EE405 - Undergraduate Project 1
Smart Transformer Control

Project Report – Group 31

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Chapter 1

Introduction

1.1 Background

Photovoltaic (PV) energy is becoming increasingly popular as a mainstream power source. In Sri Lanka, imported inverters are currently used to connect PV plants to the grid. However, since inverter manufacturers do not provide source codes, the utility does not have the flexibility to introduce some control loops that are required to receive grid support from these inverters.

This single-phase open-source solar PV inverter addresses this issue by providing the flexibility required to enhance PV connection to distribution networks. The inverter and boost converter have been designed, hardware-implemented, and tested. This smart device can use various MPPT algorithms and active reactive power controls in the boost converter and in the inverter, respectively.

Here are some additional details about the single-phase open-source solar PV inverter:

- The inverter is designed to be modular and scalable, so it can be easily adapted to different PV plant sizes.
- The inverter uses a variety of MPPT algorithms to ensure that the PV plant is always operating at its maximum power point.
- The inverter can also control the active and reactive power output of the PV plant, which can help to improve the stability of the grid.

The development of this single-phase open-source solar PV inverter is a significant step forward for the integration of PV energy into the grid in Sri Lanka. The inverter's flexibility and scalability make it well-suited for a variety of PV plant sizes, and its ability to use various MPPT algorithms and active reactive power controls can help to improve the stability of the grid.

1.2 Objectives

The main objective of this project is to design, develop, and implement a smart grid system that efficiently harnesses solar energy and battery storage to achieve sustainable and eco-friendly energy solutions. The project aims to create an intelligent grid infrastructure with advanced converters and controllers that optimize energy usage, reduce costs, and increase overall efficiency.

Specifically, the project will focus on the following key points:

- Utilizing Existing Converters and Introducing Controllers: Incorporate advanced controllers into existing converters to act as solar inverters, enabling seamless integration of solar energy into the smart grid system.
- Development of a DC-DC Converter: Design and construct a specialized DC-DC converter tailored for the solar system to efficiently manage the flow of energy between the solar panels and the battery storage.
- Comprehensive Testing of the Solar Setup: Thoroughly test and evaluate the entire solar setup, ensuring its reliability, performance, and safety.
- Testing Smart Grid Functionality: Assess specific functionalities of the smart grid, such as load management, energy optimization, and grid stability, through rigorous testing and experimentation.
- Determining Inverter Specifications: Determine the input and output voltage requirements of the inverter, based on the battery's specifications and the load requirements, to ensure seamless energy conversion and distribution within the system.

By achieving these objectives, the project aims to contribute significantly to the advancement of sustainable and environmentally conscious energy solutions, paving the way for a greener and more efficient future.

1.3 Methodology

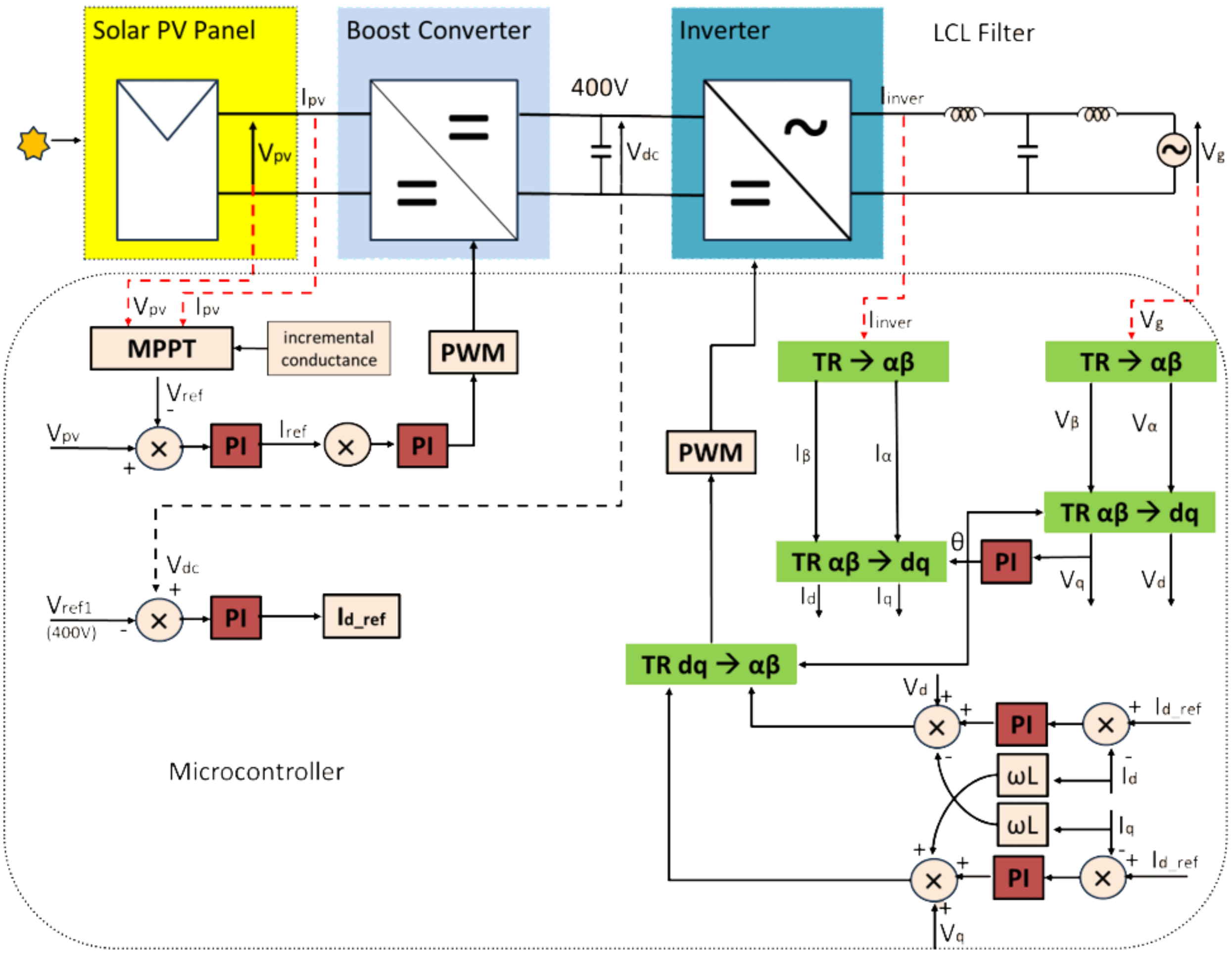


Figure 1.1: Overall Controlling System

1. **Literature Review:**

Conduct an extensive literature review to gather relevant information on smart grid systems, solar energy, battery storage, converters, and controllers. Analyze existing research, case studies, and industry best practices to understand the current state of the art and identify potential challenges and opportunities.

2. **Converter and Controller Integration:**

Integrate advanced controllers into the existing converters to enable them to function as solar inverters. Develop and implement control algorithms to optimize energy harvesting, conversion, and distribution processes.

3. **DC-DC Converter Development:**

Design the DC-DC boost converter to raise the DC voltage from the 240V solar system to 360V (open circuit stage). Implement the converter circuit and verify its functionality through simulations and prototype testing.

4. **MPPT Algorithm Development:**

Implement the Maximum Power Point Tracking (MPPT) algorithm using the incremental conductance method. Develop control algorithms to adjust the duty cycle of the PWM signal (10kHz) and efficiently track the maximum power point of the solar panels.

5. **Hardware and Software Implementation:**

Procure necessary hardware components and develop the required software to enable communication and coordination between the solar panels, battery storage, and controllers. Verify compatibility and conduct integration tests.

6. **Inverter Design and Implementation:**

Design the inverter to convert the boosted DC voltage (400V) to AC output (230V rms). Implement the inverter circuit with appropriate safety features and ensure seamless switching between grid-tied and standalone modes.

7. **Testing and Evaluation:**

Set up a comprehensive testing environment to evaluate the entire solar setup and the smart grid's functionalities. Perform performance tests, load tests, and efficiency measurements to validate the system's effectiveness and identify potential areas for improvement.

8. **Smart Grid Functionality Testing:**

Isolate and test specific functionalities of the smart grid, such as load management, energy optimization, and grid stability, using realistic scenarios and test cases. Monitor and analyze the system's performance under various conditions.

9. **Data Collection and Analysis:**

Collect data from various tests and simulations and perform a detailed analysis of the results. Use statistical tools and visualization techniques to interpret the data effectively.

10. **Conclusion and Recommendations:**

Summarize the findings from the testing and evaluation stages. Draw conclusions regarding the system's performance, efficiency, and reliability. Provide recommendations for any necessary improvements or further research.

11. **Documentation and Reporting:**

Prepare a comprehensive report documenting the entire development process, including the methodology, results, and analysis. Create clear and concise documentation to facilitate knowledge sharing and future development.

Chapter 2

Literature Review

2.1 Review of Previous Studies

The literature review is a critical component of our research, encompassing an in-depth analysis of various key areas essential to the successful development of our solar-powered smart grid system. This section provides a comprehensive overview of the extensive research and investigation conducted on five core aspects:

1. Maximum Power Point Tracking (MPPT) Design.
2. LCL Filter Design.
3. DC-DC Converter Design.
4. Inverter Design and Controller Implementation.
5. Phase-Locked Loop (PLL) Design, and Protection Implementation of the inverter.

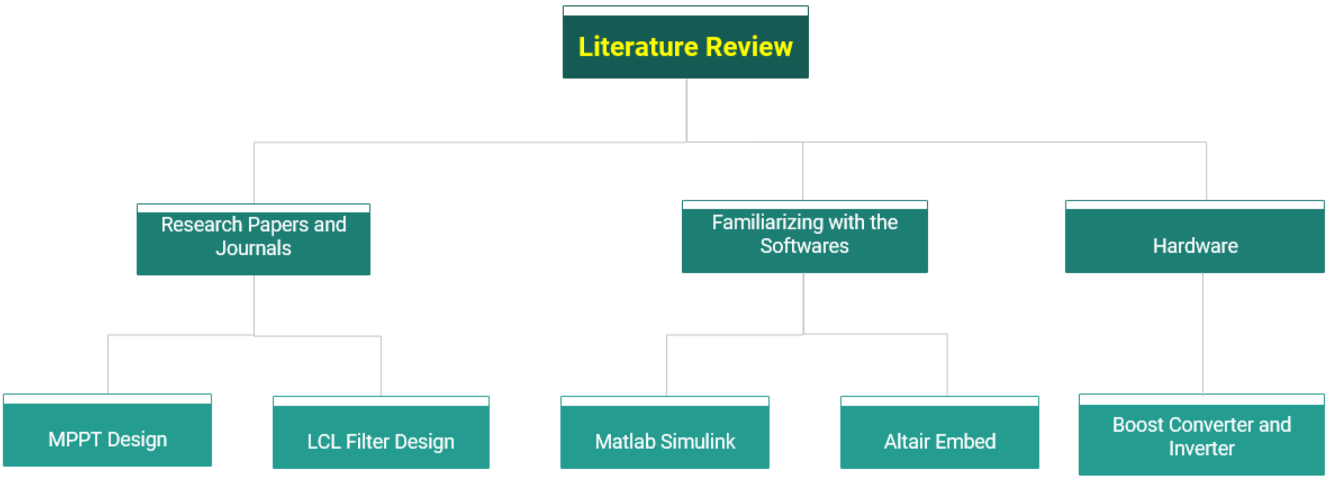


Figure 2.1: Flow Chart of Literature Review

2.2 Related Technologies

Our literature review encompasses key research papers chosen for their relevance to our smart grid project. These papers delve into essential areas like MPPT Design, LCL Filter Design, DC-DC Converter Design, Inverter Design and Controller Implementation, PLL Design, and Inverter Protection.

Each paper contributes valuable insights, methodologies, and experimental findings, enriching our understanding of the latest advancements in the field. Leveraging this authoritative knowledge, our project aims to develop an efficient solar-powered smart grid system for sustainable energy solutions.

However, despite existing literature, certain gaps persist, presenting opportunities for innovation. Our research seeks to address these gaps, proposing novel solutions and tackling unresolved challenges in solar-powered smart grid systems.

As we delve into each area, we'll identify these gaps and outline our contributions to filling them.

