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Optimizing Battery Charging With A Photovoltaic-Driven DC-DC Boost Converter System

Bondu Vijayakumar[1], Rajesh K S[2], A V Pavan Kumar[3], Yanumula Ramanjaneyulu[4]

Abstract

This paper presents the development of a photovoltaic (PV)-powered DC-DC boost converter system, optimized for battery charging applications. This system addresses the challenge of input voltage variability, which is a common issue when using PV modules as the power source. Due to fluctuations in solar irradiance, the output voltage from the PV module can vary, affecting the charging process. To ensure a stable and constant output voltage for battery charging, the system integrates a DC-DC boost converter governed by a Proportional-Integral-Derivative (PID) controller. The design specifically targets a 35V 21Ah lead-acid battery, with the converter adjusting the PV module's input voltage of 32.64V to a steady output voltage of 41.15V. The successful implementation of the PID controller mitigates voltage oscillations, maintaining the output voltage at a desired level, thereby optimizing the battery charging process and enhancing system efficiency.

Keywords*: Photovoltaic (PV) Module, DC-DC Boost Converter, Battery Charging System, Proportional-Integral-Derivative (PID) Controller, Solar Irradiance, Voltage Stability, Lead-Acid Battery, Renewable Energy Systems, Voltage Oscillation Damping, Energy Efficiency.*

I. Introduction

In recent years, the growing demand for sustainable energy solutions has propelled research into renewable energy sources and energy storage te[1]chnologies. Among these, photovoltaic (PV) systems and batteries stand out as promising options for generating and storing clean energy. However, efficient management of these systems is crucial to maximize their performance and reliability. This necessitates the development of advanced control strategies and innovative hardware solutions to optimize energy conversion and storage processes.

The integration of photovoltaic arrays with battery storage systems offers a compelling solution for sustainable energy generation and storage. Photovoltaic panels harness solar energy and convert it into electrical power, while batteries store this energy for later use. However, the intermittent nature of solar irradiance and the varying energy demand pose significant challenges for effectively utilizing solar power and charging batteries. To address these challenges, sophisticated control algorithms and power electronics are required to regulate the energy flow and optimize battery charging.

One key component in such systems is the DC-DC boost converter, which plays a critical role in efficiently transferring power from the PV array to the battery. The boost converter

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[1] Assistant Professor, Department of EEE, Madanapalle Institute Of Technology & Science, Angallu (V), Madanapalle-517325, Andhra Pradesh, India.

[2] Assistant Professor, Department of EEE, Madanapalle Institute Of Technology & Science, Angallu (V), Madanapalle-517325, Andhra Pradesh, India.

[3] Professor, Department of EEE, Madanapalle Institute Of Technology & Science, Angallu (V), Madanapalle-517325, Andhra Pradesh, India.

[4] Faculty (Lab Assistant), Department of EEE, Madanapalle Institute Of Technology & Science, Angallu (V), Madanapalle-517325, Andhra Pradesh, India.

increases the voltage of the PV output to match the charging voltage of the battery, ensuring efficient energy transfer. However, traditional boost converters may not be optimized for the dynamic operating conditions encountered in PV systems, leading to suboptimal performance and reduced energy conversion efficiency.

To overcome these limitations, researchers have been exploring novel approaches to enhance the performance of PV-driven DC-DC boost converters. Advanced control techniques, such as maximum power point tracking (MPPT), enable the converter to continuously adjust its operating point to extract maximum power from the PV array under varying environmental conditions. By dynamically adjusting the duty cycle or switching frequency of the converter, MPPT algorithms ensure that the converter operates at the optimal point on the PV curve, maximizing energy harvest.

Moreover, recent advancements in power semiconductor devices and converter topologies have paved the way for more efficient and compact DC-DC boost converters. SiC (silicon carbide) and GaN (gallium nitride) devices offer higher switching frequencies, lower losses, and improved thermal performance compared to traditional silicon devices, enabling higher efficiency and power density. Additionally, innovative converter topologies, such as interleaved and multi-level converters, provide further improvements in efficiency and reliability by reducing ripple currents and improving voltage regulation.

In this context, the focus of this paper is to explore the design, modeling, and control of a photovoltaic-driven DC-DC boost converter system optimized for battery charging applications. We aim to investigate various control strategies, including MPPT algorithms, to enhance energy conversion efficiency and battery charging performance. Furthermore, we will evaluate the impact of advanced power semiconductor devices and converter topologies on the overall system performance. Through simulation studies and experimental validation, we seek to demonstrate the effectiveness of our proposed approach in optimizing battery charging with photovoltaic-driven DC-DC boost converters. Ultimately, this research contributes to the advancement of sustainable energy solutions by improving the integration of photovoltaic systems with battery storage for enhanced energy management and utilization.

Literature Survey

[1] **Chen, Y., Li, B., & Chen, Z. (2020)**. This study presents a detailed analysis of a PV-battery system equipped with MPPT, highlighting the importance of efficient control mechanisms in optimizing the performance of PV systems. The research demonstrates the effectiveness of integrating battery storage to ensure a steady power supply, addressing the intermittent nature of solar energy.

[2] **Kouro, S., Malinowski, M., et al. (2010)**. The paper reviews recent advancements in multilevel converters, emphasizing their significance in industrial applications due to their ability to reduce the total harmonic distortion and improve the quality of power output. Multilevel converters are identified as crucial components in enhancing the efficiency and reliability of PV systems.

[3] **Iqbal, M. T., & Salam, Z. (2018)**. This review focuses on MPPT techniques for PV systems, comparing various algorithms based on their efficiency, simplicity, and suitability for different environmental conditions. The study underscores the importance of selecting appropriate MPPT techniques to maximize the power output from PV installations.

[4] **Mohan, N., Undeland, T. M., & Robbins, W. P. (2003)**. The textbook provides a comprehensive overview of power electronics, including converters, applications, and design considerations. It serves as a foundational resource for understanding the electrical principles underlying the operation of PV systems and their integration with other energy sources.

[5] **Esram, T., & Chapman, P. L. (2007)**. This comparison of PV array MPPT techniques evaluates their performance in tracking the maximum power point under various

conditions. The study contributes to the ongoing effort to improve MPPT algorithms, enhancing the overall efficiency of PV systems.

