KATHMANDU UNIVERSITY

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

FINAL REPORT

On

Design and Simulation of a PV System With Battery Storage Using Buck Boost Converter

A Fourth-Year final report submitted in the partial fulfillment of the requirements for four years of Bachelor's of Engineering in Electrical & Electronics Engineering

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ABSTRACT

This project presents the design and implementation of a photovoltaic (PV) system integrated with battery storage, utilizing a bidirectional buck-boost converter to manage energy flow. The system employs two distinct hardware modules—a buck converter and a boost converter—configured to operate manually, enabling flexible control between the PV array, battery, and load. A comprehensive simulation of the system was developed using MATLAB Simulink to evaluate its performance under diverse operating conditions. The proposed design ensures efficient energy utilization and enhances the reliability of microgrids, particularly in scenarios with variable renewable energy inputs. The results validate the system's capability to maintain stable power delivery and optimize energy management, contributing to the advancement of sustainable energy solutions.

ACKNOWLEDGEMENT

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Thank you all for your anticipated support and assistance.

LIST OF ABBREVIATIONS

Abbreviation	Full Form
AC	Alternating Current
BMS	Battery Management System
CV	Control Voltage
DC	Direct Current
DCM	Discontinuous Conduction Mode
DoEEE	Department of Electrical & Electronics Engineering
ESS	Energy Storage Systems
GND	Ground
IC	Integrated Circuit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
PI	Proportional-Integral
PV	Photovoltaic
PV-ESS	Photovoltaic and Energy Storage Systems
PWM	Pulse Width Modulation
SOC	State of Charge
STC	Standard Test Conditions
TH	Threshold
TR	Trigger
VCC	Voltage at the Common Collector
VFB	Voltage Feedback
VIN	Voltage Input
VOUT	Voltage Output

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CHAPTER I INTRODUCTION

1.1 Background

The escalating global demand for clean and sustainable energy has positioned photovoltaic (PV) systems as a cornerstone of renewable energy solutions. These systems harness sunlight to generate electricity through solar cells, offering a green alternative to fossil fuels with zero harmful emissions during power production. The environmental benefits of solar energy, coupled with its abundant availability, make it a critical component in the transition toward a low-carbon future. However, the inherent intermittency of solar energy, driven by factors such as weather variability, cloud cover, and diurnal cycles, poses significant challenges to the reliability and consistency of PV systems.

To overcome these limitations, integrating battery storage systems has emerged as a vital strategy. By storing excess energy generated during periods of high solar irradiance, battery storage ensures a continuous power supply during low or no sunlight conditions, enhancing the practicality of PV systems for both grid-connected and off-grid applications. This project focuses on designing and simulating a PV system with integrated battery storage, utilizing a bidirectional DC-DC converter to manage energy flow efficiently. The system is modeled and analyzed using MATLAB Simulink, enabling a comprehensive evaluation of its performance under standard testing conditions and varying environmental scenarios. The simulation aims to validate the system's ability to deliver stable and efficient power output, contributing to the advancement of renewable energy technologies. [1]

1.2 Motivation

The motivation for this project is rooted in the pressing global need to transition from fossil fuel-based energy systems to sustainable and renewable alternatives, driven by the escalating impacts of climate change and environmental degradation. As the world seeks to reduce greenhouse gas emissions and mitigate the adverse effects of conventional energy sources, solar energy stands out as a highly promising solution due to its widespread availability and minimal environmental footprint. However, the intermittent nature of solar power necessitates innovative approaches to ensure a reliable and uninterrupted energy supply. The integration of battery storage systems addresses this challenge by enabling the storage of surplus energy generated during peak sunlight hours, which can then be utilized during periods of low solar generation, such as nighttime, cloudy days, or seasonal variations. This capability not only enhances the reliability of PV systems but also maximizes energy utilization, making solar energy a viable primary power source for diverse applications, from residential households to remote off-grid communities. By developing a PV system with advanced energy management capabilities, this project aims to contribute to the global effort to build resilient and sustainable energy infrastructure, aligning with international goals for carbon neutrality and environmental stewardship.

1.3 Problem Definition

The global shift towards renewable energy is driven by the urgent need to reduce carbon emissions and combat climate change. However, solar energy, one of the most promising renewable sources, faces significant challenges due to its intermittent nature. Solar power generation fluctuates with environmental conditions, leading to inconsistent energy supply, particularly in remote or off-grid areas where reliable electricity is essential. Without efficient energy storage systems, excess energy generated during peak sunlight hours is wasted, and power cannot be supplied during periods of low or no sunlight. This problem hampers the effectiveness and reliability of solar energy as a primary power source.

Additionally, optimizing the efficiency of solar energy conversion is critical but complex. Without a robust control system, the PV system may not operate at its optimal capacity, leading to energy losses. To address these issues, this project focuses on designing and simulating a PV system with integrated battery storage, controlled by two DC-DC converter.

CHAPTER II PROJECT OVERVIEW

2.1 Objectives of Project

The objectives of this project focus on designing, simulating, and implementing a photovoltaic (PV) system with battery storage, using a bidirectional DC-DC converter for simulation and separate buck and boost converters for hardware. The objectives are outlined as follows:

i. **Simulate a PV System with Battery Storage**: Create a MATLAB Simulink model of a PV system with battery storage, using a bidirectional DC-DC converter to manage energy flow. Test the system under varying solar and load conditions to ensure reliable and efficient power delivery.

ii. **Simulate a PI Controller for System Stability**: Integrate a Proportional-Integral (PI) controller in the simulation to regulate the bidirectional converter, ensuring stable voltage, efficient battery charging/discharging, and minimal energy losses.

iii. **Develop Hardware with Buck and Boost Converters**: Build a hardware prototype with a boost converter (4V to 19-24V) and a buck converter (24V to 10-13V, potentiometer-adjusted) to regulate energy flow between the PV array, battery, and load, ensuring precise voltage control.

These objectives aim to deliver a reliable PV system with battery storage, combining simulation and hardware to address solar energy intermittency.