Table 1: Comparison on Literature Review

Title	Abstract Summary	Gap of Research
Model Predictive Power Control of Grid-Connected Quasi Single-Stage Converters for High-Efficiency Low-Voltage ESS Integration	The paper proposes a model predictive power control (MPPC) method for a grid-connected quasi-single-stage converter (QSSC) to enhance grid current performance.	The effectiveness of the proposed method has only been verified through experimental results, and further research may be required to evaluate its performance under different operating conditions and system configurations. Additionally, the paper does not compare the proposed method with other existing control strategies for QSSCs,
Dual loop control for single phase PWM inverter for distributed generation	The paper proposes a design for a synchronous frame DQ control based double loop control for a single-phase inverter in a distributed generation system.	The proposed system has only been simulated using Matlab, and further research may be required to evaluate its performance under different operating conditions and system configurations.
Enhanced dq current control for single-phase voltage-source inverters.	In this study, the reference-current-based OSG method is analyzed thoroughly and the dq -axes decoupling control, which is widely discussed for three-phase systems and usually neglected for single- phase systems, is studied.	The proposed techniques aim to address the challenges in designing the dq-frame current regulator for single-phase voltage-source inverters.
Design and Active Compensation of LCL Filter for Grid-Connected Inverter	A grid connected inverter with an LCL filter can attenuate high frequency harmonics generated by the high frequency switching on and off, and the design criterion and calculation procedures of LCL were introduced in detail.	The paper only focuses on the design and active compensation of LCL filters for grid-connected inverters,
Current Control Strategy for Grid Connected Photovoltaic Inverter via LCL Filter	The paper presents a control system design for a grid-connected photovoltaic inverter with an LCL filter to reduce current total harmonic distortion.	The proposed control strategy is designed for a specific type of inverter (grid-connected photovoltaic inverter with an LCL filter) and may not be directly applicable to other types of inverters or systems. Additionally, the effectiveness of the proposed strategy may depend on various factors such as the specific operating conditions and the quality of the components used.
Single-phase grid-connected power control in dq synchronous reference frame with space vector modulation using FPGA	This paper presents a method for controlling the active and reactive power of a single-phase grid-connected inverter using dq synchronous reference frame and space vector modulation (SVM) implemented by field programmable gate array (FPGA). The system has been simulated using MATLAB and the results	The results of the simulation may not necessarily reflect the performance of the system in real-world applications. Additionally, the proposed method may have limitations in terms of scalability and adaptability to different types of inverters and grid systems.

	show robust control of injected grid current, active and reactive power control, and DC link voltage control.	
Design of Transformerless Single Stage Double Switch Step Down PLL Derived Inverter using Single Phase Grid Connected PV Module with MPP Tracking	The paper proposes a single stage double switch converter for a single phase grid connected photovoltaic inverter step-down module. The proposed module uses a perturb and observe algorithm reference voltage to gain maximum power in different changing climatic conditions.	Only simulation results use to validate the operation of system
A simplified DQ controller for single-phase grid-connected PV inverters	The paper proposes a simplified dq controller scheme for single-phase grid-connected PV inverters, which does not require orthogonal quantities to be generated, making it easier to be implemented. The proposed scheme is experimentally compared to the conventional delay-based dq control method and shown to improve the poor dynamics of the conventional approach while not adding excessive complexity to the controller structure.	the proposed simplified dq controller scheme is only tested on a single-phase five-level diode-clamped grid-connected PV inverter, and its performance may vary for other types of systems. Additionally, the paper does not provide a detailed comparison of the proposed scheme with other existing methods.
A D-Q synchronous frame controller for single-phase inverters	The paper proposes a synchronous frame control strategy for single-phase inverter-based islanded distributed generation systems. The strategy uses a synchronous reference frame PI controller to regulate output voltage, an inner capacitor current regulating loop to stabilize the system, and a voltage-feedforward loop to improve system robustness.	The performance of the proposed controller is only been investigated MATLAB simulation. Interfacing small unit pv rating
Real Time Hardware in Loop Testing of Single Phase Grid Connected PV System	This paper presents the validation and performance testing of a decoupled controller for a single phase single stage rooftop PV through hardware in loop (HIL) implementation. The controller was programmed in a digital signal controller and the system was implemented using asynchronous communication between the plant in HIL box and controller in the microcontroller. The paper reports the system results for various operating conditions and analyzes the effect of grid conditions on the controller behavior.	There is no stability analysis of the proposed control algorithm. The developed control algorithm can be used to control the active and reactive power in a distribution system for maintaining the voltage profile.

Chapter 3

DC-DC Boost Converter

3.1 Controller Design

Inner Current Controller

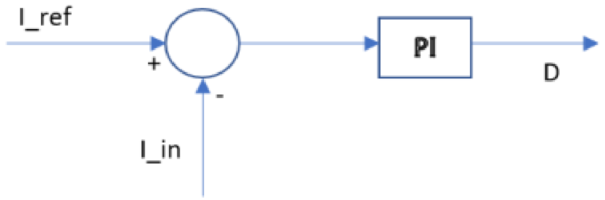


Figure 3.1: Block Diagram of Inner Current Controller

The values for the proportional gain, Kp, and the integral gain, Ki, were initially determined using a trial-and-error approach. Subsequently, these values were verified and validated through simulation studies using MATLAB Simulink to ensure their efficacy and accuracy.

Outer Voltage Controller for Input Voltage

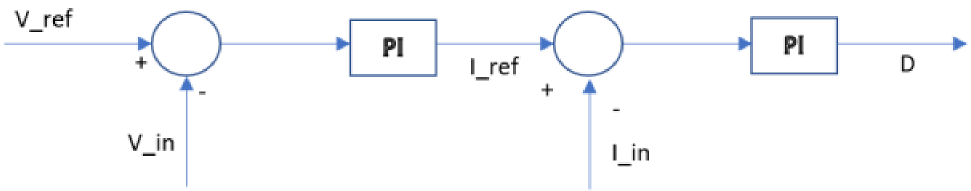


Figure 3.2: Block Diagram of Outer Voltage Controller

The proportional (Kp) and integral (Ki) gains were initially set using a trial-and-error process. These values were then confirmed for their accuracy with MATLAB Simulink simulations

MPPT Incremental Conduction Method Algorithm for Boost Converter

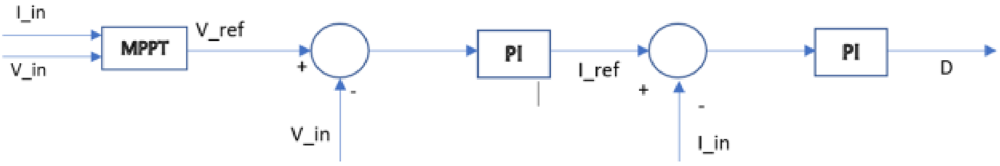


Figure 3.3: Block Diagram of PI Controller Implementation on MPPT Algorithm

The main difference between Incremental Conductance (IncCond) and Perturb and Observe (P&O) MPPT methods is that IncCond uses incremental conductance to determine the direction of the maximum power point (MPP) and offers faster convergence, better oscillation handling, and increased accuracy compared to P&O.

The Incremental Conductance method is a technique used to track the Maximum Power Point (MPP) in photovoltaic (PV) systems. It ensures that the system operates at its maximum power output, despite variations in environmental conditions. The method relies on continuously monitoring the power-voltage characteristic of the PV system and adjusting the operating point to approach and track the MPP. A controller is developed to measure the current and voltage, calculate power output, and compare the incremental conductance (a derivative of power with respect to voltage) to zero. If the incremental conductance is positive, the controller adjusts the operating point to reduce voltage and vice versa. This iterative process ensures the PV system operates at or near the MPP. Testing is conducted to evaluate the method's effectiveness under different conditions, such as sunlight intensity and temperature variations. Testing results validate the method's performance and reliability, providing insights into its suitability for maximizing the power output of PV systems.

3.2 Hardware Implementation

Our project uses a boost converter for power management. It consists of an inductor, a diode, a capacitor, and a switch, usually a MOSFET. The switch's frequency and duty cycle, controlled by a microcontroller, influence the output voltage. The converter is designed for safety, efficiency, and durability, with heat dissipation to prevent component overheating.

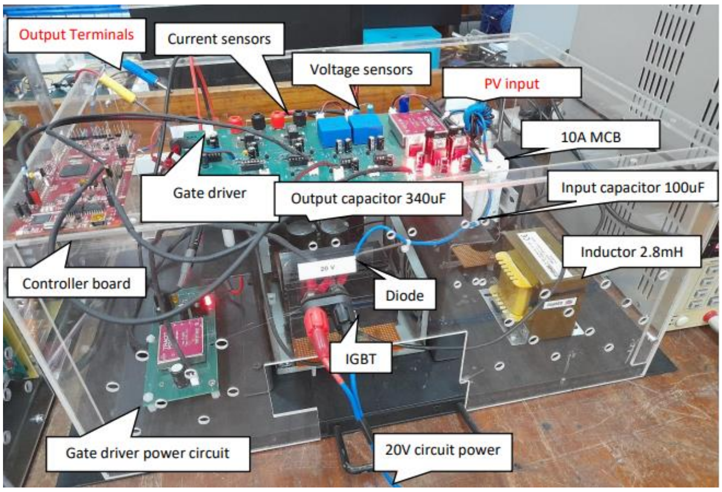


Figure 3.4: Hardware setup of Boost converter.

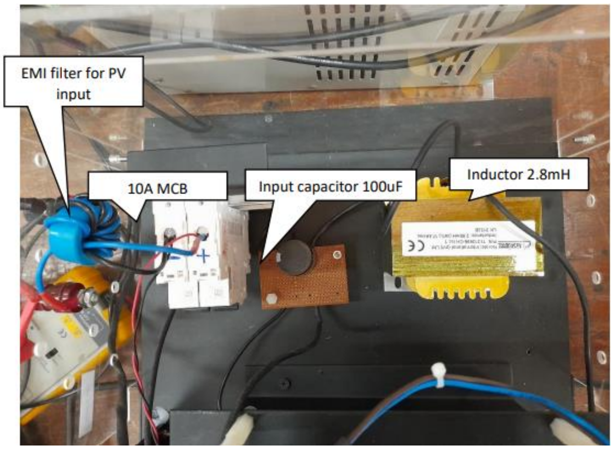


Figure 3.5: Input side hardware setup

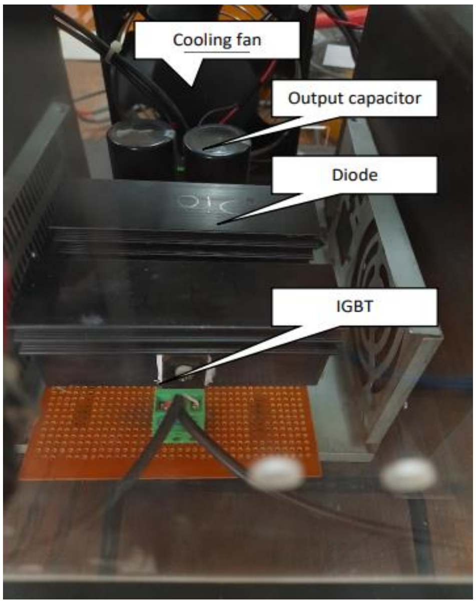


Figure 3.6: IGBT and Diode arrangement

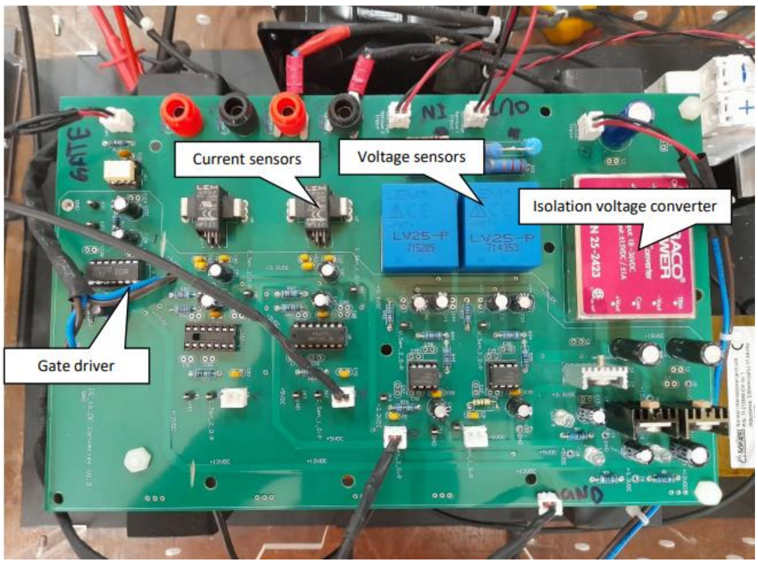


Figure 3.7: Sensor and gate driver board

When operating the hardware, there are several crucial guidelines to keep in mind to ensure safety and optimal performance. Firstly, the PWM should not be switched on for the IGBT unless there is a load connected to the output side. This helps prevent any potential damage or instability.