[6] **Kroposki, B., Pink, C., et al. (2006)**. The paper explores the development of an advanced battery charger for hybrid electric vehicles, incorporating a boost converter to optimize charging efficiency and battery lifespan. Although focused on vehicle applications, the principles discussed are relevant to the broader context of battery integration in renewable energy systems.

Problem Statement

The primary problem addressed in the project "Optimizing Battery Charging with a Photovoltaic-Driven DC-DC Boost Converter System" revolves around the challenge of maintaining a stable and constant output voltage for battery charging, despite the inherent fluctuations in input voltage sourced from a photovoltaic (PV) module. Solar irradiance, which directly influences the output voltage of PV modules, varies significantly due to factors such as time of day, weather conditions, and seasonal changes. These variations can lead to inefficient battery charging processes, potentially harming the battery's lifespan and performance due to overcharging or undercharging scenarios.

To tackle this issue, the project aims to develop a system that employs a DC-DC boost converter, regulated by a Proportional-Integral-Derivative (PID) controller. This system is designed to adaptively adjust the output voltage to optimal charging levels for a 35V 21Ah lead-acid battery, ensuring efficient and reliable charging irrespective of the variability in solar power input. The PID controller's role is crucial for damping voltage oscillations and maintaining steady-state voltage, thereby optimizing the battery charging process and extending battery life.

Limitations

- **Model Assumptions**: The study may rely on certain assumptions or simplifications in the modeling of the photovoltaic system, battery characteristics, and DC-DC boost converter operation. These assumptions may not fully capture the complexity of real-world conditions, leading to discrepancies between the model and actual performance.
- **Validation**: Validation of the proposed optimization method or control strategy may be limited to simulation or laboratory experiments, which may not fully represent the variability and challenges encountered in real-world deployment. Lack of field testing could limit the generalizability of the findings.
- **Performance Under Variability**: The effectiveness of the optimization approach may not be adequately assessed under varying environmental conditions (e.g., changes in solar irradiance, temperature, shading) and load profiles. The system's performance under such variability could significantly differ from the idealized conditions assumed in the study.
- **Component Reliability and Durability**: The study may not address long-term reliability and durability concerns of the components used in the system, such as the photovoltaic panels, DC-DC converter, and battery. Real-world deployment could reveal issues related to component degradation, efficiency loss, or failure over time.
- **Cost Considerations**: The study might not comprehensively evaluate the cost implications of implementing the proposed system, including upfront equipment costs, maintenance expenses, and economic viability compared to alternative charging methods. Cost-effectiveness analysis could provide valuable insights into the practical feasibility of the approach.
- **Scalability and Integration**: The scalability of the proposed system for different application scenarios (e.g., residential, commercial, industrial) and its integration with existing infrastructure may not be thoroughly explored. Challenges related to scalability, compatibility with grid-tied systems, and grid interaction could limit widespread adoption.
- **Regulatory and Standards Compliance**: Compliance with relevant regulatory requirements, safety standards, and grid interconnection guidelines may not be fully

addressed. Failure to meet regulatory obligations could pose barriers to deployment and commercialization.

- **Environmental Impact**: The study may not assess the environmental impact of the proposed system beyond its immediate energy efficiency benefits. Consideration of factors such as embodied energy, material sourcing, end-of-life disposal, and potential environmental consequences is essential for a comprehensive sustainability assessment.

Objective

The primary objective of this project is to model and simulate a Photovoltaic (PV) powered DC-DC Boost Converter using a PID Controller for efficient battery charging. This system aims to harness solar energy for charging batteries, optimizing the charging process to improve efficiency and reliability. By implementing the system in MATLAB SIMULINK, the project seeks to analyze and validate the effectiveness of the DC-DC Boost Converter and PID Controller in maintaining a constant output voltage for battery charging, regardless of variations in solar irradiance. This innovative approach addresses the need for sustainable and efficient energy solutions in electrical engineering applications.

II. Methodology

The methodology for optimizing battery charging with a Photovoltaic-Driven DC-DC Boost Converter System involves several key steps. Initially, a comprehensive review of relevant literature and existing technologies sets the foundation. The project objectives are formulated with precise requirements. A DC-DC boost converter, integrated with a PID controller, is designed to efficiently convert and regulate solar energy for battery charging. MATLAB SIMULINK is utilized to simulate the system, allowing for detailed analysis and validation of performance. The simulation studies focus on optimizing the converter's parameters to achieve stable output voltage, ensuring efficient battery charging under varying solar irradiance conditions.

Proposed System

The proposed system is designed to optimize battery charging using a photovoltaic-driven DC-DC boost converter integrated with a PID controller. This innovative system harnesses solar energy to charge batteries efficiently, addressing the variability of solar power with advanced control mechanisms. The PV module captures solar irradiance, converting it into electrical energy. The DC-DC boost converter then steps up the voltage to the required charging level, with the PID controller ensuring stable output regardless of solar intensity fluctuations. This setup not only maximizes the use of renewable energy but also enhances battery lifespan through precise charging control, making it an eco-friendly solution for energy storage.

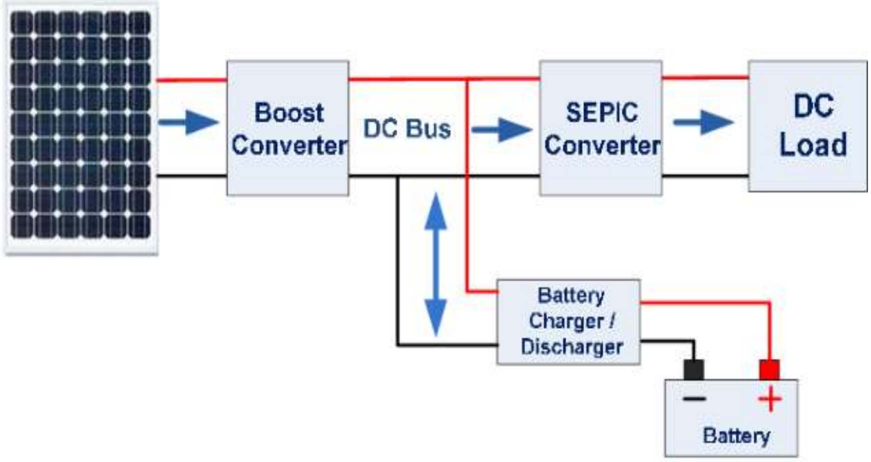

Fig 1: Proposed System Block Diagram

PV Systems

Photovoltaic (PV) technology converts sunlight directly into electricity using semiconductor materials that exhibit the photovoltaic effect. This effect occurs when photons from sunlight strike a semiconductor material (usually silicon), causing the absorption of photons to liberate electrons from their atomic orbits, thereby generating an electrical current.

