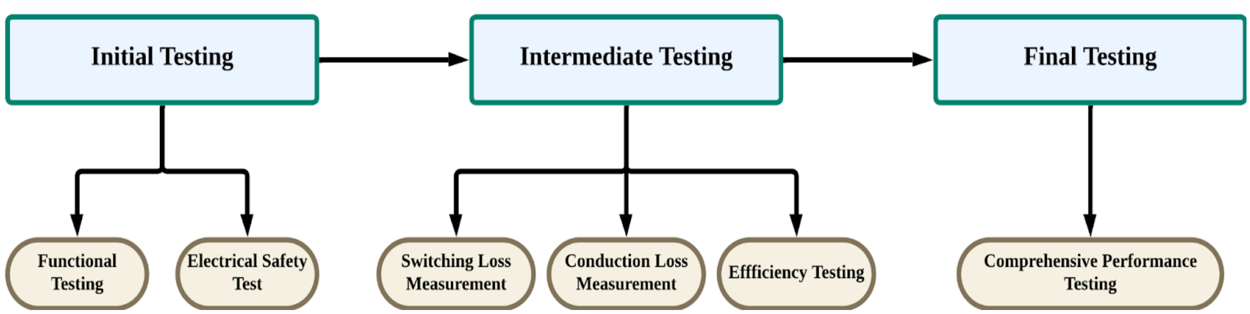

Figure 3.8 - Testing and Efficiency Process

3.7.1 Initial Testing

The initial testing phase was focused on verifying the basic functionality and ensuring the safe operation of the inverter. This phase began with functional testing, where the primary task was to confirm that the inverter correctly converted DC to AC power, following the design specifications. Electrical safety testing was conducted next to ensure that the inverter complied with relevant safety standards, minimizing the risk of electrical hazards during operation. To assess the operational integrity of the inverter various electrical parameters including voltage, current, and waveform integrity, were measured. This provided confirmation that the inverter was functioning within the specified limits and was ready for more advanced testing phases.

3.7.1.1 Individual Testing

In this sub-phase, individual components of the inverter were tested to verify that each part functioned as intended.

3.7.1.1a ESP32 with 16-Bit ADC

The first component to be tested was the ESP32 microcontroller which featured a 16-bit Analog-to-Digital Converter (ADC). The ADC was tested to ensure its accuracy and reliability in converting analog signals from the inverter into digital data for further processing. The testing involved feeding known reference voltages to the ADC input and comparing the output with expected digital values to confirm proper calibration. The performance of the ADC was validated across a range of voltages to ensure that it could consistently measure and convert the analog input with a high degree of precision.

3.7.1.1b Current Measurements

Current measurements were taken to assess the inverter's ability to handle the expected load. A current sensor was used to monitor the flow of electricity throughout the system. The system's output was tested at various load conditions and the current measurements were compared with expected values based on the load. Any discrepancies between measured and expected current values were investigated to ensure that the inverter's power handling capabilities were within safe operational limits. The performance of the current sensing circuit was also checked to ensure it functioned accurately under different current conditions.

3.7.1.1c Voltage Measurements

Voltage measurements were conducted to ensure that the inverter provided stable output within the designed voltage range. A voltage meter was used to measure both the DC input voltage and the AC output voltage of the inverter. These measurements were compared with the expected values to ensure that the inverter was properly regulating the voltage and that no voltage spikes or drops occurred. Additionally, the voltage waveform was analyzed to ensure that it conformed to the specified waveform quality, which is crucial for the safe operation of connected devices.

3.7.1.1d ESP32 PWM Output

The Pulse Width Modulation (PWM) output from the ESP32 was tested to ensure that the microcontroller could generate the required control signals for the inverter's switching elements. The frequency, duty cycle, and signal integrity of the PWM were verified using an oscilloscope. The PWM signals were checked to ensure they matched the expected output based on the inverter's design specifications. Any irregularities in the PWM waveform could affect the inverter's switching performance, so this test was essential for ensuring proper inverter operation.

3.7.1.1e Active Gate Driver PWM Output

The next step was to test the active gate driver which was responsible for generating PWM signals to drive the power transistors in the inverter. The gate driver's output was tested using an oscilloscope to confirm that it provided the correct voltage and frequency for the transistors to switch effectively. This test ensured that the gate driver could handle the required switching speed and voltage levels to operate the power transistors correctly ensuring that the inverter could efficiently convert DC to AC power without issues such as cross-conduction or inefficient switching.

3.7.1.2 Electrical Safety Test

Once individual components were verified a comprehensive electrical safety test was carried out. This test ensured that the inverter adhered to international safety standards and was safe to operate without posing any risk of electrical shock or fire. The safety test involved verifying insulation resistance, ensuring proper grounding, and checking for the potential of electric arcs or short circuits under normal operating conditions. Grounding tests confirmed that the inverter's casing and exposed conductive parts were properly grounded, preventing any potential hazards. Additionally, the protection circuits, such as over-voltage, over-current, and thermal shutdown, were verified to ensure they functioned correctly and would prevent any damage or safety concerns in case of system malfunctions. The electrical safety test concluded by confirming that the inverter met all safety requirements, ensuring its readiness for more advanced performance testing.

3.7.2 Intermediate Testing

This phase includes switching loss measurement, conduction loss measurement, and efficiency testing. Switching loss measurement involves using an oscilloscope and a power meter to measure the power loss during the switching actions of the transistors at different frequencies and loads. Conduction loss measurement assesses the power loss due to the resistance of conducting paths within the inverter. These measurements help in understanding the efficiency of the inverter under various operating conditions. Efficiency testing evaluates the overall efficiency by comparing the input power from the power source to the output power delivered to the load.