A UPS should be employed to consistently power the sensor and gate driver during testing, avoiding unexpected power disruptions. It's also important to activate the cooling fan before initiating any tests to ensure adequate heat dissipation and prevent overheating of the components. Furthermore, the power supply for the gate driver should be distinct from the sensor power supply to avoid interference or power issues. Finally, the controller USB needs to be connected to the laptop. This ensures a seamless data transfer and effective monitoring and control during testing. By adhering to these instructions, the operation of the hardware can be conducted safely and efficiently.

Controller Board

The c2000 controller board in our setup has specific roles assigned to various pins. PWM 1A pin and GND pin manage IGBT gate signals. ADC pins C2 and B2 are used to monitor input current and voltage respectively. Although currently unused, ADC pin A2 is set for output voltage tracking, useful for implementing protection measures if output exceeds certain limits.

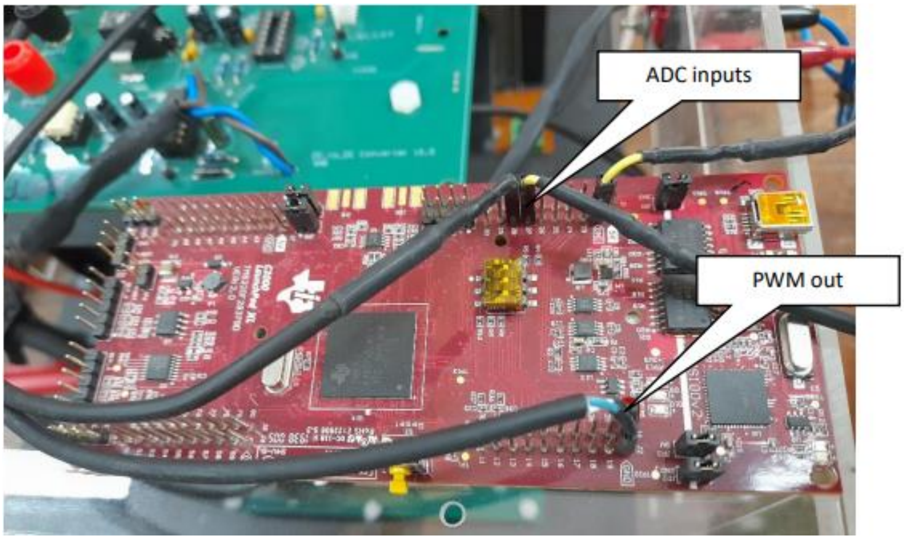


Figure 3.8: Controller board connections

3.3 Controller Implementation in Software

In our setup, the controller operation is handled by the Texas Instruments C2000 TMS320F28379D, a sophisticated microcontroller known for its excellent performance in handling complex control tasks. The controller's implementation was carried out using Altair Embed 2019.1BUILD53, a robust and user-friendly software tool.

Main two vital files, namely boost_aug.vsm and boost_aug_d.vsm, were created in the process. The file boost_aug.vsm serves as the primary controller, managing the core operations of our setup. On the other hand, boost_aug_d.vsm functions as the debug mode of the controller, enabling real-time monitoring of the controller's signals, enhancing transparency, and facilitating better control.

An added advantage of the debug mode is its capacity to alter parameters in real-time while the controller is running. This functionality allows us to fine-tune our system on-the-go, optimizing performance and responsiveness in different operating conditions.

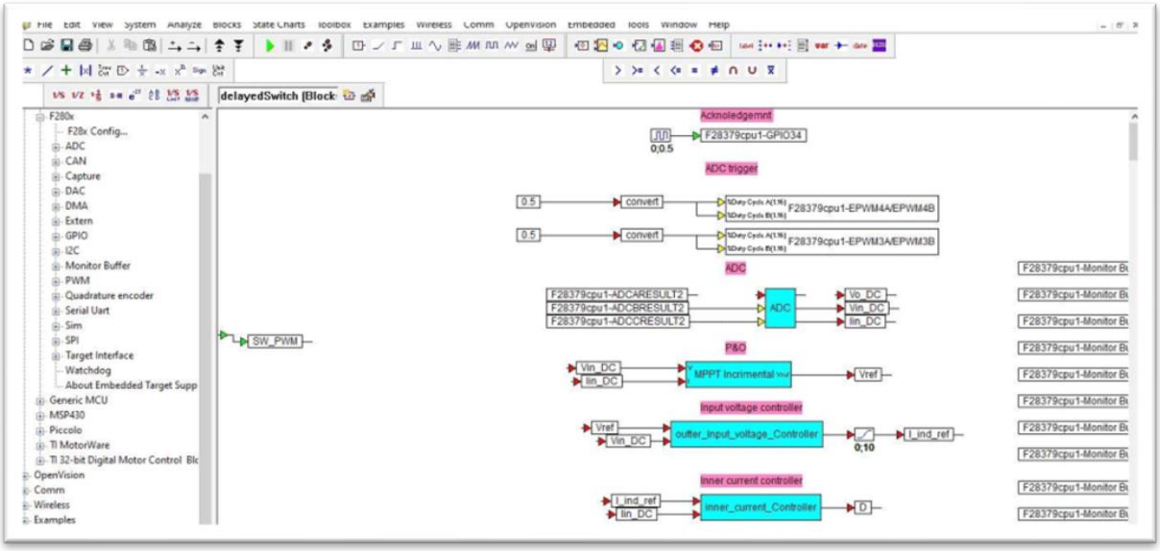


Figure 3.9: Controller main window blocks

Project utilizes the Incremental Conduction Method (ICM) for Maximum Power Point Tracking (MPPT), an effective algorithm for maximizing the power output of photovoltaic (PV) systems. To access the details of the MPPT block, a double-tap is needed.

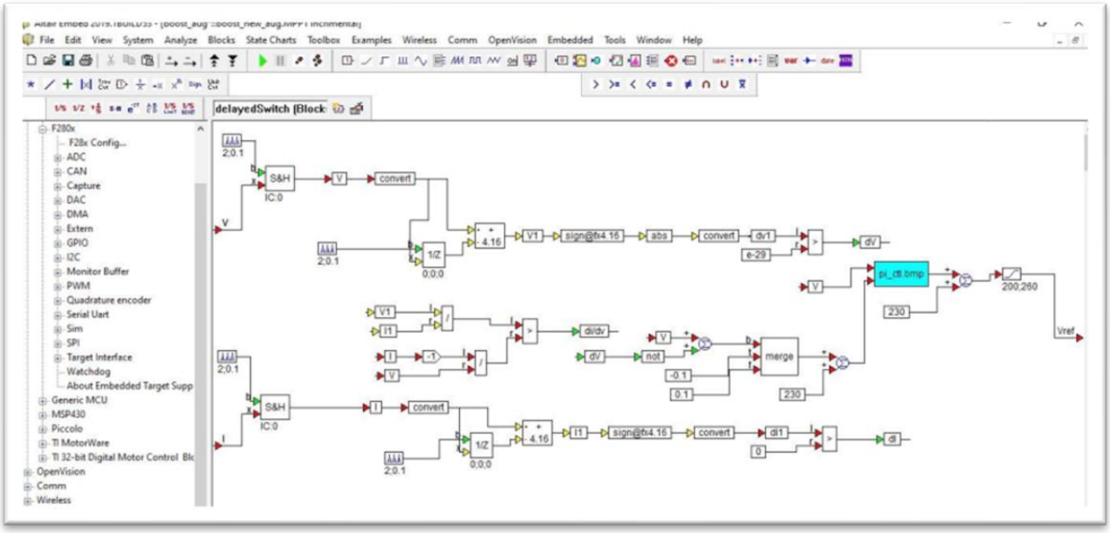


Figure 3.10: MPPT Algorithm

At the heart of the control system is an outer input voltage controller. This crucial component manipulates the PV voltage to track the maximum power point, ensuring optimal power output under varying conditions.

The selection of the proportional (Kp) and integral (Ki) gains for the controller was performed using a trial-and-error method, followed by MATLAB simulation for verification. These gains play a critical role in the controller's performance, influencing its speed of response and stability. Through a careful process of adjustment and testing, these values were determined to deliver the best performance for our specific PV system setup.

3.4 Boost Converter Testing Without Inverter

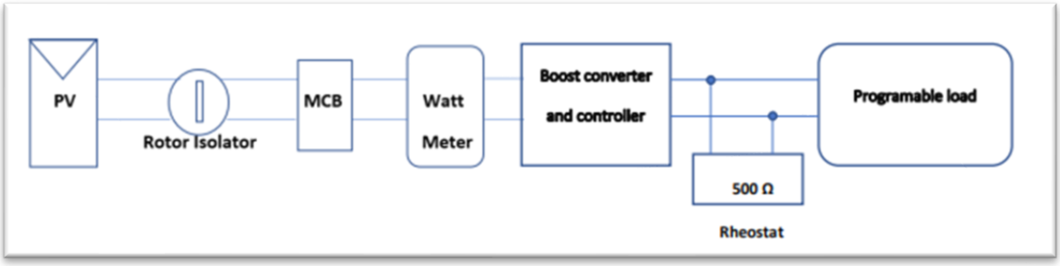


Figure 3.11: Test Arrangement (Without Inverter)

Startup procedure

- Connect all the equipment as shown and Set rheostat to 500 Ω.
- Setup the configurations of the programable load (Constant Voltage mode/DC voltage = 260V/current 10A).
- Press the run button on the debug mode of boost converter controller.
- Switch on Rotor isolator and the MCB (You can see Vin and Vout are same voltage magnitude).
- Switch on programmable load to absorb the excess power.
- Switch on PWM on the controller.
- Set programable load voltage to 400V and press enter to activate (Output maintains at 400V by CV mode of programable load)
- Using V ref we can manually set the input side voltage to catch the MPP voltage (If we have MPPT algorithm
- we do not need to change the V ref, it will automatically change according MPPT algorithm to catch MPP).

Shutdown procedure

- Switch off rotor isolator
- Switch off PWM

Important!

Please refer to the user guide of Boost Converter before the startup process.

Bost Converter User Guide

Chapter 4

Grid-tied Inverter

4.1 Controller Design and Simulation

Inner Current Controller Design and Testing

The Inner Current Controller design for a grid-tie inverter aims to regulate the current flowing between the inverter and the utility grid. This control strategy ensures that the inverter injects the desired amount of power into the grid while maintaining a stable and accurate current waveform.

One common approach to achieve this is by using a Proportional-Integral (PI) controller. The PI controller continuously compares the reference current (the desired current waveform) with the actual current flowing through the inverter. Based on this error, the PI controller generates a control signal that adjusts the inverter's operation to minimize the discrepancy between the reference and actual currents.

The PI controller consists of two main components: the proportional term (P) and the integral term (I). The proportional term responds to the instantaneous error between the reference and actual currents and provides a control signal proportional to this error. The integral term integrates the error over time and adds a control signal proportional to the cumulative error. The combination of these two terms enables the PI controller to respond to both transient and steady-state errors.

By tuning the proportional and integral gains of the PI controller, the system can be optimized to achieve a fast response while maintaining stability. The gains are adjusted based on the characteristics of the grid and the inverter, as well as the specific control objectives.

Overall, the Inner Current Controller design using a PI controller for a grid-tie inverter ensures accurate and stable current injection into the utility grid, contributing to the overall performance and reliability of the grid-tied system.