Key Components of PV Systems:

- **PV Cells:** The basic unit of a PV system, which is made from semiconductor materials. When exposed to sunlight, these cells generate a direct current (DC) voltage.
- **PV Modules:** Also known as solar panels, these are assemblies of multiple PV cells connected in series and/or parallel to increase voltage and current to desired levels. Modules are encapsulated with durable materials for protection against environmental conditions.
- **Inverters:** Devices that convert the DC output of PV modules into alternating current (AC), suitable for use by electrical grids or household electrical systems.
- **Mounting Systems:** Structures that hold PV modules in the optimal position to capture sunlight. They can be fixed or designed to track the sun across the sky.
- **Balance of System (BOS):** Includes all components of a PV system other than the PV modules themselves, such as wiring, inverters, battery storage (for off-grid systems), charge controllers, and monitoring systems.

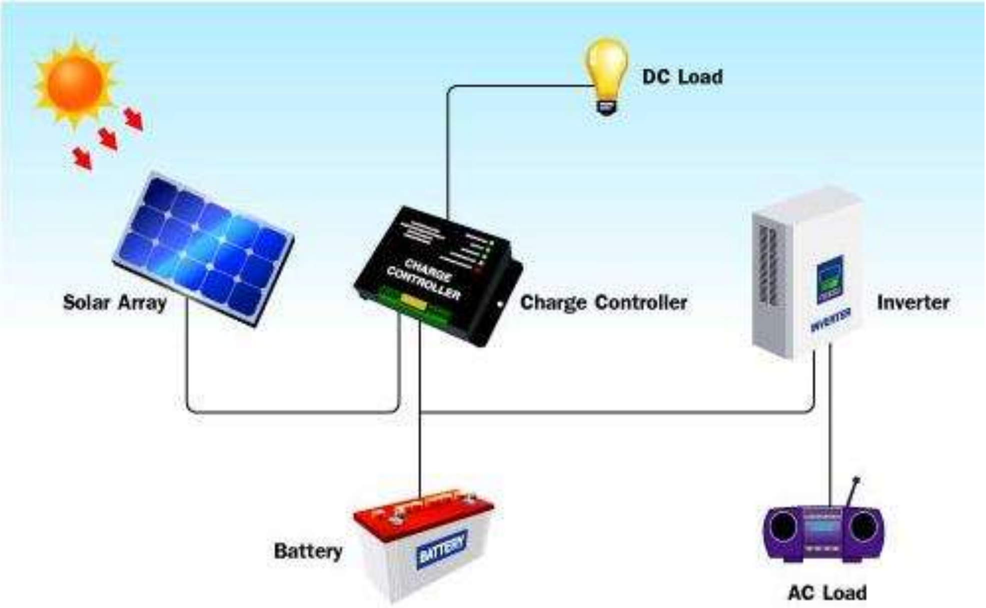

Fig 2: PV Systems

How PV Systems Work:

(a) **Light Absorption:** When sunlight (photons) hits the PV cells within modules, it excites electrons, creating electron-hole pairs.

(b) **Electric Field:** Within the cell, a built-in electric field at the junction between different semiconductor materials (typically n-type and p-type silicon) separates the excited electrons and holes, preventing them from recombining.

(c) **Current Generation:** This separation creates a flow of electrical current when the cell is connected to an external load.

(d) **Power Production:** The electrical current and the cell's voltage (determined by its materials and design) define the power that the cell can produce.

Applications:

PV technology is versatile, ranging from small-scale applications like solar-powered calculators and road signs to large-scale solar farms that feed electricity into the grid. It's also used in remote telecommunications equipment, portable power supplies, and residential solar power systems, contributing to renewable energy generation and reducing dependence on fossil fuels.

PV systems can be standalone or grid-connected. Standalone systems often include batteries for storing electricity, making solar power available during nighttime or cloudy weather. Grid-connected systems can supply excess power back to the grid, allowing for net metering or feed-in tariffs in some regions.

Overall, photovoltaic technology is a key component of the global shift towards sustainable energy, offering a clean, renewable source of power with the potential for significant environmental and economic benefits.

DC-DC Converters

DC-DC converters are electronic devices that convert direct current (DC) electrical power from one voltage level to another. They are crucial in applications where the available power supply voltage needs to be adjusted to match the requirements of the load. Among the various types of DC-DC converters, the boost converter is specifically designed to step up the input voltage to a higher output voltage.

Operational Principles of Boost Converters

A boost converter, also known as a step-up converter, increases (boosts) the input voltage to a higher output voltage. It operates by storing energy in an inductor during the first phase (when the switch is closed) and releasing that energy to the load at a higher voltage during the second phase (when the switch is open).

The key components of a boost converter include an inductor, a diode, a switch (typically a transistor), and a capacitor. The operational cycle can be divided into two phases:

- **On Phase:** When the switch is closed, current flows through the inductor, and energy is stored in it. The diode is reverse-biased and blocks current flow to the output.
- **Off Phase:** When the switch is opened, the inductor tries to maintain the current flow, causing the diode to become forward-biased. The inductor discharges its stored energy to the output, increasing the output voltage.

Design Considerations

Designing a boost converter involves selecting appropriate values for the inductor and capacitor, which are critical for the converter's efficiency, performance, and stability.

- **Inductor Selection:** The inductor's value is chosen based on the desired ripple current and the switching frequency of the converter. A larger inductance value reduces the ripple current but may lead to a larger and more expensive inductor. The inductor must also be able to handle the peak current without saturating.
- **Capacitor Selection:** The output capacitor filters the output voltage and reduces ripple. Its value is determined by the acceptable voltage ripple and the load's current requirements. A larger capacitance provides better filtering but results in a larger physical size and potentially higher cost.