2.2 Significance of Study

This project holds significant importance in the broader context of advancing renewable energy technologies and addressing pressing global challenges related to energy sustainability, climate change, and energy access. By focusing on the development and optimization of a photovoltaic (PV) system integrated with battery storage and controlled through a bidirectional DC-DC converter, the project aims to contribute to ongoing efforts to enhance the efficiency, reliability, and accessibility of renewable energy systems. Key aspects of the project include:

i. **Addressing Energy Intermittency**: Solar power generation is inherently variable, dependent on environmental factors such as sunlight availability, which can fluctuate throughout the day and across seasons. This intermittency is a significant challenge for consistent energy supply, especially in regions with high energy demand.

ii. **Integration of Battery Storage**: The inclusion of a battery storage system addresses the issue of energy intermittency by storing excess energy generated during peak sunlight hours. This stored energy can then be used during periods when solar energy is unavailable, such as at night or during cloudy weather.

iii. **Ensuring Consistent Power Supply**: The battery storage ensures that a reliable and steady power supply is available, even in the absence of sunlight, making the system more adaptable for a variety of applications.

iv. **Enhancing Efficiency and Reducing Energy Waste**: By optimizing energy storage and consumption, the system reduces wasted energy and ensures that solar resources are used effectively, enhancing the overall efficiency of the energy system.

CHAPTER III LITERATURE AND TECHNOLOGY SURVEY

3.1 Literature Review

We studied different papers and products in the market and identified the problem with each problem as well as identified its features that we can use in our project. Several projects have been done surrounding this idea, few of the research papers have been listed below:

1. Design, Simulation, and Implementation of Bidirectional Converter using Synchronous Switching for Microgrid Application

    This paper focuses on the implementation of a bidirectional DC-DC converter using synchronous switching for DC storage systems in medium power microgrid applications. The study highlights the importance of efficient power modulators in DC microgrids, particularly those integrating PV systems and battery storage. By adopting a two-quadrant buck-boost topology and synchronous switching, the authors achieved increased efficiency by eliminating power diode losses. [2]

2. Bidirectional DC-DC Converter Topologies and Control Strategies for Interfacing Energy Storage Systems in Microgrids: An Overview

    This paper provides an overview of bidirectional DC-DC converter topologies and control strategies crucial for interfacing energy storage systems within microgrids. Microgrids, which can operate both as part of the larger distribution system and in an islanded mode, rely heavily on energy storage systems to maintain stability, power quality, and reliability. [3]

3. High-Efficiency Bidirectional Buck-Boost Converter for Photovoltaic and Energy Storage Systems in a Smart Grid

    This paper introduces a novel bidirectional buck-boost converter designed to enhance performance in photovoltaic and energy storage systems (PV-ESS) within smart grids. Traditional bidirectional buck-boost converters typically operate in discontinuous conduction mode (DCM), leading to high output voltage and current ripples and reduced efficiency. The proposed converter improves upon conventional designs by integrating a cascaded buck-boost converter with an auxiliary capacitor, which minimizes output current ripple and enhances overall efficiency. [4]

4. Buck Boost Converter Design with the Help of dSPACE

    This project report presents a design for a Buck-Boost converter utilizing dSPACE for control and simulation. The report focuses on the implementation of a voltage tracking system for a DC-DC Buck-Boost converter, exploring both open-loop and closed-loop control methods. Due to the inherent nonlinearity of the Buck-Boost converter, conventional open-loop control systems are inadequate for precise voltage regulation. To address this challenge, a closed-loop control system using dSPACE is developed and tested. [5]

5. PV System with Battery Storage Using Bidirectional DC-DC Converter

    Photovoltaic (PV) systems represent a prominent renewable energy technology that converts sunlight directly into electricity using photovoltaic cells. Solar energy, unlike fossil fuels, is environmentally friendly as it generates power without harmful emissions. This paper presents the design and simulation of a PV system with integrated battery storage, utilizing a bidirectional DC-DC converter, modeled and analyzed using MATLAB Simulink. [1]

6. Voltage Control in a Solar-PV based DC Microgrid Using Simulink

    This paper discusses a solar photovoltaic (PV) DC microgrid system consisting of a PV array, a battery, DC-DC converters, and a load, where all these elements are simulated in a MATLAB/Simulink environment. The design and testing entail the functions of a boost converter and a bidirectional converter and how they work together to maintain stable control of the DC bus voltage and its energy management. [6]

3.2 Technology Survey

3.2.1 Solar Energy and Photovoltaic Systems

Solar energy is harnessed using photovoltaic (PV) systems, which convert sunlight directly into electricity through the photoelectric effect. Over the years, various PV technologies have been developed, each with unique advantages and applications.

- **Types of Solar PV Technologies**
  1. **Monocrystalline Silicon Solar Cells**: These are made from a single crystal structure, offering high efficiency (15-22%) and durability. They are widely used in residential and commercial applications due to their space efficiency.
  2. **Polycrystalline Silicon Solar Cells**: These are composed of multiple crystal structures, making them more affordable but slightly less efficient (13-18%).
  3. **Perovskite Solar Cells**: A rapidly emerging technology with high efficiency potential (~20%) and lower production costs. However, stability and scalability remain challenges.

3.2.2 Battery Storage Systems

Battery storage is integral to mitigating the intermittent nature of solar energy. Key technologies include:

i. **Lead-Acid Batteries**: Traditional and cost-effective but have a shorter lifespan and lower energy density.

ii. **Lithium-Ion Batteries**: Widely adopted for their high energy density, efficiency, and long cycle life. They are preferred for modern PV systems.

iii. **Flow Batteries**: Offer scalability and long life by storing energy in liquid electrolytes. However, they have lower energy densities compared to lithium-ion batteries.

3.2.3 DC-DC Converter Topologies

DC-DC converters are critical for managing energy flow in PV systems with battery storage, enabling efficient voltage regulation and bidirectional energy transfer. The proposed system employs two distinct converters: a boost converter and a buck converter, manually configured to optimize energy management.