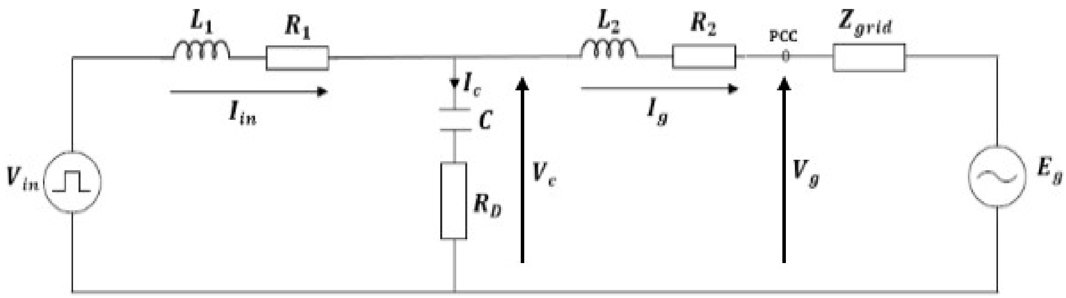


Figure 4.1:*Single Phase equivalent circuit*

In the model of the LCL filter, we consider that;

- At frequencies other than the fundamental frequency, the grid behaves essentially as a short circuit, i.e. Vg = 0.

An important transfer function for the LCL filter is given as;

$$H = \frac{i_g}{V_{in}} = \frac{Filter\ output\ current}{input\ voltage} \tag{1.1}$$

Therefore, *H* is an admittance transfer function and in the complex *S* domain, we have;

$$H(s) = \frac{I_g(s)}{V_{in}(s)} \tag{1.2}$$

Applying Kirchhoff's laws, the equivalent circuit in Fig. 2, the mathematical model of the filter in s-plane is given by these equations:

$$I_{in} - I_c - I_g = 0 \tag{1.3}$$

$$V_{in} - V_c = I_{in}(sL_1 + R_1) \tag{1.4}$$

$$V_c - V_g = I_g(sL_2 + R_2) \tag{1.5}$$

$$V_c = I_c\,(\frac{1}{sC} + R_D) \tag{1.6}$$

The circuit parameters are defined as;

V_{in}	Inverter Voltage
I_{in}	Inverter Current
V_c	Voltage across Filter Capacitor
I_c	Filter Capacitor Current
I_g	Grid Current
L_1	Inverter side inductor
L_2	Grid side inductor
C	Capacitor
R_D	Damping Resistor
V_g	Grid voltage
R_1	Inverter Side Parasitic Resistance
R_2	Grid Side Parasitic Resistance

Figure 15 gives the block diagram of the LCL Filter in the frequency domain.

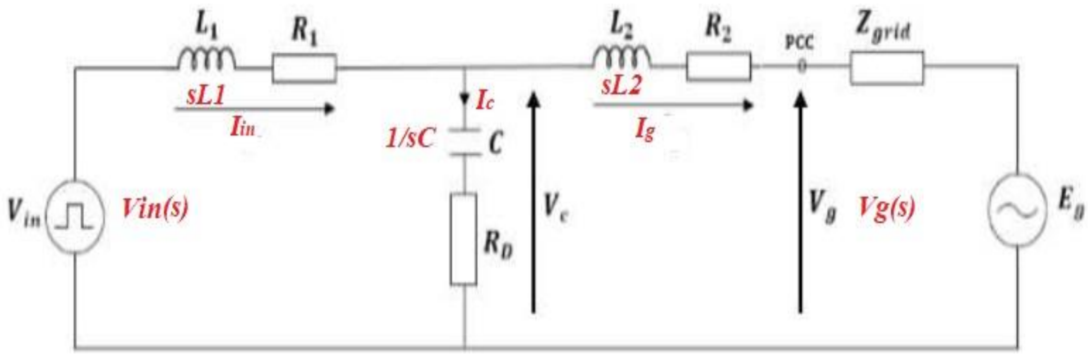


Figure 4.2: Block diagram of LCL Filter in S – Plane

Recall that for frequencies other than the fundamental frequency, Vg = 0.

Putting Vg = 0 in equation 1.5, gives;

$$V_c = I_g(sL_2 + R_2) \tag{1.7}$$

Equating 1.6 with 1.7 yields;

$$I_g(sL_2 + R_2) = I_c\,(\frac{1}{sC} + R_D) \tag{1.8}$$

This implies that;

$$I_c = I_g\,(\frac{s^2CL_2 + sCR_2}{sCR_D + 1}) \tag{1.9}$$

From equation 1.3,

$$I_{in} = I_c + I_g \tag{1.10}$$

Putting equation 1.9 into equation 1.10 gives;

$$I_{in} = I_g + I_g\,(\frac{s^2CL_2 + sCR_2}{sCR_D + 1}) \tag{1.11}$$

Also, from equation 1.4,

$$V_{in} = V_c + I_{in}(sL_1 + R_1) \tag{1.12}$$

Substituting equations 1.7 and 1.11 into 1.12 gives;

$$V_{in} = I_g(sL_2 + R_2) + (sL_1 + R_1)\,[I_g + \; I_g\,(\frac{s^2CL_2 + sCR_2}{sCR_D + 1})] \tag{1.13}$$

$$V_{in} = I_g\,[(sL_1 + R_1) + (sL_2 + R_2) + \frac{(sL_1 + R_1)(s^2CL_2 + sCR_2)}{sCR_D + 1}] \tag{1.14}$$

$$V_{in} = I_g \left| \frac{s^3CL_1L_2 + s^2C(L_1(R_2 + R_D) + L_2(R_1 + R_D)) + s(L_1 + L_2 + C(R_1R_2 + R_1R_D + R_2R_D)) + R_1 + R_2}{sCR_D + 1} \right| \quad (1.15)$$

Therefore, the transfer function according to equation 1.2 is:

$$Hd_{LCL}(s) = \frac{sCR_D + 1}{s^3CL_1L_2 + s^2C(L_1(R_2 + R_D) + L_2(R_1 + R_D)) + s(L_1 + L_2 + C(R_1R_2 + R_1R_D + R_2R_D)) + R_1 + R_2} \quad (1.16)$$

4.2 Hardware Implementation

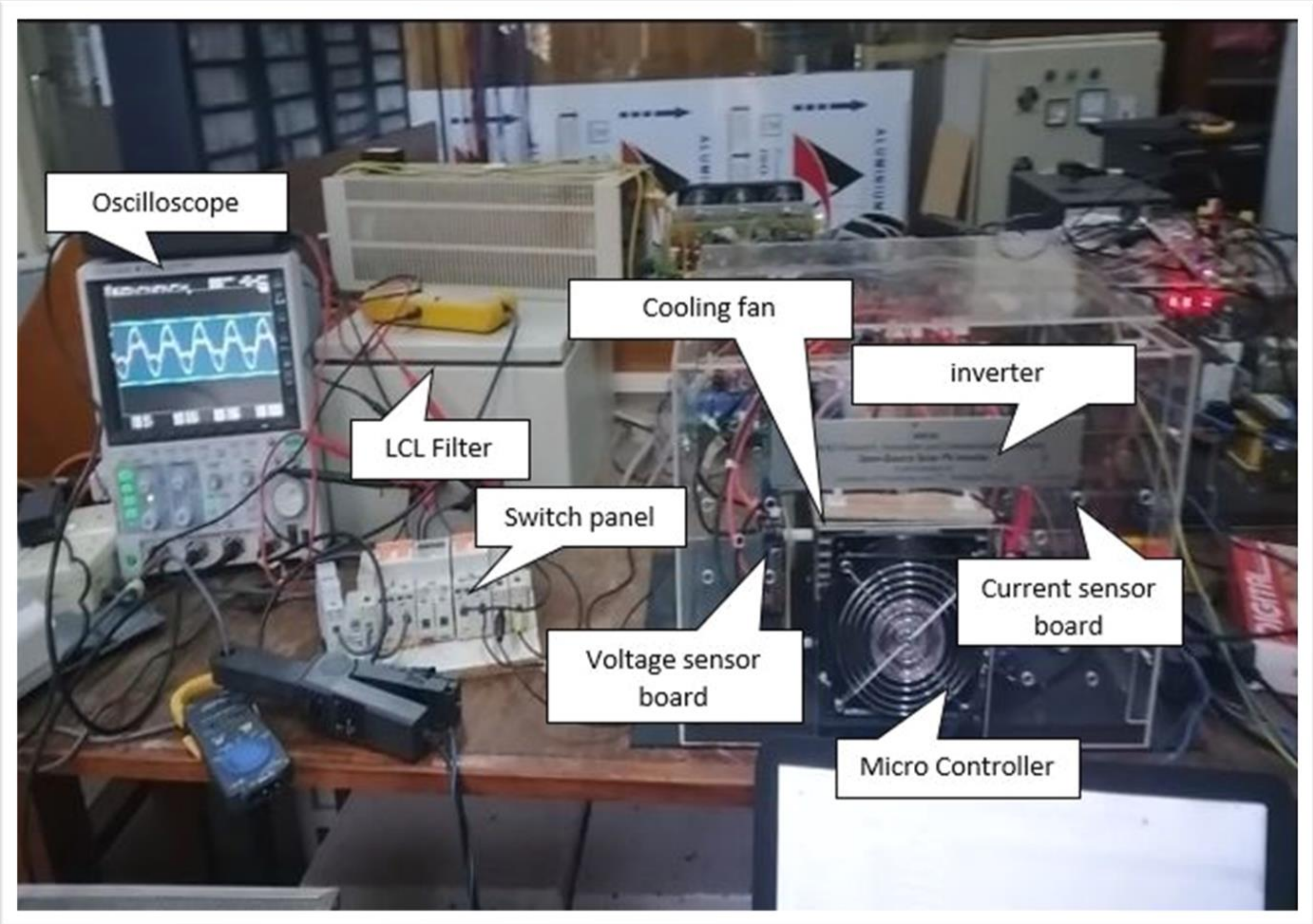


Figure 4.3: Inverter hardware setup

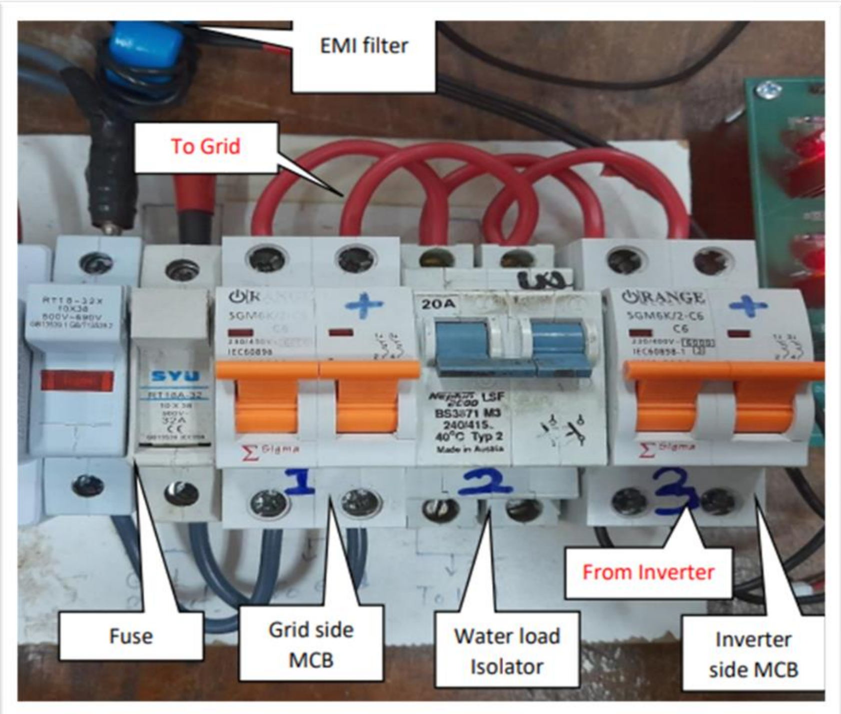


Figure 4.4: Switch panel connections

MCB 1 (Grid-side MCB):

MCB 1 functions as an isolator and provides overcurrent protection on the grid side. This critical component ensures that any electrical anomalies or excessive currents in the grid are promptly detected and isolated to prevent damage to the system or connected equipment. By incorporating MCB 1 into our design, we enhance the safety and reliability of the grid-tied operation.

MCB 2 (Water Load Isolator):

During off-grid operation, MCB 2 acts as an isolator specifically for the water load. This mechanism ensures that the water load remains separated from the rest of the system, preventing any potential interference or disturbances. By effectively isolating the water load, we ensure the stability and integrity of the off-grid configuration.

MCB 3 (Inverter-side MCB):

MCB 3 plays a crucial role in providing isolating capabilities and overcurrent protection on the inverter side. It safeguards the inverter and associated components from excessive currents or faults, thereby promoting safe and efficient energy conversion. By integrating MCB 3 into our system, we enhance the overall reliability and longevity of the inverter.