Theoretical Background

The voltage conversion ratio of a boost converter (output voltage to input voltage) depends on the duty cycle of the switch (the ratio of the on-time to the total switching period). The ideal boost converter equation, ignoring losses, is given by:

$$\mathbf{Vout=Vin/1-D} \qquad \mathbf{(1)}$$

where **Vout** is the output voltage, **Vin** is the input voltage, and **D** is the duty cycle of the switch.

Practical Considerations

In practice, the efficiency of a boost converter is affected by several factors, including the resistance of the inductor, the voltage drop across the diode and switch, and the ESR (Equivalent Series Resistance) of the capacitor. Selecting components with low resistance and high quality can significantly improve the converter's efficiency.

Moreover, the stability and transient response of the converter are influenced by the control method used, such as voltage mode, current mode, or PID control, with PID control providing a means to fine-tune the converter's response to changes in load or input voltage.

In summary, the design and implementation of a boost converter require careful consideration of the operational principles, component selection, and control strategy to achieve the desired voltage conversion, efficiency, and performance characteristics.

Battery Specifications:

The selected lithium-ion battery for this system is characterized by its high energy density, efficiency, and longevity. Key specifications include:

- **Nominal Voltage:** Typically around 3.6V to 3.7V per cell, with the system designed to accommodate the series connection of cells to achieve higher voltage requirements for the application.
- **Capacity:** Expressed in ampere-hours (Ah), indicating the battery's storage capability. The project uses a battery with a capacity suited to meet the expected load demands over a specified period.
- **Charge/Discharge Rates:** Defined by the C-rate, which impacts how quickly the battery can be charged or discharged safely without affecting its lifespan.

State of Charge (SOC) Considerations:

The SOC is a critical parameter representing the current charge level of the battery relative to its total capacity, usually expressed as a percentage. Accurate SOC estimation is vital for efficient battery management, ensuring optimal charging strategies and preventing overcharging or deep discharging, which could degrade battery health. The project employs algorithms within the Simulink model to monitor and control the SOC based on the input from the PV module and the performance of the DC-DC boost converter.

PID controller:

A Proportional-Integral-Derivative (PID) controller is a control loop feedback mechanism widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired setpoint. It aims to minimize the error by adjusting the process control inputs in a way that affects the process variable. The controller's operation is characterized by three parameters: Proportional (P), Integral (I), and Derivative (D), which give the PID its name. Each of these parameters plays a critical role in the controller's ability to achieve stable and efficient process control.

Proportional Term (P)

The proportional term produces an output proportional to the current error value. The proportional response can be adjusted by multiplying the error by a proportional gain (Kp). A high Kp reduces the rise time, improving the system's responsiveness, but can lead to overshoot and oscillations.

Integral Term (I)

The integral term is concerned with the accumulation of past errors, providing a correction for cumulative past errors. This term aims to eliminate the steady-state error that can occur with a purely proportional controller. By integrating the error over time and multiplying it by the integral gain (Ki), the controller can counteract biases that lead steady-state errors.

Derivative Term (D)

The derivative term predicts system behavior by considering the rate of change of the error, effectively dampening the system's response to reduce overshoot and improve stability. It is achieved by multiplying the rate of change of the error by the derivative gain (Kd). This term helps to quickly counteract changes in the error, thus improving the system's stability and settling time.

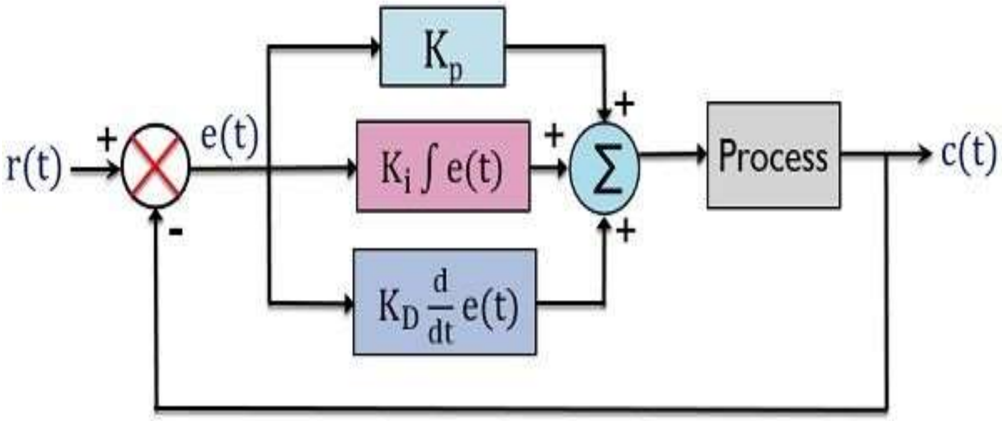

Fig 3: Closed loop control system with PID controller

$$u(t)=Kp\cdot e(t)+Ki\int_0^t e(\tau)\, d\tau+K\frac{d}{dt}de(t) \quad (2)$$

Implementation in Battery Charging System

In the context of a photovoltaic-driven DC-DC boost converter system for battery charging, the PID controller plays a crucial role in managing the output voltage to ensure efficient and safe charging of the battery. By adjusting the duty cycle of the MOSFET in the boost converter based on the PID algorithm, the system can maintain a stable output voltage for battery charging despite fluctuations in solar irradiance and load. The PID controller adapts to changing conditions to minimize the error between the actual and desired battery charging voltage, ensuring optimal charging performance and prolonging battery life.

The effectiveness of a PID controller in such a system is highly dependent on the tuning of its parameters (Kp, Ki, Kd), which must be optimized based on the specific characteristics of the system and the desired performance criteria. Proper tuning ensures that the system achieves a balance between responsiveness and stability, maximizing the efficiency of solar energy utilization for battery charging.

III. Results & Discussion

The Simulink model incorporates the PV module, DC-DC boost converter, PID controller, MOSFET, diode, and the lithium-ion battery into a comprehensive simulation environment. The model is structured to reflect the system's real-world operation, including the dynamic interaction between the solar energy input, voltage conversion, and battery charging processes.