Converter Configurations in the System

a. **Boost Converter**: This converter steps up a constant input voltage of 4V to a variable output range of 19-24V, enabling efficient power delivery from the PV array to the load or battery during charging. Its design ensures stable voltage boosting, accommodating the system's requirements for higher voltage applications.
b. **Buck Converter**: The buck converter steps down a 24V input to a variable output of 10-13V, adjusted via a potentiometer. This flexibility allows precise voltage regulation to meet the needs of the load or battery during discharge, enhancing system adaptability.

Common Bidirectional Converter Topologies

a. **Two-Quadrant Buck-Boost Converters**: These support bidirectional energy flow with both step-up and step-down capabilities, commonly used in PV systems to manage energy between the PV array, battery, and load.
b. **Full-Bridge Converters**: Employed in high-power applications, these converters provide efficient bidirectional energy transfer with robust performance, suitable for large-scale PV systems.
c. **Multilevel Converters**: These offer improved efficiency and reduced harmonic distortion, making them ideal for complex, high-voltage systems. However, their complexity may not be necessary for smaller-scale applications like the proposed system.

CHAPTER IV PROJECT METHODOLOGY

4.1 Flowchart

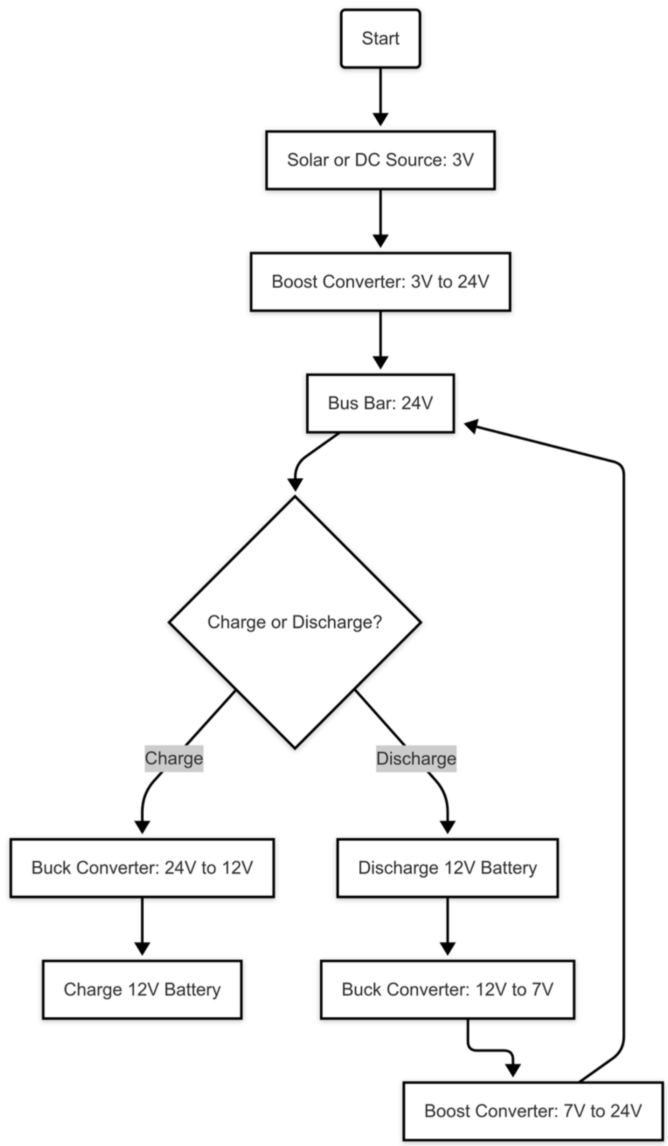

Figure 1: Flowchart for Overall System

4.2 Block Diagram

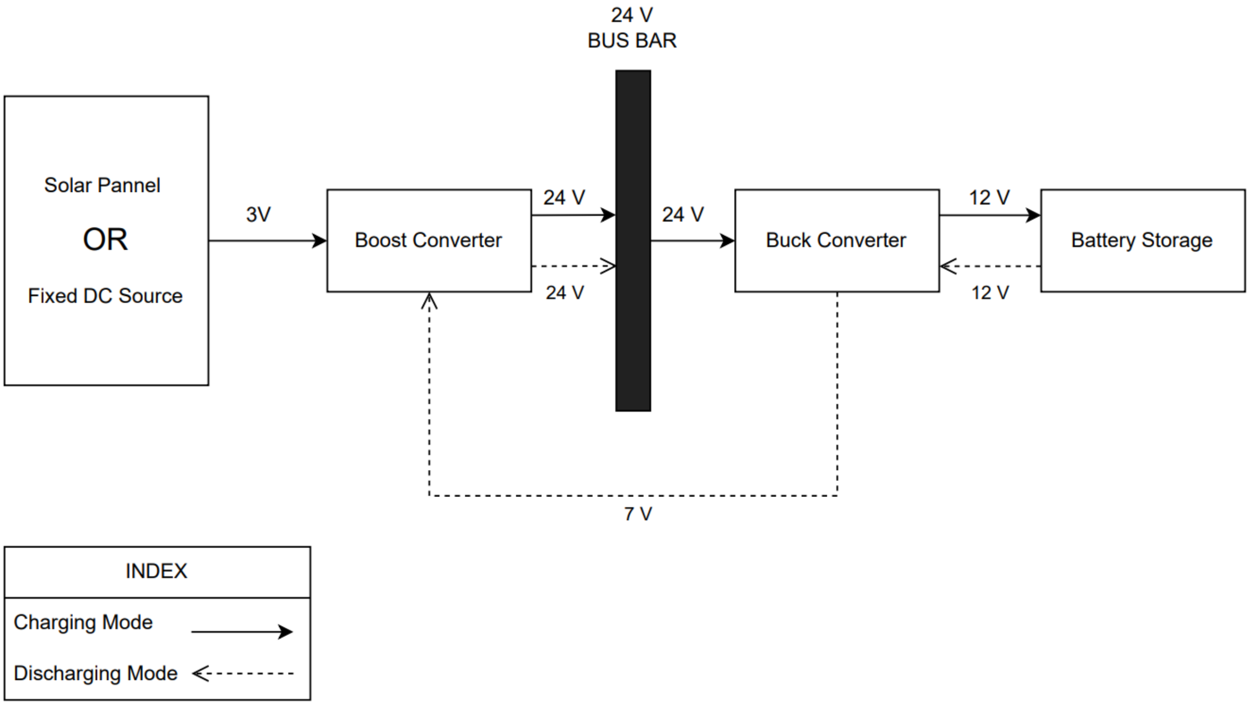

Figure 2: Block Diagram of the System

4.3 Working

The operation of the photovoltaic (PV) system with battery storage integrates simulation and hardware components, utilizing a bidirectional DC-DC converter in simulation and separate buck and boost converters in hardware. The system's working is described as follows:

1. **Photovoltaic Module (PV) as Input Source**:

   The system uses a PV module as the primary energy source, converting sunlight into direct current (DC) electricity. The PV module's output voltage varies with environmental conditions, such as sunlight intensity, requiring regulation to meet the system's energy demands efficiently.

2. **Boost Converter for Voltage Optimization**:

   A boost converter steps up the PV module's constant 4V output to a variable 19-24V in the hardware setup, optimizing power extraction under varying conditions. In simulation, this is part of the bidirectional DC-DC converter, ensuring maximum energy harvest from the PV module.

3. **Buck Converter for Voltage Regulation**:

   The hardware includes a buck converter that steps down a 24V input to a variable 10-13V output, adjusted via a potentiometer, to supply the load or charge the battery. In simulation, the bidirectional DC-DC converter's buck mode handles this function, directing excess energy to the battery during high PV output.

4. **Bidirectional Energy Flow in Simulation**:

   In the MATLAB Simulink model, a bidirectional DC-DC converter manages energy flow:

   i. **Charging Mode**: When PV output exceeds load demand, the converter operates in buck mode, stepping down voltage to charge the battery.

   ii. **Discharging Mode**: During low PV output (e.g., at night), the converter switches to boost mode, stepping up battery voltage to power the load. This bidirectional functionality ensures efficient energy storage and utilization.

5. **PI Controller for System Stability**:

   A Proportional-Integral (PI) controller, implemented in the simulation, regulates the bidirectional DC-DC converter. It monitors the battery's state of charge (SOC) to control charging and discharging, maintaining stable voltage and current. The PI controller prevents overcharging or deep discharging, enhancing battery lifespan and system reliability.

This working mechanism combines a simulated bidirectional converter with hardware-based buck and boost converters, ensuring efficient energy management and stable operation of the PV system with battery storage.

4.4 Circuit Diagram

4.4.1 Buck Converter Circuit Diagram

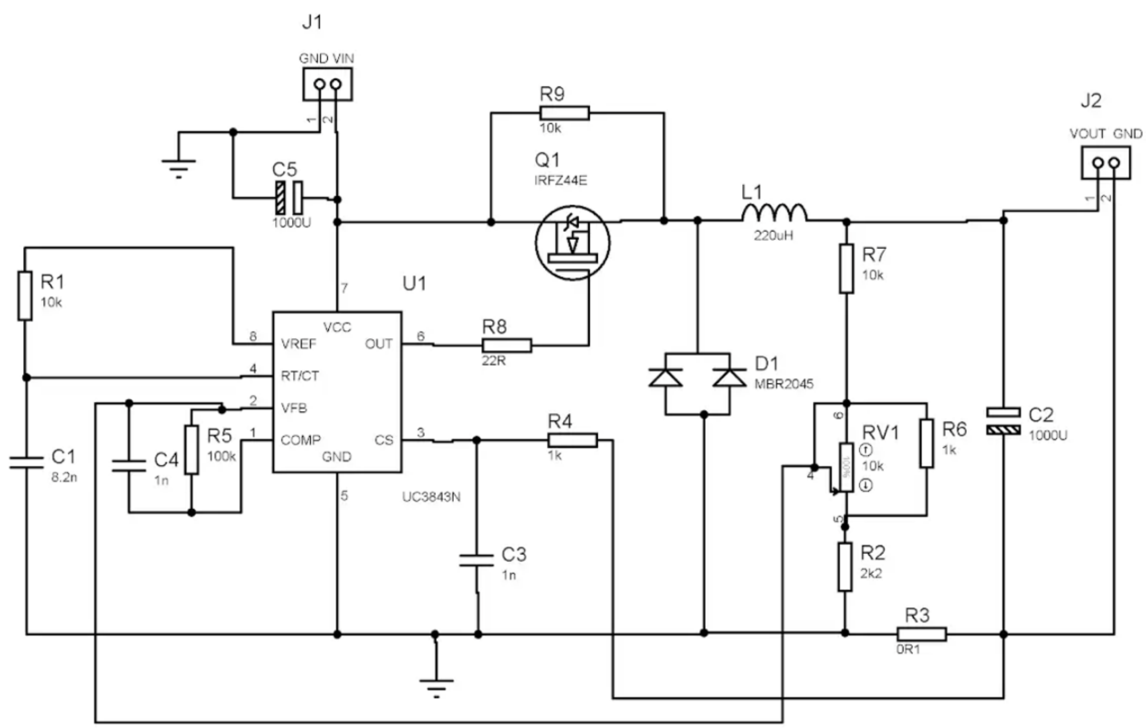

Figure 3: Buck Converter Circuit Diagram

The buck converter circuit diagram showcases a step-down DC-DC converter designed to regulate voltage in the PV system with battery storage. It steps down a 24V input from the bus bar to a variable 10-13V output, adjustable via a potentiometer to charge a 12V battery or reduce to 7V during discharge mode. The circuit employs an UC358 timer IC as a PWM controller, with a 220µH inductor, diode, and capacitors ensuring stable energy transfer and output regulation, as validated in hardware testing.