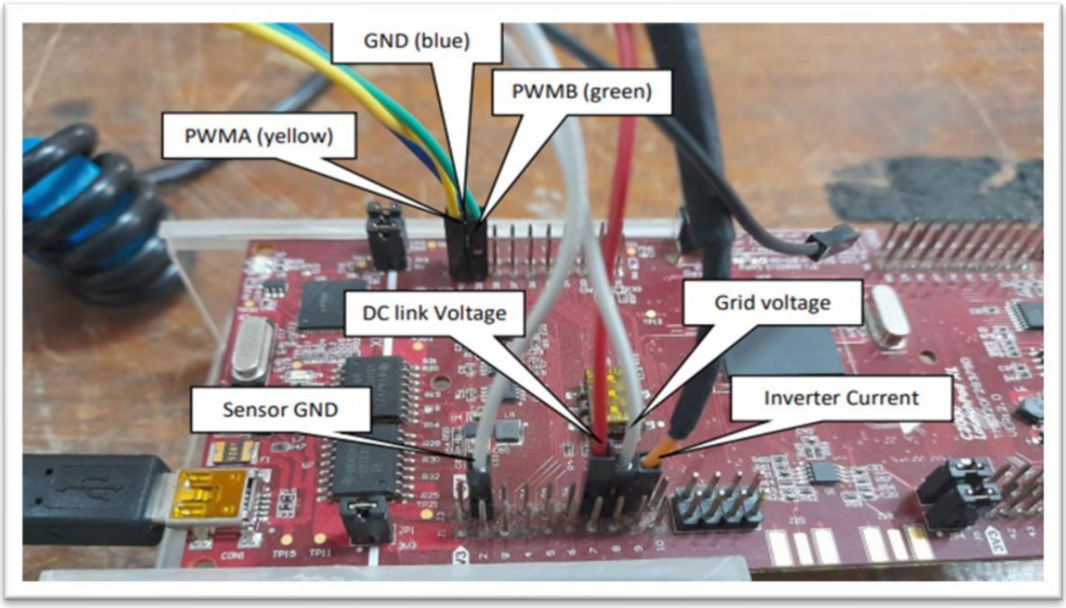


Figure 4.5: Microcontroller input and output connections

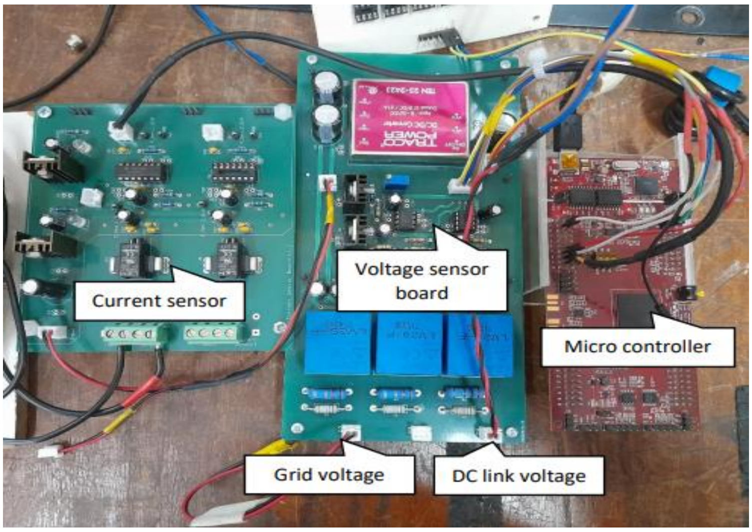


Figure 4.6: Sensor board connections and micro controller

4.3 Controller Implementation in Software

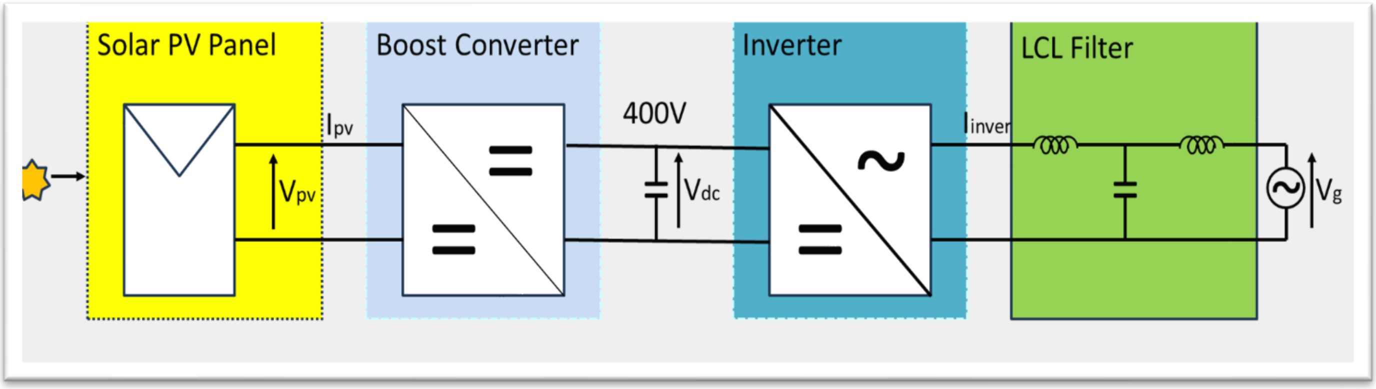


Figure 4.7: Full Setup

In our project, we employed the Texas Instruments C2000 TMS320F28379D microcontroller to execute the controller functions effectively. To implement the controller, we utilized Altair Embed 2019.1BUILD53, which facilitated the seamless integration and deployment of the controller into our smart grid system.

We have two files essential for the controller implementation and monitoring. The first file, named "Test_1_control_1_sep_No_filters_With_New_controller_and_PLL," contains the controller logic itself. The second file, labeled "Test_1_control_1_sep_No_filters_With_New_controller_and_PLL_1d," serves as the debug mode of the controller. This mode allows us to monitor real-time signals generated by the controller during its operation.

The debug mode presents a unique advantage, enabling us to dynamically modify controller parameters in real time while it is running. This capability empowers us to fine-tune and optimize the controller's performance, adjusting critical parameters on the fly for enhanced efficiency and accuracy.

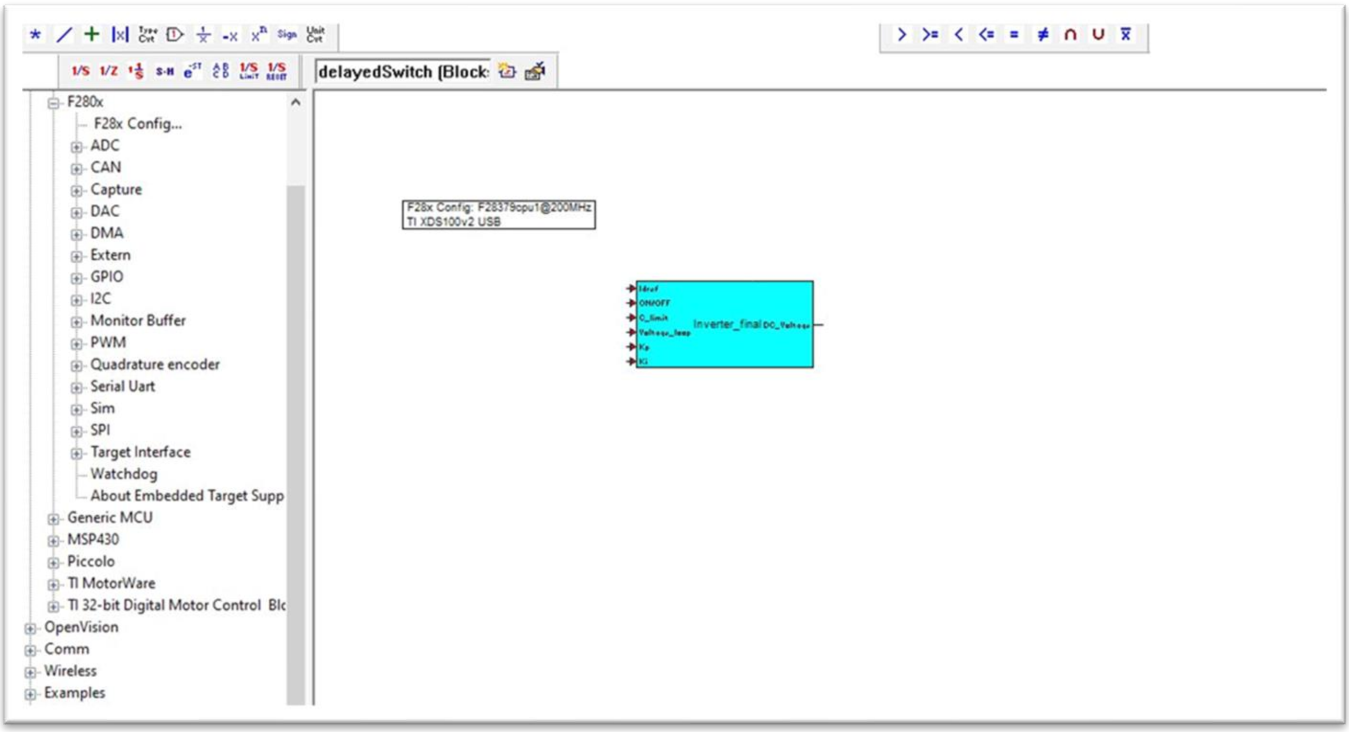


Figure 4.8: Controller main window blocks

- To go inside the main controller double tap on Controller main block in blue color.

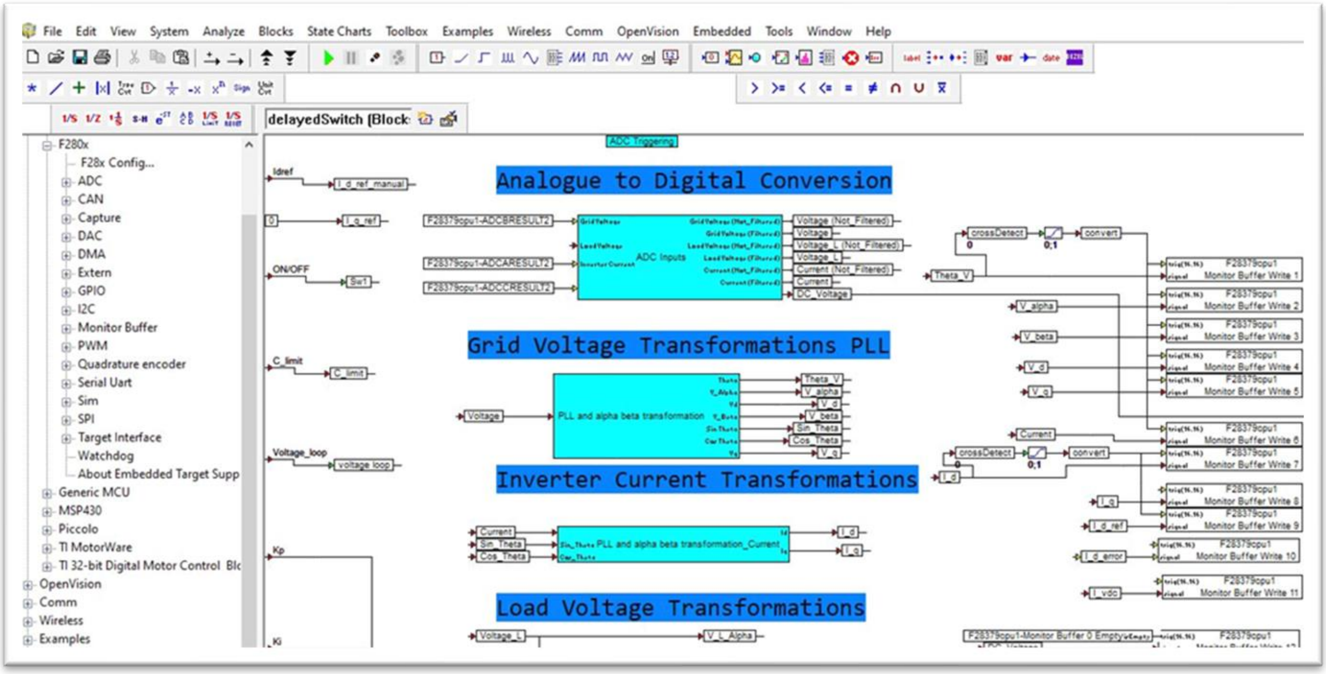


Figure 4.9: Inside the main Controller block

Phase Lock Loop – PLL Block

Synchronous and Reference Frame

The transformation of the three-phase system from the stationary frame to the synchronousrotating frame can be done by the following steps.