Key aspects of the Simulink model include:

- **PV Module Simulation:** Represents the solar energy input, with parameters adjustable to simulate different irradiance levels and temperatures, affecting the output power and voltage.
- **DC-DC Boost Converter:** Utilizes the MOSFET switching controlled by the PID controller to step up the PV module's voltage to the required level for battery charging.
- **Battery Charging Module:** Simulates the charging of the lithium-ion battery, incorporating SOC estimation and management to ensure the battery is charged efficiently and safely.

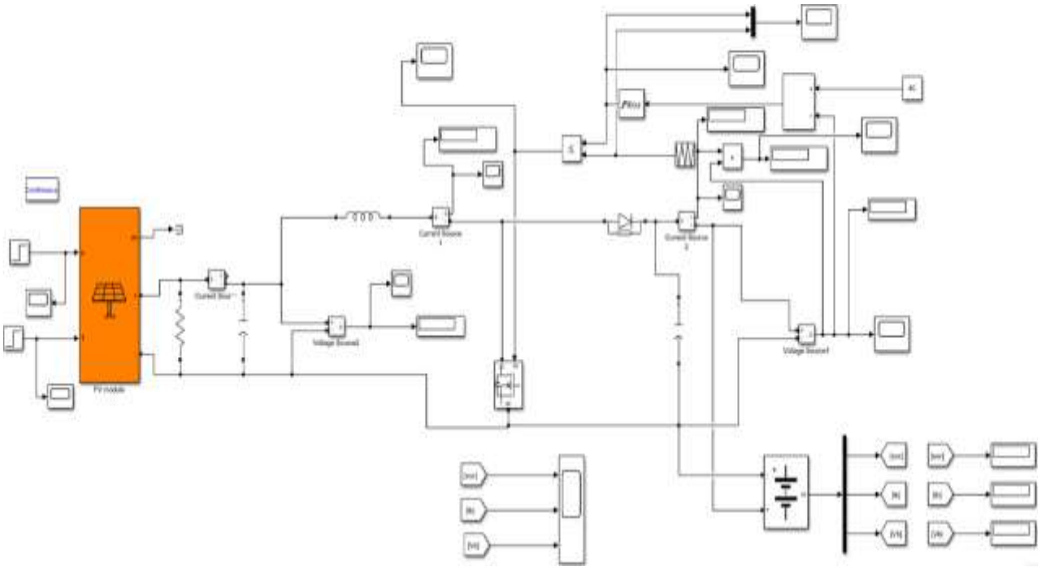

Fig 4: Proposed Simulink

Results: The simulation results demonstrate the system's ability to maintain the desired output voltage for battery charging, even under varying solar irradiance conditions. The PID controller effectively adjusts the duty cycle of the MOSFET in the boost converter, ensuring stable voltage levels suitable for charging the lithium-ion battery. The SOC management within the Simulink model enables precise control over the charging process, optimizing battery health and efficiency.

In conclusion, the Simulink model validates the effectiveness of the proposed system in harnessing solar energy for efficient lithium-ion battery charging, highlighting the importance of integrated component design and SOC management.

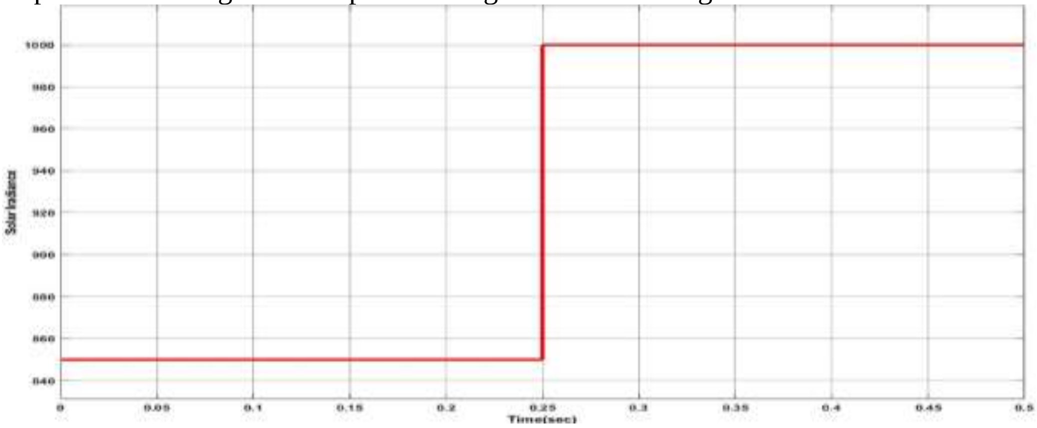

Fig 5: Solar Irradiance

"Fig 5: Solar Irradiance" displays a graphical representation of solar irradiance levels impacting a photovoltaic (PV) system over time. This curve highlights the variability of solar energy available to the PV module, showing peaks during periods of maximum sunlight exposure and dips when sunlight is less intense or obstructed. The graph underscores the direct correlation between solar irradiance and the amount of electrical energy generated by the PV module. Understanding these fluctuations is vital for optimizing the efficiency of solar power systems, as it informs the design and deployment of PV modules to maximize energy capture throughout varying environmental conditions.