4.4.2 Boost Converter Circuit Diagram

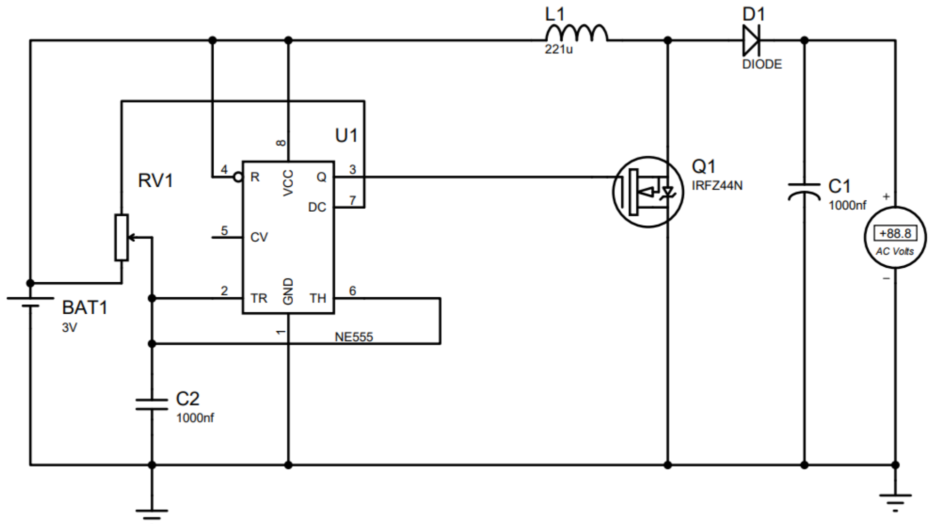

Figure 4: Boost Converter Circuit Diagram

The boost converter circuit diagram depicts a step-up DC-DC converter essential for the system, boosting a 4V input from the PV module (or 2V solar cell in testing) to a 19-24V output to maintain the 24V bus bar. It features a NE555 timer IC driving an IRFZ44N MOSFET (, with a 220µH inductor (L1) and MBR2045 diode (D1) managing energy transfer. Capacitors stabilize the output, while resistors handle feedback and current sensing, ensuring efficient power delivery under varying sunlight, as demonstrated in the prototype.

CHAPTER V RESULTS AND ANALYSIS

5.1 Simulation of the Entire System

The photovoltaic (PV) system, incorporating battery storage and a bidirectional DC-DC converter, was comprehensively simulated in MATLAB Simulink to evaluate its performance and reliability. The simulation included all critical components: the PV module, bidirectional DC-DC converter, and Proportional-Integral (PI) controller. Key outcomes of the simulation are as follows:

5.1.1 Photovoltaic Module Modeling:

The PV module was accurately modeled to generate DC electricity under standard test conditions (STC) and varying sunlight intensities, enabling analysis of system behavior across diverse irradiance levels and environmental scenarios.

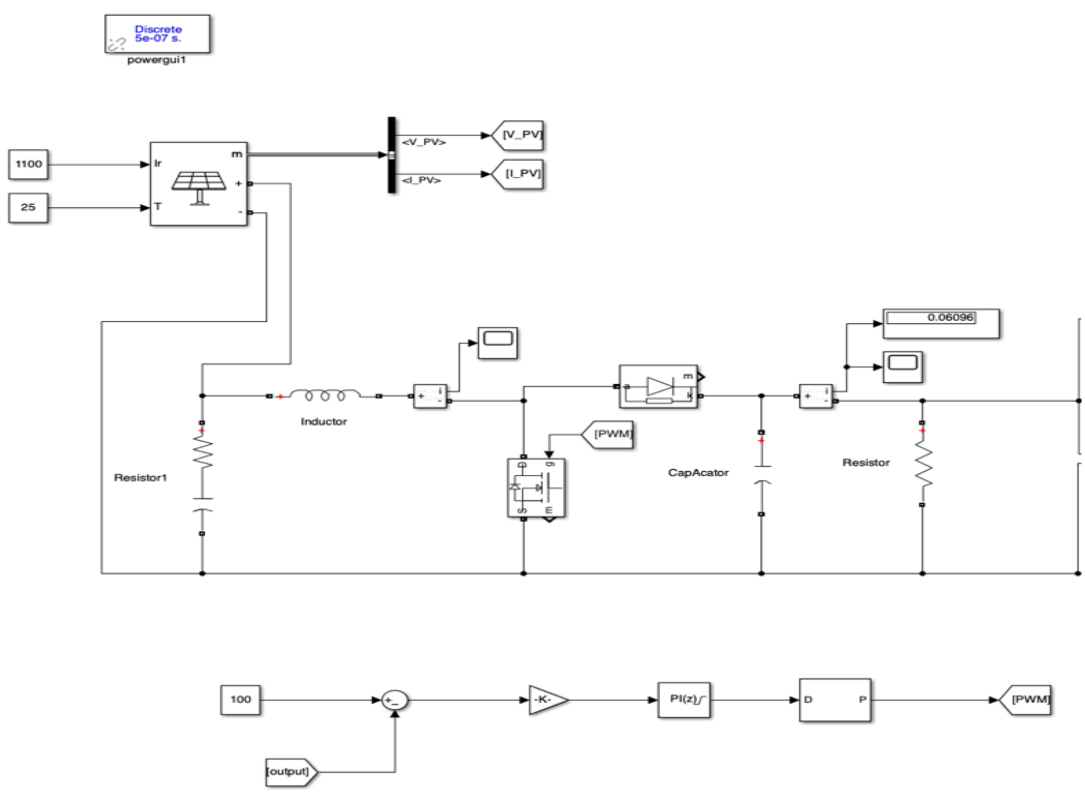

Figure 5: Simulation for PV module arrangement

5.1.2 Bidirectional DC-DC Converter Implementation:

A bidirectional buck-boost converter was designed to manage energy flow, seamlessly switching between buck mode (charging the battery during excess PV output) and boost mode (discharging the battery to supply the load during low sunlight). The converter's performance was validated under dynamic load and battery conditions.