Step 1

The three-phase stationary reference frame components are projected onto two orthogonalaxes (Vα and Vβ)

$$\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Where a, b and c represent three-phase stationary frame components and Vα and Vβrepresent the components projected onto the two stationary orthogonal axes.

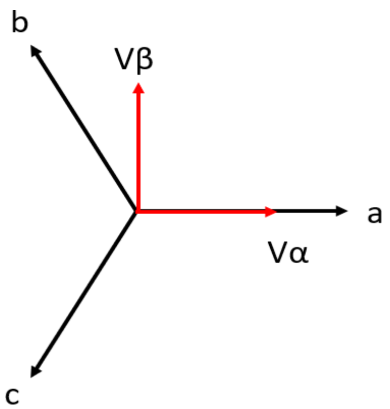


Figure 4.10: Clarke transformation vectors

Step 2

Transforming the two-phase quantities (Vα and Vβ) from the stationary reference frame to the synchronous rotation frame (with the corresponding d and q axes).

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V\alpha \\ V\beta \end{bmatrix}$$

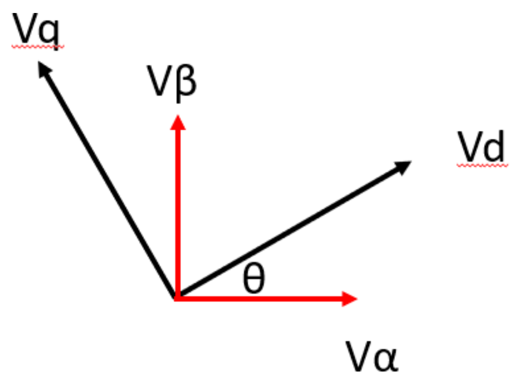


Figure 4.11: Park transformation vectors.

Orthogonal signal generation.

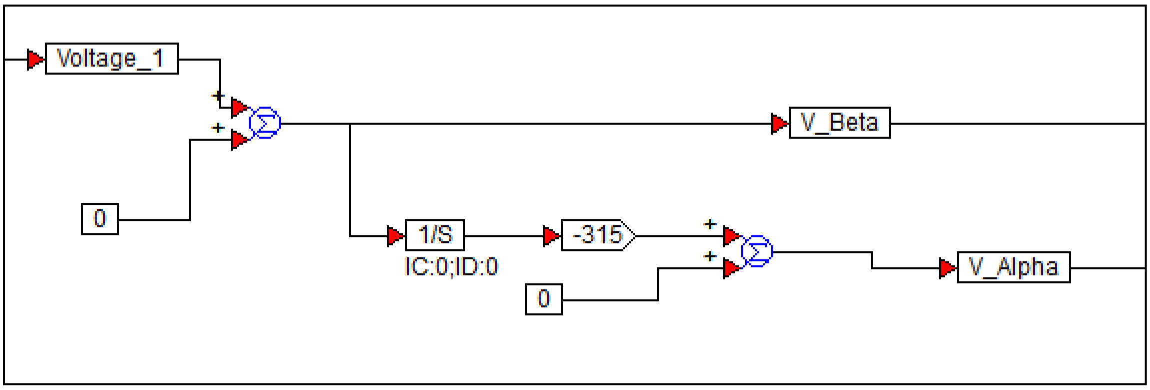


Figure 4.12: Block diagram of orthogonal signal generation using Integrator.

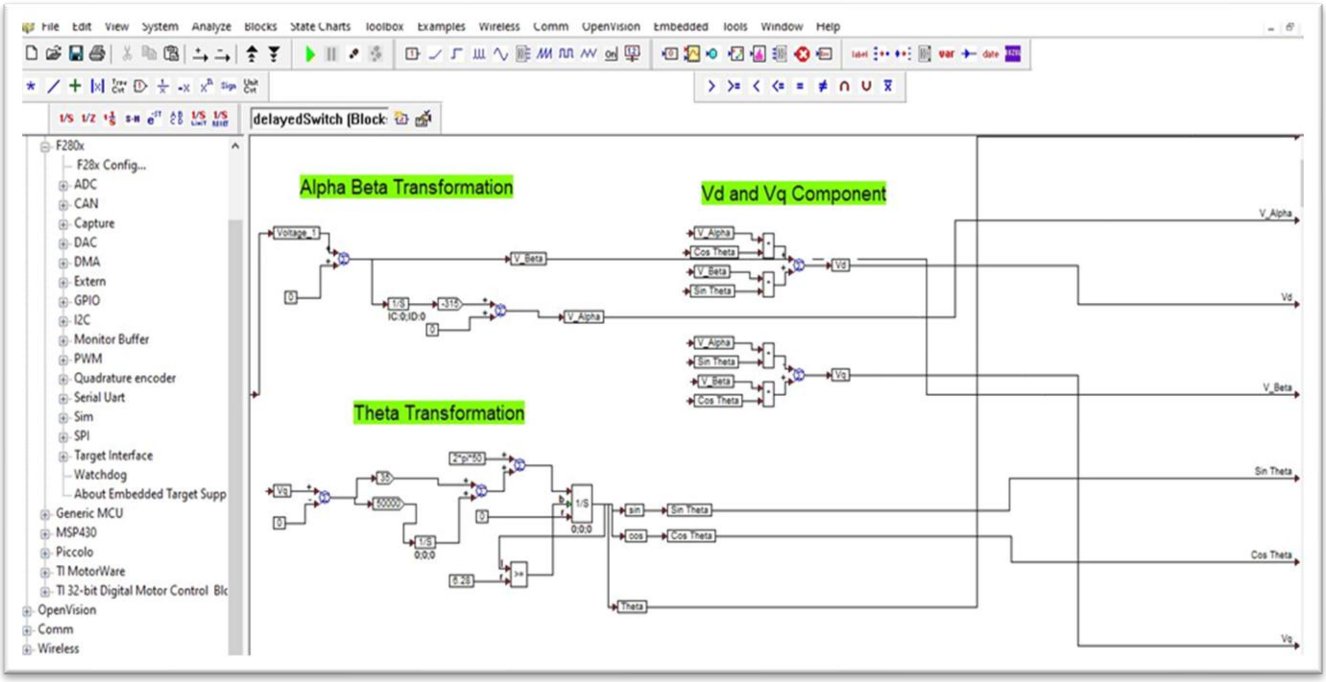


Figure 4.13: PLL Block (Clark & Park Transforms)

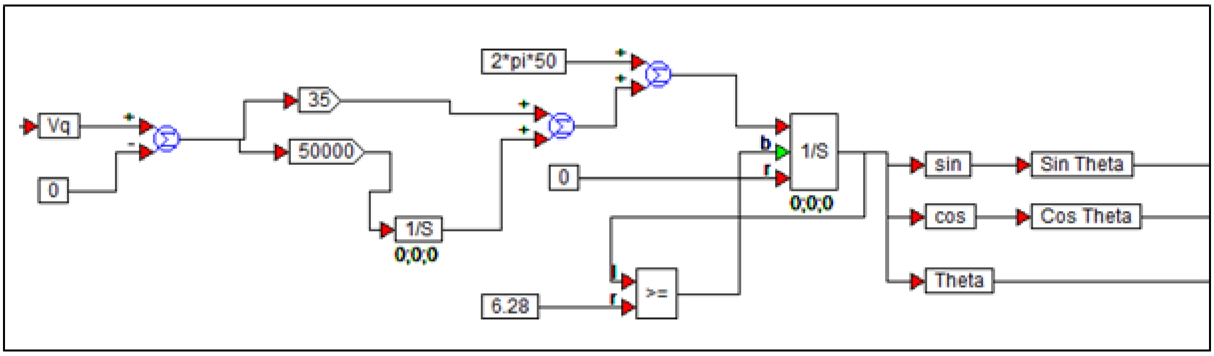


Figure 4.14: PI Controller Block diagram of the PLL.

Current controller

The Inner Current Controller design for a grid-tie inverter aims to regulate the current flowing between the inverter and the utility grid. This control strategy ensures that the inverter injects the desired amount of power into the grid while maintaining a stable and accurate current waveform.

One common approach to achieve this is by using a Proportional-Integral (PI) controller. The PI controller continuously compares the reference current (the desired current waveform) with the actual current flowing through the inverter. Based on this error, the PI controller generates a control signal that adjusts the inverter's operation to minimize the discrepancy between the reference and actual currents.

The PI controller consists of two main components: the proportional term (P) and the integral term (I). The proportional term responds to the instantaneous error between the reference and actual currents and provides a control signal proportional to this error. The integral term integrates the error over time and adds a control signal proportional to the cumulative error. The combination of these two terms enables the PI controller to respond to both transient and steady-state errors.

By tuning the proportional and integral gains of the PI controller, the system can be optimized to achieve a fast response while maintaining stability. The gains are adjusted based on the characteristics of the grid and the inverter, as well as the specific control objectives.

Overall, the Inner Current Controller design using a PI controller for a grid-tie inverter ensures accurate and stable current injection into the utility grid, contributing to the overall performance and reliability of the grid-tied system.

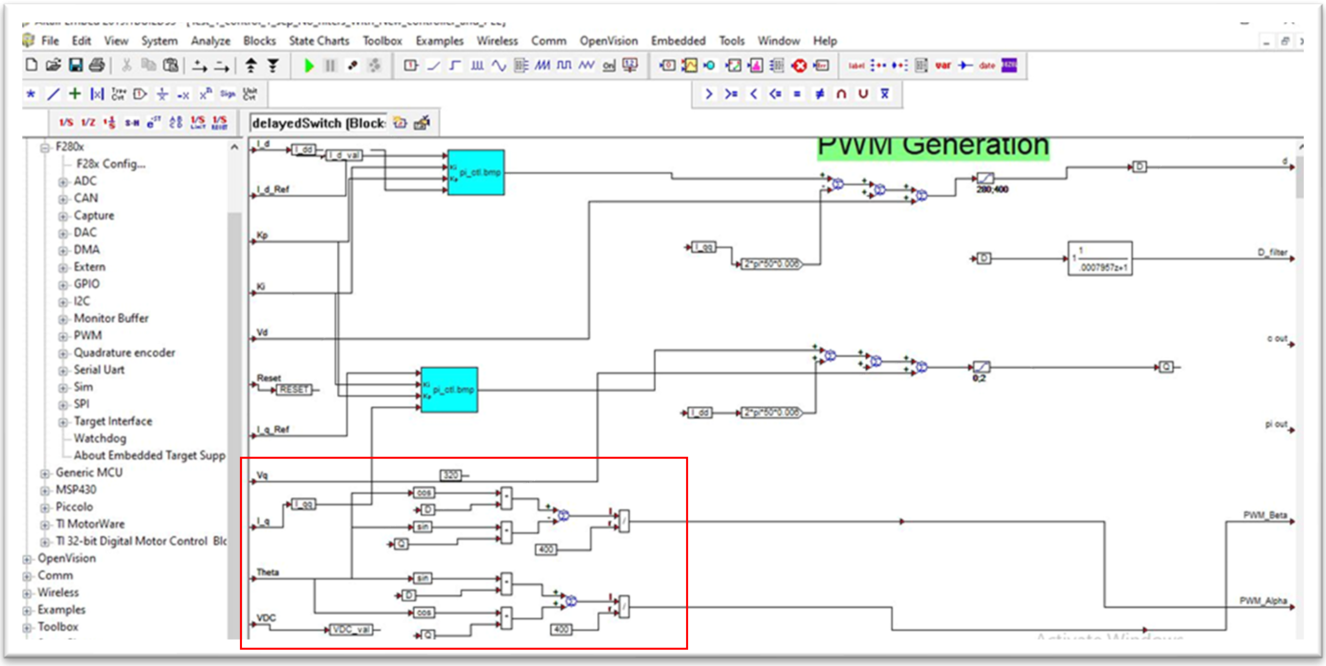


Figure 4.15: PI Current Controller Block

DC link voltage Controller

This DC link voltage controller keeps the voltage at a given value by using a small amount of boost converter output current, the excess current from boost converter output is pushed to the grid through the inverter. With the irradiance and the MPPT algorithm boost converter output current changes. As a result, the inverter current also changes, but DC link voltage is kept at a given value throughout the process. (Practically it will change in the range 395V-405V)