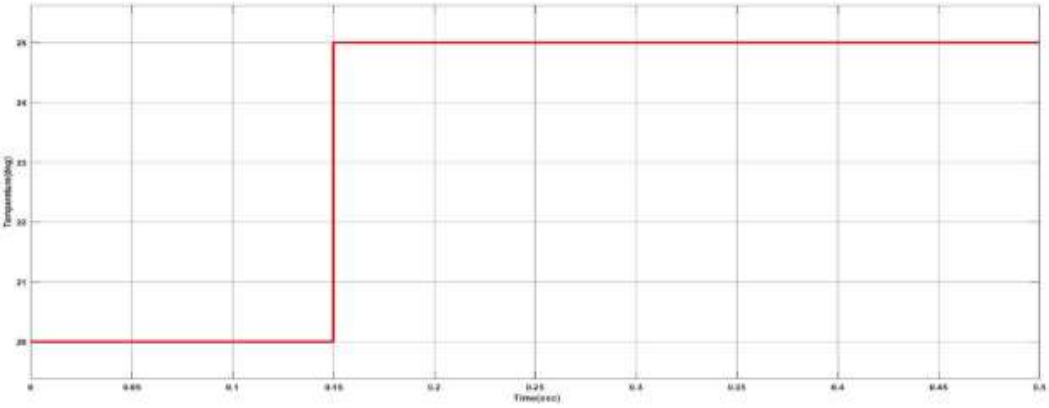

Fig 6: Temperature

"Fig 6: Temperature" illustrates the impact of temperature on the performance of the photovoltaic (PV) module over a specific time frame. This graph demonstrates the inverse relationship between temperature and the efficiency of the PV module, showcasing how increases in temperature can lead to decreases in the electrical output. The curve provides valuable insights into the thermal characteristics of PV systems, emphasizing the need for effective thermal management to maintain optimal operating conditions. Understanding this temperature dependency is crucial for predicting the performance of solar panels in various environmental conditions and designing systems that can withstand the fluctuations in temperature without significant losses in efficiency.

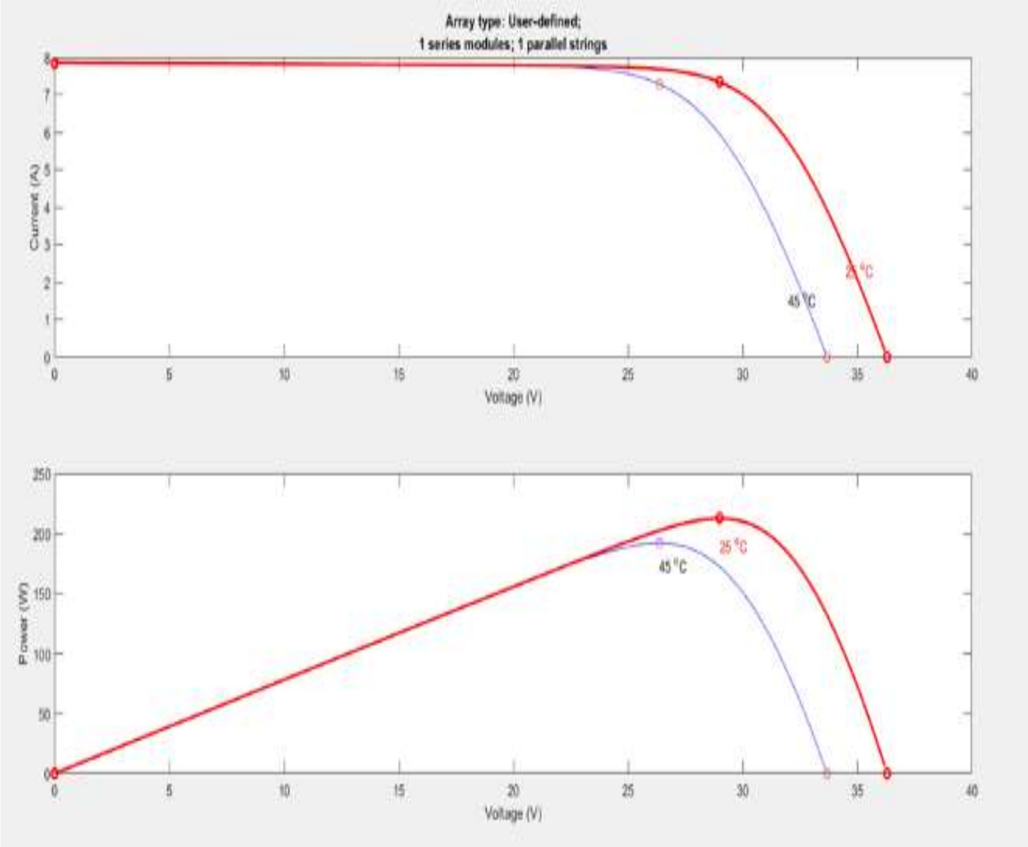

Fig 7: PV-IV characteristics of PV Module

"Fig 7: PV-IV Characteristics of PV Module" graphically represents the relationship between the current (I) and voltage (V) of a photovoltaic (PV) module under varying conditions of solar irradiance. This curve is crucial for understanding the module's performance, illustrating how the current output changes with voltage at different levels of sunlight exposure. The graph highlights the maximum power point (MPP), where the product of current and voltage is at its peak, indicating the most efficient operating point for the PV module. This characteristic curve is essential for optimizing the design and implementation of solar energy systems, ensuring maximum efficiency in converting solar energy into electrical power.

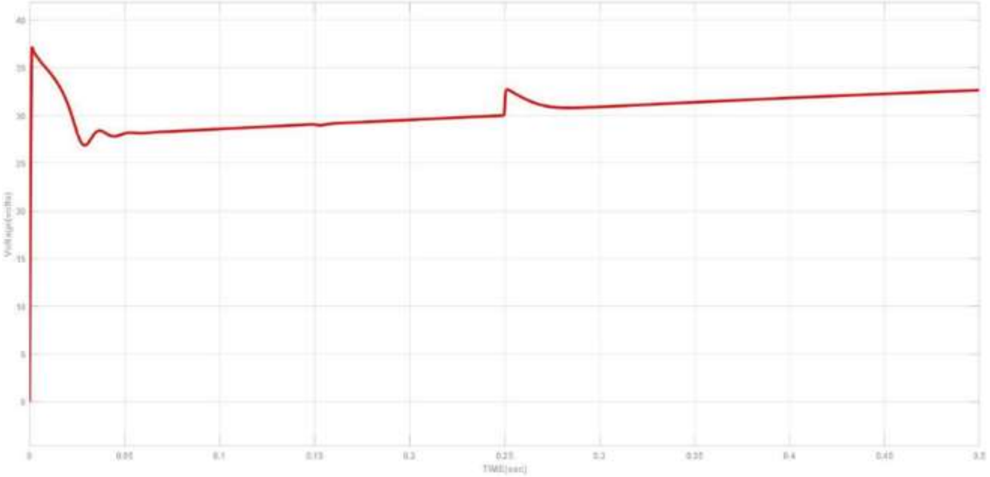

Fig 8: Input Voltage

"Fig.8: Input Voltage" showcases the voltage input from the photovoltaic (PV) module to the DC-DC boost converter over a set period, highlighting the system's initial response and subsequent stabilization. This figure captures the variation in PV module voltage due to changing solar irradiance levels, followed by a leveling off as the system adapts to these changes, ensuring a consistent voltage supply to the converter. The graph illustrates the PV module's efficiency in converting solar energy into electrical voltage and the boost converter's role in adjusting this input to meet the system's requirements, demonstrating the dynamic interaction between solar input and technological adaptation for optimal performance.