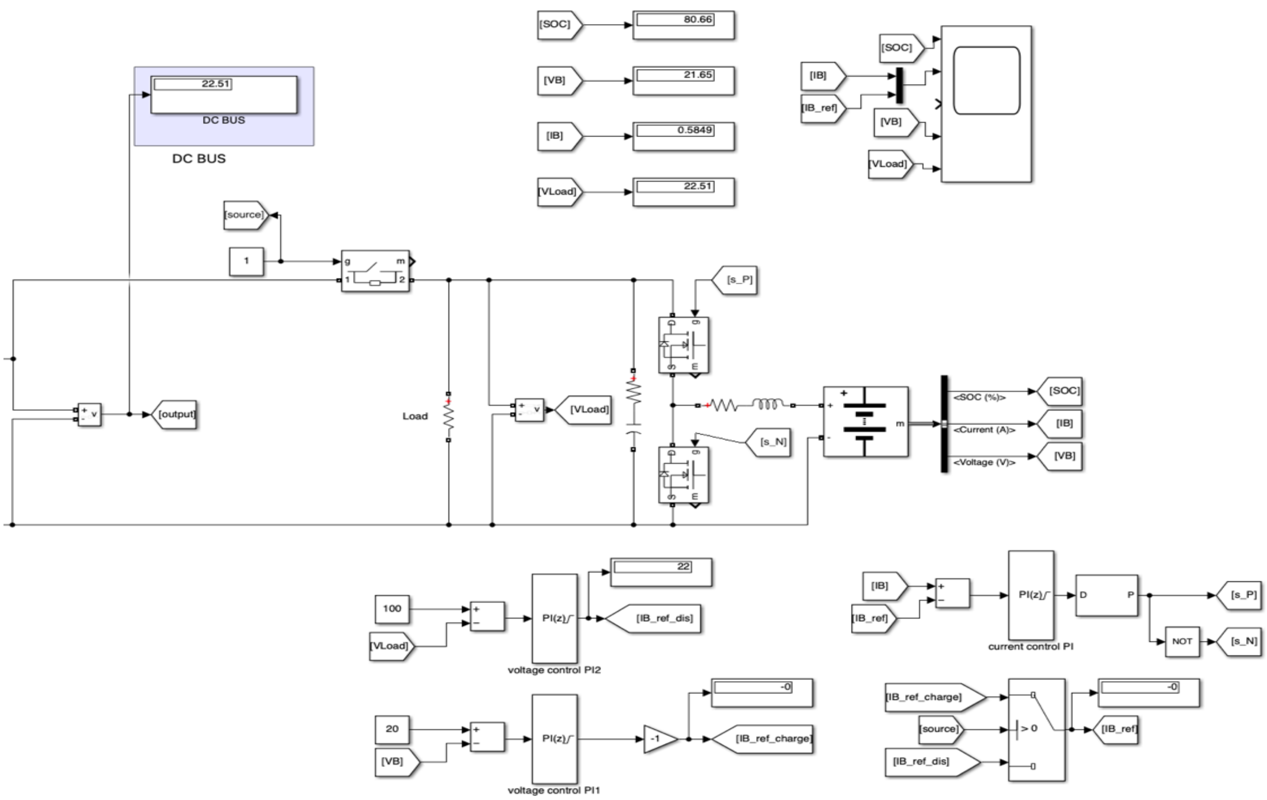

Figure 6: Simulation for Bidirectional DC-DC Converter

i. **PI Controller Integration**: The PI controller was implemented to regulate the battery's state of charge (SOC), with tuned parameters ensuring stable voltage and current outputs. This facilitated efficient battery management and protected against overcharging or deep discharging.

ii. **Energy Flow Management**: The simulation confirmed the system's ability to store surplus energy in the battery during peak sunlight hours and deliver it to the load during periods of low or no sunlight, demonstrating robust mitigation of solar energy intermittency and reliable power delivery for microgrid applications.

5.2 Hardware Validation with Buck and Boost Converters

To validate the system's design in a practical setting, a hardware prototype was developed using a 2V solar cell as the input source, with separate buck and boost converters for energy management. The hardware study provided tangible evidence of the system's functionality, with the following results:

5.2.1 Physical Testing of Components:

A 2V solar cell was employed to mimic the PV module's behavior, with its DC voltage output measured under varying lighting conditions to assess real-world performance.

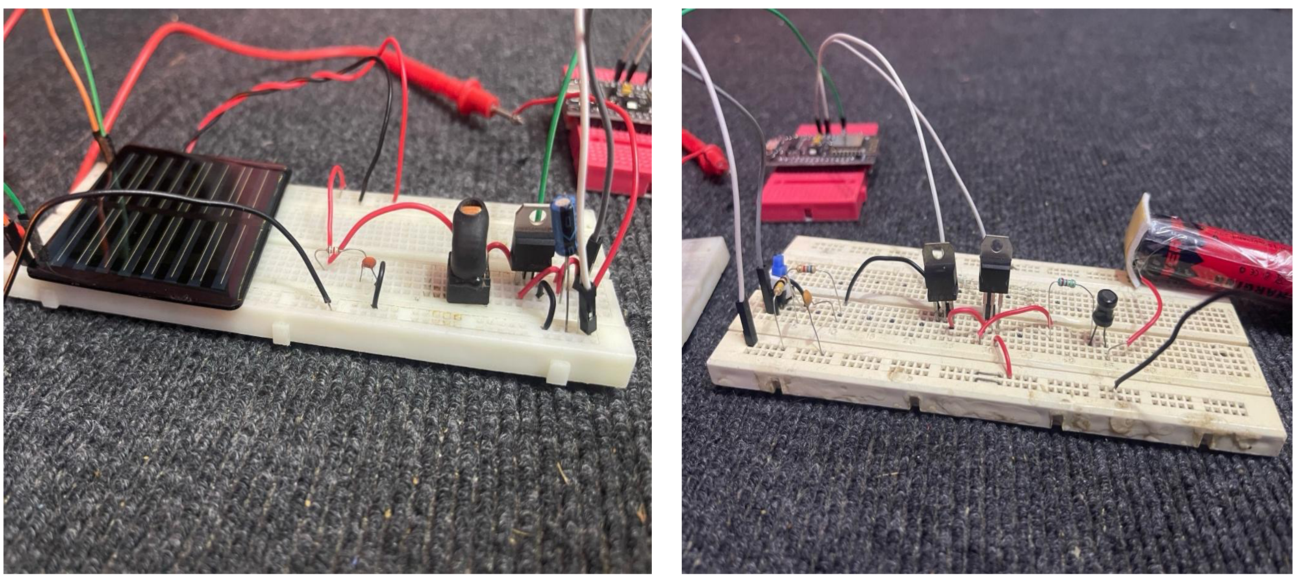

Figure 7: Miniature Circuit Testing

5.2.2 Boost Converter Functionality:

The boost converter successfully stepped up a constant 4V input from the solar cell to a variable 19-24V output, optimizing power extraction and confirming its role in enhancing energy harvest under fluctuating light conditions.