To keep the Id_ref on the positive side we get the dc link voltage error by subtracting the given voltage reference by actual measurement (commonly if it needs to get an error, measurement is subtracted by reference)

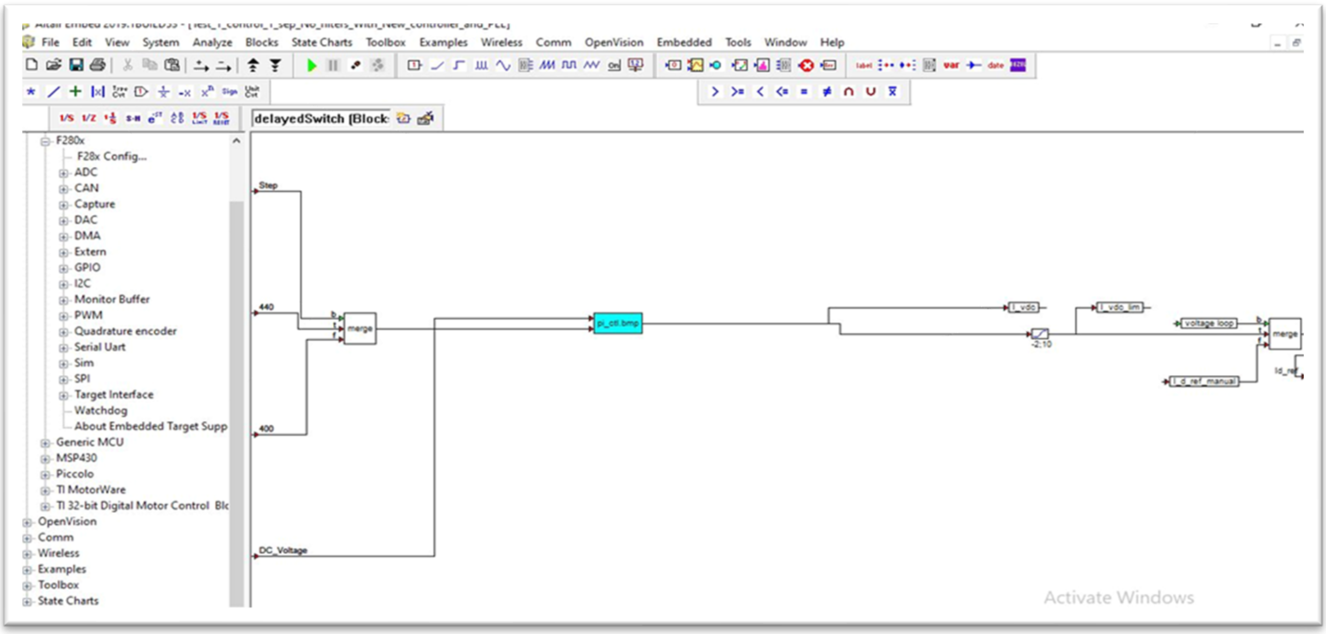


Figure 4.16: Outer Voltage Controller Block

Protection Implementation

PWM Protection – Switch of inverter PWM if there is any error.

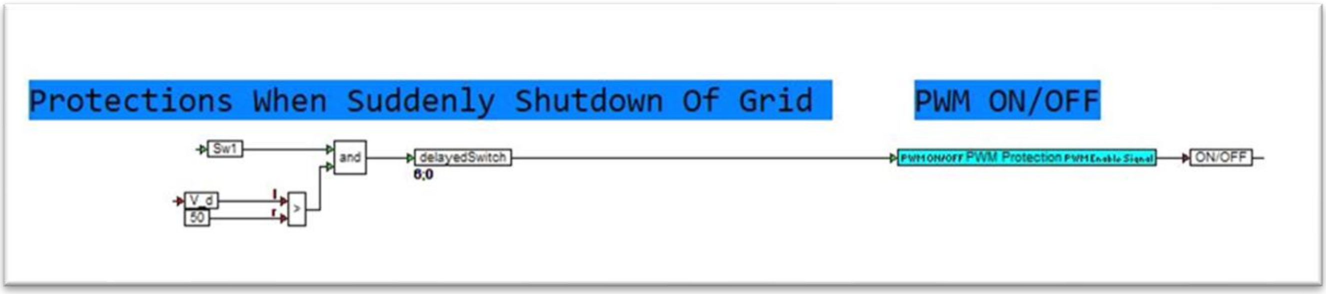


Figure 4.17: PWM Protection Block

When the supply is disconnected due to a sudden interruption in the grid, the PWM signal is automatically stopped due to protection. When the Grid supply is restored, the PWM will automatically turn on after 12 seconds.

DC Link Protection (Over voltage Protection)

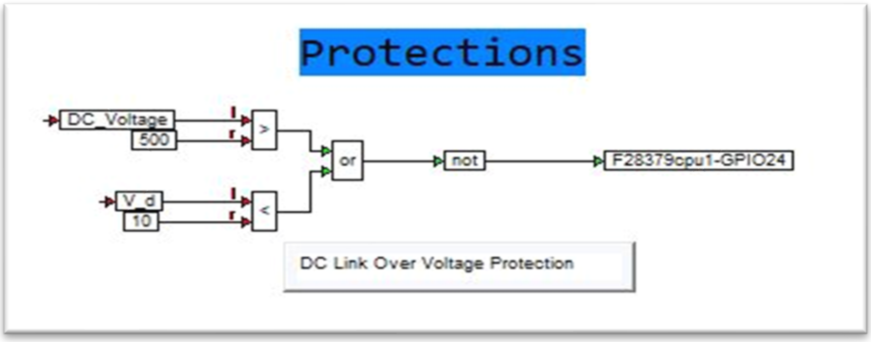


Figure 4.18: DC Link Protection Block

The output signal is connected to the contactor and the solar supply is disconnected when the DC link exceeds 500V or the grid connection is broken down.

Debug Mode of the Controller

The block consists of six inputs that are crucial for its operation:

- Id_ref manual (for initial startup only):

This input allows for the manual adjustment of the Id reference during the initial startup phase. It aids in setting the desired value for the Id current component, providing flexibility during the initial system calibration.

- PWM on/off (Controller ON/OFF):

The PWM on/off input controls the activation or deactivation of the controller. When turned on, the controller starts its operation, regulating the inverter output accordingly. Conversely, when turned off, the controller ceases its activity, allowing for manual control or system maintenance.

- C_limit:

The C_limit input sets the current limit, restricting the maximum allowable current flow within the system. This parameter ensures safe operation by preventing excessive currents that could lead to system damage or instability.

- Voltage loop on/off:

The voltage loop on/off input determines the activation or deactivation of the voltage loop control. When enabled, the controller actively regulates the voltage output of the system. Disabling it allows for manual control or specific operational scenarios.

- Kp (Do not change this value - 1):

The Kp input represents the proportional gain of the controller and is set to a fixed value of 1. It remains constant to maintain stability and desired control performance.

- Ki (Do not change this value - 1.2):

The Ki input denotes the integral gain of the controller and is set to a constant value of 1.2. It remains unchanged to ensure optimal integral control and eliminate steady-state errors.

Moreover, the block allows monitoring of voltages, currents, and controller signals in real-time while the controller is operational. This feature provides valuable insights into the system's performance, allowing for fine-tuning and optimization during runtime to achieve the desired operational efficiency and stability.

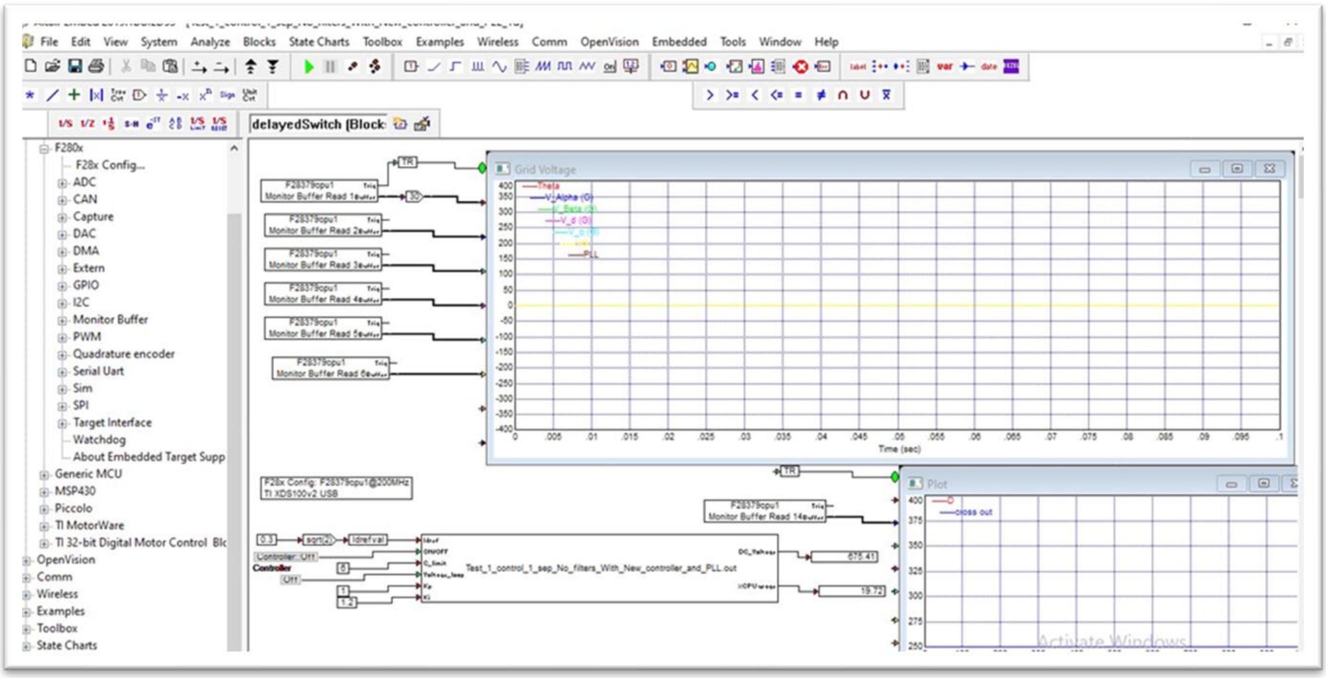


Figure 4.19: Debugging Mode

4.4 Inverter Grid-tied Mode

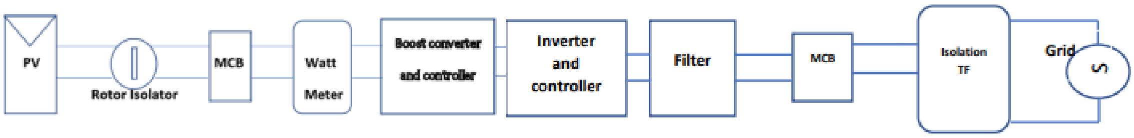


Figure 4.20: Grid connected inverter block diagram.

To start up the inverter, follow these steps: Connect all wires and components properly. Use separate laptops for the boost converter and inverter controllers. Connect the inverter to the boost converter and place the multimeter on the DC link for voltage monitoring. Power on the 20V supplies, probes, and oscilloscopes. Connect the inverter controller USB to the laptop and press the run button on the debug mode. Turn on all breakers and switch on the grid supply (optional isolation transformer). Activate the inverter PWM signals using the debug mode in the software, resulting in a DC link voltage around 345V. Then switch on the outer voltage loop, allowing it to stabilize at approximately 400V (takes nearly 8 minutes). Connect the boost converter controller USB to the laptop and press the run button on the debug mode. Switch on the solar power input isolator (before turning on PWM). Finally, switch on the boost converter PWM.

For the shutdown procedure: Switch off the PWM signals of the boost converter controller, followed by the grid connection. Turn off both voltage loop and PWM signals in the inverter controller and disconnect the grid connection.

Important points: Switch on cooling fans, use a UPS for 20V DC supplies, wear fully covered shoes, regularly monitor DC link voltage with a voltmeter. If DC link voltage exceeds 600V, switch off the solar input using the rotor isolator (automatically happens if DC link exceeds 500V in unexpected situations). At the beginning, switch off all switches on both controllers. Use differential probes for voltage measurement and switch off current probe power after testing to ensure safety.

Inverter Start up Procedure.

As soon as the grid power is turned on and connected to the output side of the inverter, the DC link capacitor undergoes a rectification process, resulting in a charge of 300 volts. During this phase, the L filter plays a crucial role in connecting the grid voltage and the PWM voltage of the inverter, as illustrated below.