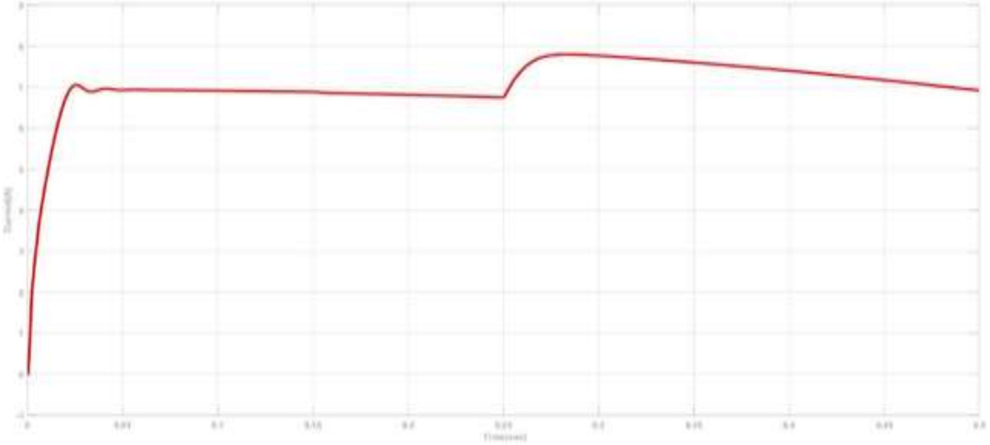

Fig 9: Current Waveform

"Fig.9: Current Waveform" displays the fluctuation and stabilization of current within the DC-DC boost converter system as it charges the battery. Initially, the waveform shows a transient behavior with rapid fluctuations, indicative of the system adjusting to the charging process. This is followed by a period of stability, where the current levels off, signifying that the system has reached a steady state of operation. This graph highlights the converter's effectiveness in managing the current flow to the battery, ensuring it receives a steady and safe charge. The waveform's behavior reflects the system's response to dynamic conditions and its capability to provide consistent current for optimal battery charging.

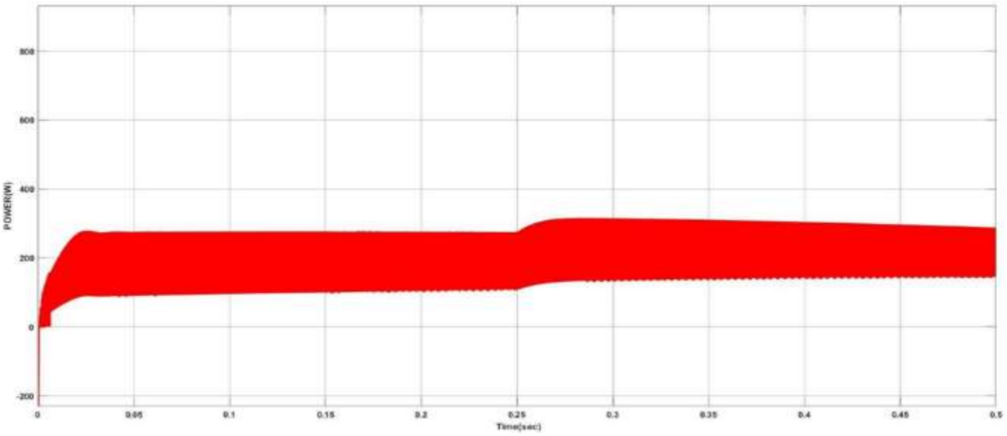

Fig 10: Power Waveform

"Fig.10: Power Waveform" illustrates the power output of the photovoltaic-driven DC-DC boost converter system over time during the battery charging process. The waveform begins with a rapid escalation to peak power output, followed by a plateau that represents a stable and continuous delivery of power to the battery. This stability is critical for efficient battery charging, ensuring that the power supplied matches the battery's requirements without overloading it. The graph demonstrates the system's capability to harness solar energy effectively and convert it into a consistent power output, showcasing the efficiency of the PID controller in maintaining optimal power levels throughout the charging cycle.

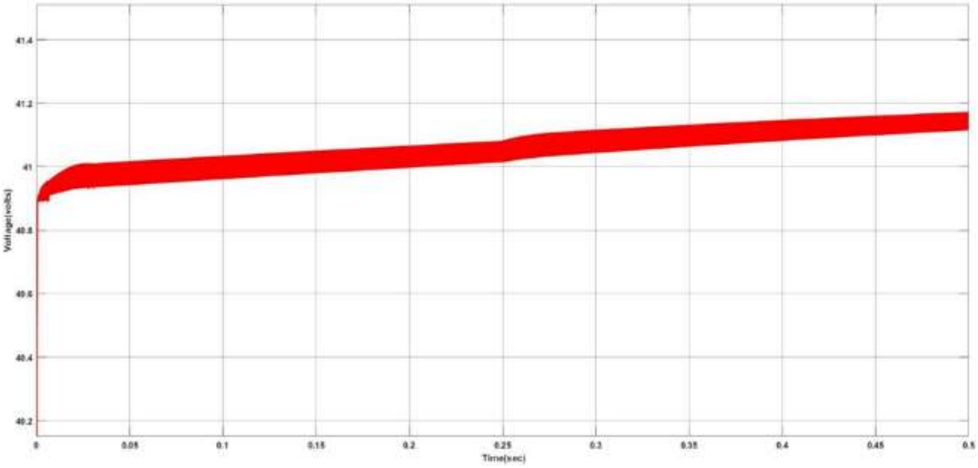

Fig 11: Output Voltage

"Fig.11: Output Voltage" presents a graphical depiction of the voltage output from the DC-DC boost converter to the battery throughout the charging cycle. This figure showcases a quick rise to the target voltage, followed by a sustained, stable output, indicating the converter's efficiency in reaching and maintaining the required charging voltage. The stability of the output voltage, despite potential variations in solar input or load demands, highlights the effectiveness of the PID controller in the system. This steady voltage is crucial for ensuring the battery is charged efficiently and safely, reflecting the system's capability to adapt and provide consistent performance under varying conditions.