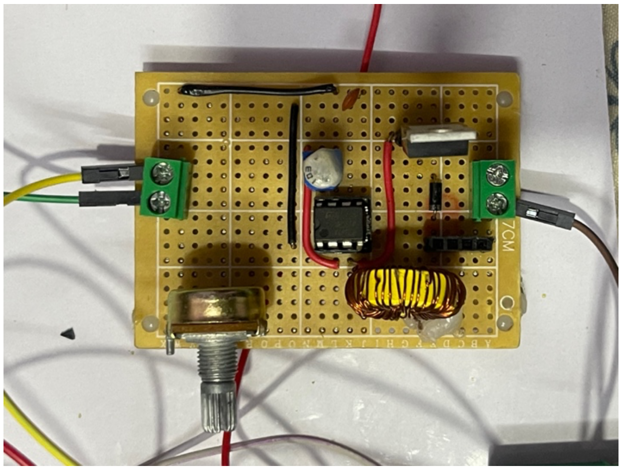

Figure 8: Hardware Implementation for Boost Converter

5.2.3 Buck Converter Operation:

The buck converter stepped down a 24V input to a variable 10-13V output, adjustable via a potentiometer, to charge the battery or power the load. This demonstrated flexible voltage regulation tailored to system requirements.

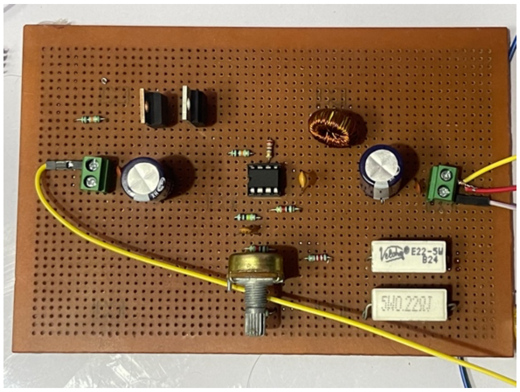

Figure 9: Hardware Implementation for Buck Converter

5.2.4 Energy Flow Validation:

The hardware prototype successfully managed energy flow, charging a small battery during excess energy periods and discharging it to supply the load when PV output was insufficient, aligning with simulation results and verifying practical applicability.

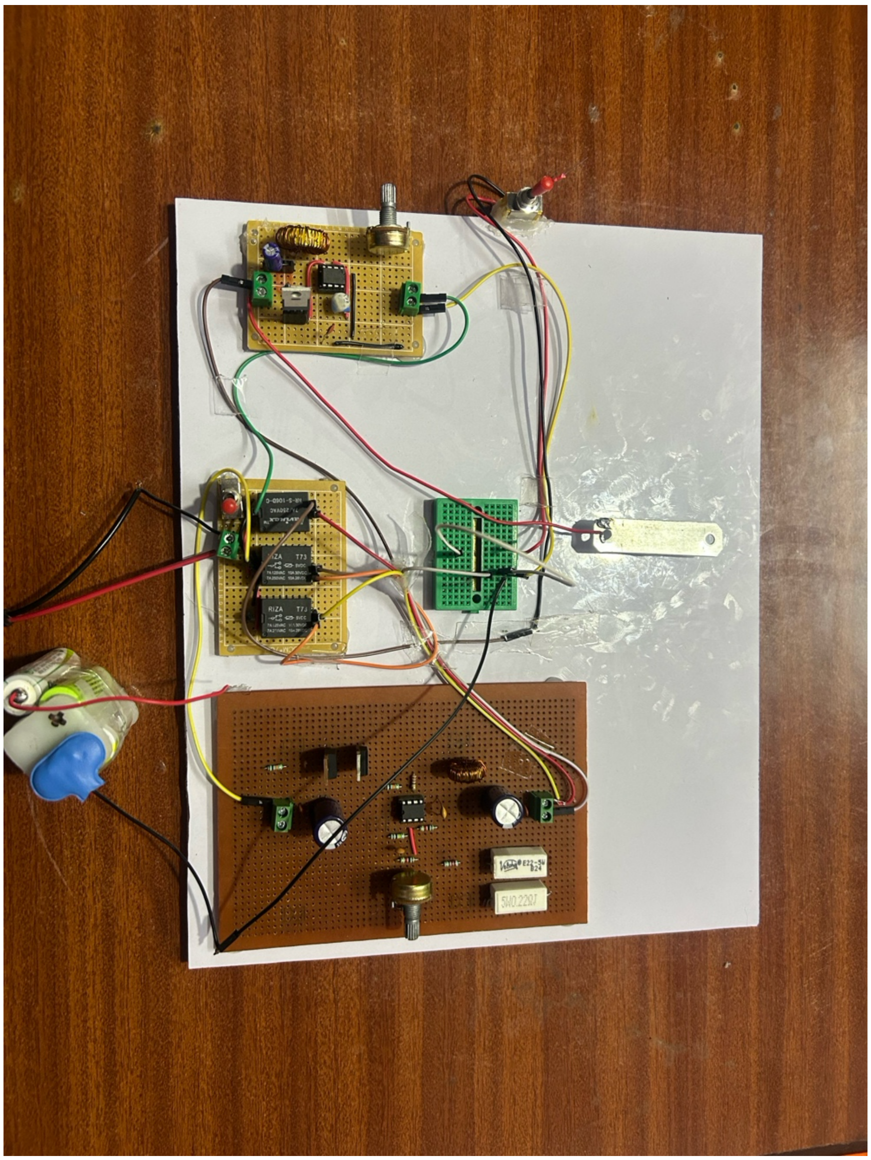

Figure 10: Overall System for Hardware

5.3 Detailed Component Analysis

This section presents the detailed results and analysis for each component of the PV system with battery storage, covering both simulation (MATLAB Simulink with bidirectional DC-DC converter) and hardware (boost and buck converters). The system maintains a 24V bus bar, with a boost converter stepping up 3V (or 4V in hardware) to 24V, and a buck converter managing battery charging (24V to 12V) and discharging (12V to 7V). The tables below provide a framework for recording measured/simulated values and analyzing performance.