3.7.2.1 Efficiency Calculation Metrics

In this phase, the efficiency of the inverter was calculated to assess its overall performance and identify areas for optimization. The process involved measuring the different types of power losses and then calculating the inverter's overall efficiency by comparing the input and output power.

3.7.2.1a Switching Loss

To calculate switching loss, power loss resulting from the switching actions of the transistors was measured. The switching loss was assessed by using an oscilloscope and power meter at varying switching frequencies and load conditions. The measurement process involved monitoring the drain-source voltage (Vds), load current (I_{load}), switching frequency (f_{sw}), and gate charge (Q_g). The switching loss was calculated using the formula (Keim, 2024):

$$P_{sw} = (\frac{1}{2})(Vds)(I_{load})(f_{sw})(Q_g)$$

Where Vds is the drain-source voltage, I_{load} is the load current, f_{sw} is the switching frequency, and Q_g is the gate charge. This calculation provided insight into how much energy was being lost during the switching cycles of the transistors, which was essential for understanding the inverter's efficiency.

3.7.2.1b Conduction Loss

Next, conduction losses were measured to evaluate the power loss due to the resistance in the conducting paths of the inverter. The resistance was determined by measuring the load current (I_{load}) under different load conditions and applying it to the formula for conduction loss (Wei et al., 2024):

$$P_{cond} = (I_{load})^2(Rds_{(on)})$$

Where $Rds_{(on)}$ is the on-resistance of the MOSFET. These measurements provided an understanding of the energy lost as heat due to resistance within the inverter's electrical components, particularly the transistors.

3.7.2.1c Overall Efficiency

The overall efficiency of the inverter was calculated by comparing the output power to the input power. The output power (P_{out}) was determined by multiplying the output current (I_{out}) by the output voltage (V_{out}), while the input power (P_{in}) was calculated by multiplying the input current (I_{in}) by the input voltage (V_{in}):

$$P_{out} = I_{out} \times V_{out}$$

$$P_{in} = I_{in} \times V_{in}$$

The overall efficiency was then calculated using the formula:

$$Efficiency(\eta) = \frac{P_{out}}{P_{in}} \times 100\%$$

This provided the percentage of input power converted into usable output power, indicating the inverter's efficiency in converting DC power to AC power. The final result revealed how much energy was being lost in the process, allowing for potential adjustments to improve the inverter's overall performance and achieve higher efficiency.

3.7.3 Final Testing

The Final Testing phase was conducted to validate the design and ensure that the inverter performed reliably under various operational scenarios. This phase involved comprehensive evaluations and was divided into several subcomponents to thoroughly assess performance:

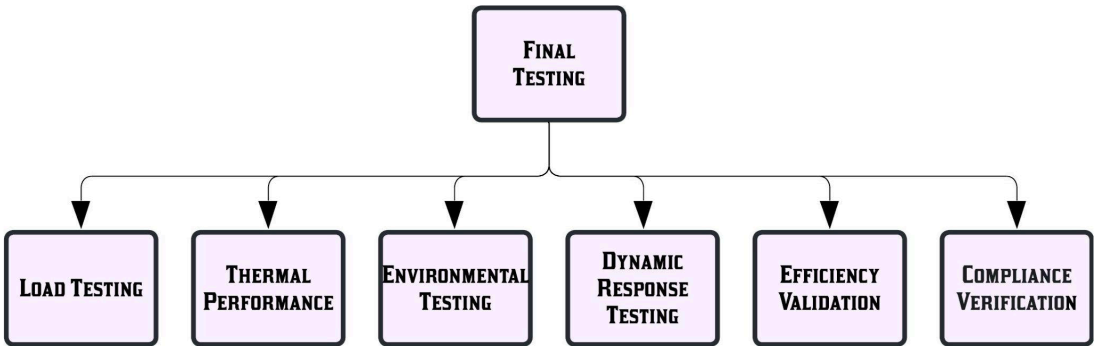

Figure 3.9 - Final Testing Procedure

3.7.3.1 Load Testing

Load testing was performed using resistive, inductive, and mixed loads to evaluate the inverter's performance under different operational conditions. The output voltage, current, and waveform were continuously monitored to ensure stable operation and conformity to design specifications. High-load scenarios were simulated to stress-test the system and identify potential weaknesses.

3.7.3.2 Thermal Performance

Testing The inverter's thermal performance was evaluated to ensure that all components could operate within safe temperature limits. Thermal sensors were used to measure the temperature of critical components such as MOSFETs, gate drivers, and the PCB. Cooling mechanisms, including heatsinks and ventilation, were tested for efficiency under prolonged operation.

3.7.3.3 Environmental Testing

Environmental testing was conducted to assess the inverter's resilience under varying environmental conditions, including temperature fluctuations, humidity, and vibration. This ensured that the inverter could maintain stable performance in real-world usage scenarios.

3.7.3.4 Dynamic Response Testing

Dynamic response testing evaluated the inverter's ability to handle sudden changes in load or input voltage. The system's response time and stability were measured using a combination of step-load tests and voltage fluctuation simulations.

3.7.3.5 Efficiency Validation

Efficiency validation was repeated with the refined system to ensure that the inverter consistently achieved the target efficiency range of 95-99%. Any deviations were analyzed, and further adjustments were implemented as needed.

3.7.3.6 Compliance Verification

The final step involved verifying that the inverter met all regulatory and safety standards. Certification tests were performed to confirm compliance with industry standards for electrical safety, electromagnetic interference, and energy efficiency.

By the end of this phase, the inverter had undergone thorough verification, confirming its readiness for deployment and its capacity to integrate seamlessly with photovoltaic systems while supporting sustainable energy objectives.