Fig 12: **Output Current**

"Fig.12: Output Current" graphically illustrates the flow of electrical current from the DC-DC boost converter to the battery over a specified time period during the charging process. This figure demonstrates a transient phase where the current fluctuates before stabilizing to a steady state, indicative of the converter's response to initial conditions. The stabilized current value signifies effective regulation by the system, ensuring a consistent current supply for battery charging. The curve reflects the system's performance in managing the output current, crucial for optimizing the charging process and protecting the battery from overcurrent conditions, thereby showcasing the effectiveness of the photovoltaic-driven charging system's design and control strategy.

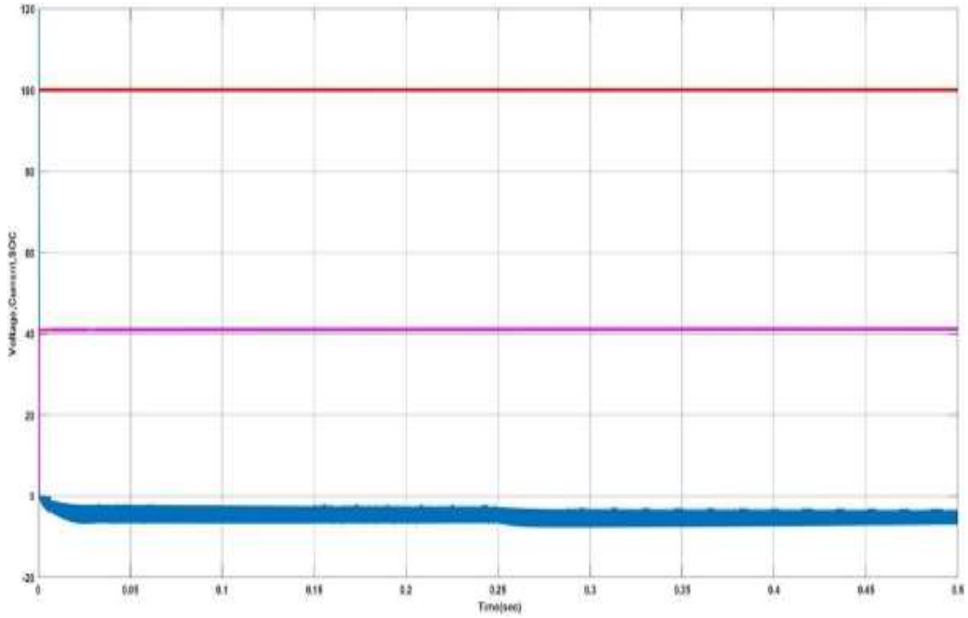

Fig 13: Battery Voltage, Current and SOC

"Fig.13: Battery Voltage, Current and SOC" depicts a graphical representation of the battery's voltage and current over time alongside its State of Charge (SOC). The voltage curve shows a stable output, aligning with the desired charging voltage as regulated by the DC-DC boost converter. The current curve illustrates the charging process, indicating the flow of current into the battery. The SOC graph demonstrates the battery's charging progress, starting from an initial percentage and increasing towards full capacity. This figure effectively captures the dynamic relationship between the battery's voltage, current, and SOC during the charging process, highlighting the efficiency of the photovoltaic-driven DC-DC boost converter system in optimizing battery charging under varying solar conditions.

Table 1: Comparison table for output responses

Figure	Description	Focus
Fig 5: Solar Irradiance	Graphical representation of solar irradiance levels impacting the PV system over time, showing variability in solar energy available.	Solar Irradiance Variability
Fig 6: Temperature	Illustrates the impact of temperature on PV module performance, highlighting the inverse relationship between temperature and efficiency.	Temperature Impact on Efficiency
Fig 7: PV-IV Characteristics of PV Module	Graphically represents the relationship between current and voltage of a PV module, emphasizing the module's performance under varying sunlight.	PV Module Performance
Fig 8: Input Voltage	Showcases voltage input from the PV module to the DC-DC boost converter, highlighting system's response to changing solar irradiance.	Input Voltage Stability
Fig 9: Current Waveform	Displays fluctuation and stabilization of current within the DC-DC boost converter system during battery charging.	Current Management
Fig 10: Power Waveform	Illustrates the power output from the DC-DC boost converter system over time during battery charging, highlighting stability in power delivery.	Power Output Stability
Fig 11: Output Voltage	Presents the voltage output from the DC-DC boost converter to the battery, indicating efficient and stable charging voltage.	Voltage Output Stability
Fig 12: Output Current	Graphically illustrates the flow of electrical current from the DC-DC boost converter to the battery, showing system's effective current management.	Output Current Stability
Fig 13: Battery Voltage, Current and SOC	Depicts battery's voltage and current over time alongside its State of Charge (SOC), showing efficient battery charging process.	Battery Charging Efficiency

IV. Conclusion

The paper on optimizing battery charging with a photovoltaic-driven DC-DC boost converter system has successfully demonstrated an effective solution to stabilize the charging process under variable solar irradiance. By integrating a Proportional-Integral-Derivative (PID) controller with a DC-DC boost converter, the system consistently maintains an optimal output voltage for charging a 35V 21Ah lead-acid battery. This approach not only improves the efficiency of the battery charging process but also potentially extends the battery's lifespan by preventing overcharging or undercharging. Experimental validation under various solar conditions confirmed the system's reliability and effectiveness. The project highlights the significance of renewable energy technologies in achieving sustainable energy solutions and sets the stage for further research into scalable PV installations and intelligent control algorithms. It marks a step forward in enhancing the utility of solar power for reliable and efficient battery charging applications.

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