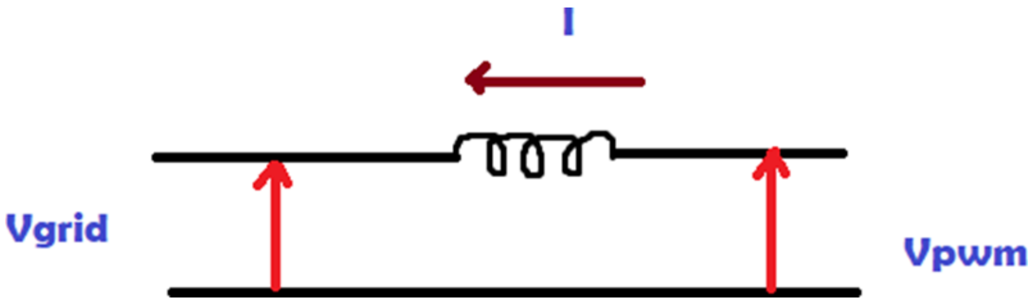


Figure 4.21:Grid voltage and the PWM voltage of the inverter.

In the static compensator mode of the inverter, it is observed that the grid voltage and Vpwm are in phase, while the grid current is perpendicular to the grid voltage. This situation arises because, during this stage, the transformations being performed are not functioning perfectly.

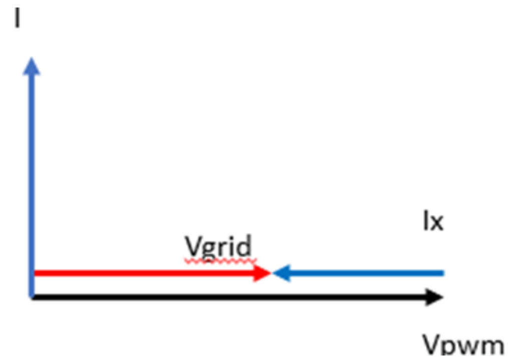


Figure 4.22: Phasor diagram grid voltage and Vpwm at the static compensator mode.

To achieve an in-phase relationship between the grid voltage and current, it is necessary to apply the Vpwm waveform as depicted in the following phase diagram. This ensures proper alignment and synchronization between the two electrical quantities.

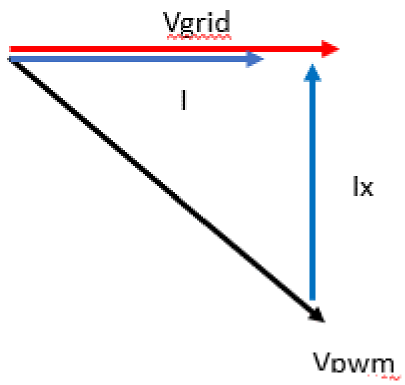


Figure 4.23: In-phase relationship between the grid voltage and current.

During this particular stage, all transformations are functioning optimally, resulting in the grid current being in phase with the grid voltage, as illustrated in Figure 14. To achieve this, it is necessary to connect the solar panel with the boost converter to the inverter through an active power transformation process. This ensures efficient power transfer and synchronization between the solar source and the grid.

Chapter 5

Results and Analysis

5.1 Performance Evaluation

The performance evaluation of our smart grid project involves a comprehensive assessment of its achievements, efficiency, and impact on meeting the defined objectives. This evaluation encompasses various aspects of the project's implementation, including design, development, testing, and ongoing works. The following sections provide a detailed content for each aspect of the performance evaluation:

- Design and Development:

Evaluate the design process, focusing on the integration of advanced converters and controllers to create grid infrastructure. Assess the effectiveness of utilizing existing converters and introducing controllers as solar inverters, enhancing the system's flexibility and control capabilities.

Analyze the development of the specialized DC-DC converter for efficient energy management between solar panels and battery storage. Evaluate the success of determining inverter specifications based on battery and load requirements to ensure seamless energy conversion and distribution.

- Testing and Validation:

Assess the thoroughness of the comprehensive testing conducted on the solar setup to verify its reliability, performance, and safety. Evaluate the rigorous testing of smart grid functionalities, including MPPT Algorithm, Energy Optimization, and grid stability (Continues stable Current and Voltage output), to validate system efficiency.

Evaluate the progress and effectiveness of the ongoing works in designing and developing the battery storage system. Assess the impact of the battery storage system on enhancing energy storage capacity and grid stability.

- Full System Protections:

Analyze the implementation and effectiveness of full system protections to safeguard against potential faults and ensure system reliability.Evaluate the impact of enhanced PV penetration on overall energy efficiency and grid stability.

- Impact and Contribution:

Measure the project's overall contribution to sustainable and eco-friendly energy solutions.

- Challenges and Mitigation:

Identify any challenges faced during the project implementation and evaluate the strategies used to mitigate them. Analyze how the project addressed technical, operational, and logistical challenges.

- Future Potential and Recommendations:

Assess the future potential of the smart grid system in scaling up and accommodating larger renewable energy capacities.Provide recommendations for further improvements, such as integrating additional renewable energy sources, enhancing control algorithms, or expanding grid functionalities.

In conclusion, the performance evaluation provides a comprehensive overview of the project's accomplishments and areas of improvement. By analyzing design, testing, ongoing works, and the system's impact, the evaluation highlights the project's success in achieving sustainable and efficient energy solutions.

5.2 Results Analysis

The results analysis of our smart grid project reveals a successful implementation of two MPPT algorithms, namely the Perturb and Observe (P&O) method and the Incremental Conductance (IncCond) method. The evaluation highlights the drawbacks of the P&O method, such as oscillations, slow convergence, sensitivity to noise, steady-state errors, partial shading issues, start-up delays, reduced efficiency, and limited information utilization. In response to these limitations, the project opted for the IncCond method, which overcomes the drawbacks and offers faster convergence, improved oscillation handling, and increased accuracy in tracking the maximum power point (MPP).

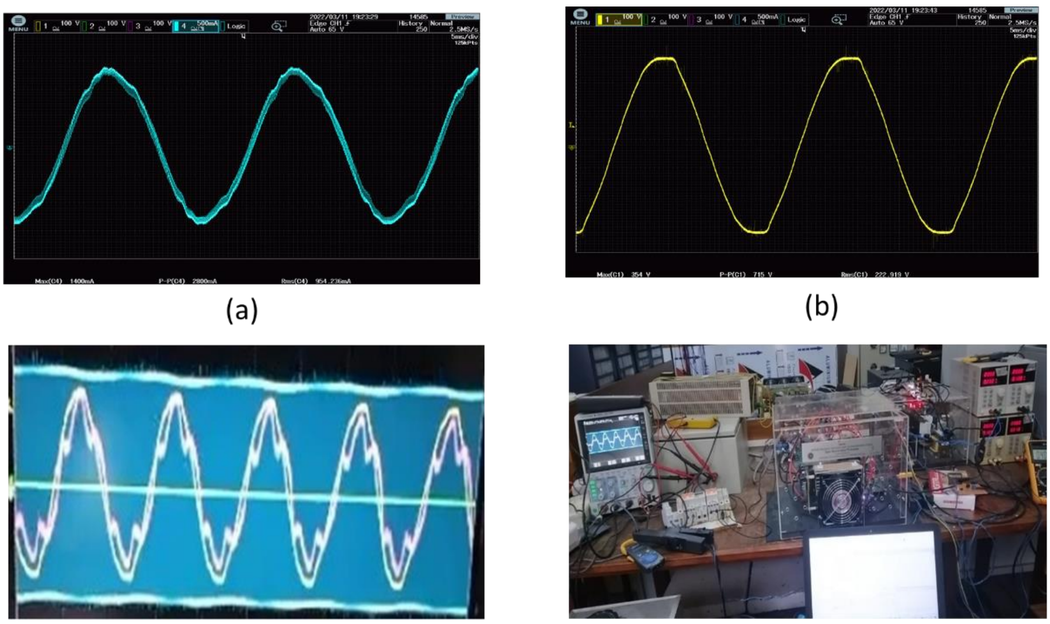
The design and implementation of precise and accurate controllers for both the converter and inverter are a significant achievements of the project. Rigorous testing and analysis confirmed the successful integration of these controllers into the system, contributing to efficient energy management and grid stability.

Furthermore, the project successfully developed and tested protection mechanisms for overvoltage, overcurrent, and undervoltage conditions. These protections played a crucial role in ensuring the system's safety and reliability during real-time operation. The high accuracy of the protection systems attests to their robustness and effectiveness in safeguarding the smart grid.

The final milestone of grid connection and feeding the maximum power to the grid demonstrated the successful integration of the smart grid system into the existing power distribution infrastructure. The ability to supply the maximum power to the grid showcases the system's capability to contribute to overall energy generation and support the grid's stability.

In conclusion, the project achieved commendable results through the successful design, development, and implementation of the smart grid system. The selection of the IncCond MPPT method addressed the limitations of the P&O method, resulting in improved efficiency and accurate power tracking. The development of high-accuracy controllers and effective protection mechanisms further strengthened the system's performance and reliability. The successful grid connection and power feeding reflect the system's readiness for practical implementation.

The project's results highlight its contribution to sustainable energy solutions, addressing challenges in solar energy integration and grid stability. The implementation of advanced algorithms, precise controllers, and robust protection mechanisms showcases the project's innovation and commitment to environmental consciousness.



(a) (b) (c) (d)

Figure 5.1: (a) Inverter output voltage, (b) Grid voltage, (c) Inverter current and (d) Full system

Chapter 6

Comparison and Conclusion

6.1 Comparison with Objectives

In comparison to general solar inverters used in Sri Lanka and other countries, the project's single-phase open-source solar PV inverter offers several significant advantages and unique features. While imported proprietary inverters limit access to control functions, the developed open-source inverter provides the flexibility to access and edit grid supporting functions required for seamless integration with the distribution network in the grid.

One key distinction lies in the ability to introduce various MPPT algorithms, active power control functions, and reactive power control functions in both the boost converter and the inverter. This capability allows for advanced optimization and customization of the system's performance, ensuring efficient power generation and grid interaction.

Furthermore, the proprietary inverters may lack the necessary functionalities needed by the utility to implement essential grid supporting functions. In contrast, the open-source inverter empowers the utility to tailor the system according to specific requirements, enhancing the grid stability and overall performance.

The hardware implementation and testing of the inverter and boost converter add to the project's reliability and real-world viability. By providing a smart device solution, the project opens the door for future innovations and upgrades, enabling the integration of emerging technologies and further enhancing the system's efficiency.

Overall, the project's open-source solar PV inverter represents a forward-looking approach that fosters greater flexibility, control, and adaptability in harnessing photovoltaic energy.

6.2 Conclusion

In conclusion, the successful completion of Phase One of our project marks a significant milestone in our mission to design and implement a smart grid system powered by solar energy. The primary objective of achieving sustainable and eco-friendly energy solutions has been accomplished through the development of an intelligent grid infrastructure equipped with advanced converters and controllers. This infrastructure optimizes energy usage, reduces costs, and enhances overall efficiency, paving the way for a greener and more sustainable future.

During Phase One, we achieved several key objectives. By utilizing existing converters and introducing controllers, we seamlessly integrated solar energy into the smart grid system, providing a solid foundation for efficient energy management. The design and construction of a specialized DC-DC converter further enhanced the system's capability to manage energy flow between solar panels and battery storage effectively.

Comprehensive testing of the solar setup ensured its reliability, performance, and safety, validating the system's readiness for practical implementation. Rigorous testing of smart grid functionalities demonstrated the system's efficiency and versatility.

As we move into Phase Two, our ongoing efforts focus on the design and development of the battery storage system, a crucial component in enhancing energy storage capacity and grid stability. Additionally, the implementation of a SCADA system will empower us with comprehensive real-time monitoring and control capabilities.

To ensure the system's robustness and security, we are diligently working on implementing full system protections, safeguarding against potential faults, and ensuring the reliability of the entire smart grid.

In conclusion, the achievements of Phase One and the ongoing progress in Phase Two represent significant contributions to the advancement of sustainable energy solutions. Our dedication to designing and developing a smart grid system that harnesses solar energy and battery storage is driving us closer to a more environmentally conscious and energy-efficient future. Through continuous innovation and collaboration, we are confident that our project will have a lasting impact on promoting sustainable energy practices and addressing global energy challenges.

References

1. Dual loop control for single phase PWM inverter for distributed generation.