5.3.1 PV Module (Input Source)

Parameter	Symbol	Measured Value	Analysis Notes
Input Voltage	V_in	3 V	Compare with PV module output under varying irradiance.
Input Current	I_in	100 mA	Check for stability under load.
Power Input	P_in	0.3 Watts	Calculate as V_in × I_in.

5.3.2 Buck Converter (Hardware: UC3843 and IRFZ44N)

Component	Parameter	Symbol	Measured Value	Analysis Notes
MOSFET (Q1: IRFZ44E)	Drain-Source Voltage	V_DS	18 V	Should be low when ON, high when OFF.
Inductor (L1)	Inductance	L	222 uH	
Diode (D1: MBR2045)	Forward Voltage	V_F	0.57 V	Check for efficiency loss or overheating.
IC (U1: UC3843N)	Output Voltage	V_out	24 V	Compare with bus bar voltage.
	Duty Cycle	D	80%	
Capacitors (C1–C5)	Capacitance	C	1000 uF	
Resistors (R1–R9)	Resistance	R	100k, 10k, 2.2k	Verify feedback loop (VFB pin) and current sense (CS pin).
Output Voltage	V_out		12 V and 7V	Measure at J2, ensure stability.
Output Current	I_out		Variable	Measure at bus bar input.

5.3.3 Boost Converter (Hardware)

Parameter	Symbol	Measured Value	Analysis Notes
Input Voltage	V_in	3 V	From bus bar (charging) or battery (discharging).
Output Voltage	V_out	24 V	Hardware: 10-13V (potentiometer-adjusted).
Output Current	I_out	Variable	Measure at battery or load.
Duty Cycle	D	80 %	

5.3.4 Battery

Parameter	Symbol	Measured Value	Analysis Notes
Voltage	V_bat	12 V	Check charge/discharge levels.
Current	I_bat	1.2 A	

5.3.5 Bus Bar

Parameter	Symbol	Measured Value	Analysis Notes
Voltage	V_bus	24V	Critical parameter, ensure stability.

CHAPTER VI CHALLENGES AND LIMITATIONS

6.1 Problems Encountered

i. **Intermittent Nature of Solar Energy**: Simulating the variability of solar irradiance due to weather conditions was challenging. Accurately modeling these variations and their impact on system performance required extensive parameter tuning.
ii. **Complexity in Bidirectional DC-DC Converter Design**: Designing and simulating the bidirectional DC-DC converter presented challenges, particularly in achieving seamless switching between buck (charging) and boost (discharging) modes while maintaining efficiency and stability.
iii. **Energy Losses in Simulation**: Losses in the boost and bidirectional converters were higher than anticipated during initial simulations, requiring several iterations to optimize circuit design and component selection.
iv. **Battery Model Complexity**: Accurate simulation of the battery's behavior, including state of charge (SOC), voltage response, and aging effects, was more complex than expected, leading to delays in validating the battery management system.

6.2 Limitations

Here are some potential limitations of the project:

i. Despite integrating battery storage, the system's effectiveness is still influenced by the availability of sunlight, which can be highly variable due to weather conditions and geographic location.
ii. The project focuses on simulation in MATLAB Simulink, which may not fully capture real-world variables such as temperature fluctuations, shading, and system wear over time.

GANTT CHART

The timeline of our project for this semester is shown with the help of Gantt Chart below:

Work Plan	January	February	March	April	May
Literature Review					
Hardware Development					
Simulation and testing					
Mid-term presentation					
Fabrication					
Final Presentation					

Index:

Work Completed	
Work Remaining	

CONCLUSION

The completion of this project deliverins a PV system with battery storage that effectively addresses solar energy intermittency. Through robust design and implementation, we have developed a system that maintains a stable 24V bus bar, leveraging both simulation and hardware approaches. The MATLAB Simulink model, featuring a bidirectional DC-DC converter with a PI controller, successfully simulated energy flow, in managing the charging of a 12V battery from the 24V bus bar and discharging it to sustain power during low sunlight conditions. This software framework allowed us to test the system under varying irradiance levels, demonstrating its reliability for microgrid applications and providing a solid foundation for further optimization.

The hardware implementation brought the design into the physical realm, utilizing a solar cell as the input source to power a boost converter and a buck converter. The boost converter, built with the PWM controller and MOSFET, efficiently stepped input to a variable output, feeding the bus bar with consistent voltage. Meanwhile, the buck converter, adjustable via a potentiometer to deliver 10-13V, facilitated battery charging and load supply, with energy flow validated during both excess and deficient PV output scenarios.

In simulation, accurately modeling battery aging and environmental factors like temperature fluctuations proved complex, necessitating iterative tuning of the PI controller to ensure stability. The hardware faced real-world constraints, including heat dissipation in the MOSFET and the need for precise component matching to minimize losses.

Looking ahead, this project lays a robust groundwork for advancing renewable energy solutions. We recommend integrating a battery management system (BMS) to prevent overcharge or deep discharge, conducting field tests under varying weather conditions to validate scalability, and exploring advanced converter topologies like multilevel converters to boost efficiency. These steps will enhance the system’s adaptability for off-grid communities and align with global sustainability goals. As we conclude , this work not only fulfills our academic requirements but also contributes meaningfully to the pursuit of a carbon-neutral future, inspiring further research and practical deployment in the field of electrical engineering.

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