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Simulation of Solar Power Based EV Charging Station

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Abstract

This work presents the design and implementation of a hybrid power conversion system integrating solar energy, battery storage, and grid support to ensure reliable and efficient energy management. The proposed system employs a multi-stage power electronic architecture consisting of a DC–DC boost converter, a bidirectional buck–boost converter, and an AC–DC converter interconnected through a common DC link. The boost converter is utilized to regulate and enhance the variable output of the photovoltaic source, while the bidirectional converter facilitates controlled charging and discharging of the battery, enabling energy storage and supply balancing. The grid interface operates as a supplementary power source to maintain continuity during fluctuations in solar generation. A proportional–integral (PI) controller is implemented as the primary control strategy for regulating voltage and current across the system. To maximize energy extraction from the photovoltaic source, an incremental conductance (INC)-based maximum power point tracking (MPPT) algorithm is employed in conjunction with the PI controller. This approach ensures accurate tracking of the optimal operating point under varying environmental conditions. The bidirectional converter control is also governed by PI regulation to achieve stable energy transfer between the battery and DC link, thereby maintaining system equilibrium. The proposed configuration offers a simple, cost-effective, and reliable solution for hybrid energy systems. It demonstrates effective coordination between renewable generation, storage, and grid support while maintaining system stability and performance. The results validate that the combined use of PI control and INC-based MPPT provides satisfactory dynamic response, reduced steady-state error, and improved energy utilization. This work highlights the feasibility of implementing conventional control techniques for efficient operation of integrated renewable energy systems.

Keywords: Hybrid system, PI controller, incremental conductance, MPPT, bidirectional converter, DC link, energy management.

1. Introduction

The increasing demand for electrical energy and the growing concerns regarding environmental pollution and depletion of fossil fuel resources have accelerated the adoption of renewable energy technologies. Among the various renewable energy sources, solar photovoltaic (PV) energy has emerged as one of the most reliable and sustainable solutions due to its abundance, cleanliness, and availability. However, the intermittent nature of solar energy and fluctuations in environmental conditions affect the stability and reliability of power generation. To overcome these challenges, hybrid energy systems that combine solar PV, battery energy storage, and grid support have gained significant attention[1]-[12].

This project presents a PI-Controlled Hybrid Solar–Battery–Grid Power Conversion System with Incremental Conductance Maximum Power Point Tracking (INC-MPPT). The system integrates a photovoltaic source, battery storage unit, and utility grid through a common DC-link architecture. A DC–DC boost converter is used to regulate and enhance the PV output voltage, while a bidirectional buck–boost converter facilitates battery charging and discharging operations. The utility grid acts as a backup source to ensure uninterrupted power supply under varying operating conditions.

The Incremental Conductance MPPT algorithm is employed to maximize power extraction from the photovoltaic source under changing irradiance and temperature conditions. In addition, a Proportional–Integral (PI) controller is implemented to regulate voltage and current across the system, ensuring stable operation and efficient energy management[13]-[25]. The proposed system offers improved reliability, better energy utilization, and enhanced system performance while maintaining a simple and cost-effective control structure.

1.1 Problem Statement

Solar photovoltaic (PV) systems are affected by changes in solar irradiance and temperature, causing fluctuations in voltage and power output. These variations reduce system efficiency and reliability. Standalone PV systems cannot supply power continuously during low sunlight conditions or at night. Poor coordination between solar panels, batteries, and the grid can lead to power imbalance and voltage instability. Therefore, an efficient hybrid energy system is required to ensure stable, reliable, and continuous power supply while maximizing renewable energy utilization[26]-[35].

1.2 Objectives

The main objective of this project is to develop an efficient hybrid solar–battery–grid power conversion system capable of providing reliable and continuous power. The system aims to maximize the utilization of solar energy by implementing the Incremental Conductance (INC) MPPT algorithm for optimal power extraction from the photovoltaic source. A PI controller is employed to regulate voltage and current, ensuring stable operation under varying conditions. The project also integrates a battery energy storage system through a bidirectional DC–DC converter to enable controlled charging and discharging. Another objective is to maintain a constant DC-link voltage despite fluctuations in solar irradiance, battery state, and load demand. Seamless grid integration is incorporated to provide backup support and uninterrupted power supply. Overall, the proposed system seeks to enhance energy management, improve conversion efficiency, increase reliability, and reduce dependence on conventional energy sources [36]-[45].

1.3 Significance of the Project

The proposed hybrid solar–battery–grid system plays an important role in improving the reliability and efficiency of renewable energy utilization. By integrating solar power, battery storage, and grid support, the system ensures a continuous and stable power supply under varying operating conditions. The Incremental Conductance (INC) MPPT algorithm enhances solar energy harvesting by extracting maximum available power from the photovoltaic source. The battery storage system improves energy availability by storing excess energy and supplying power during low solar generation periods. Grid integration provides additional backup support, increasing overall system reliability. The use of a PI controller ensures effective voltage regulation and stable operation. The proposed system reduces dependence on conventional fossil-fuel-based energy sources, promotes sustainable energy management, and contributes to environmental protection. Its cost-effective and flexible design makes it suitable for residential, commercial, and industrial applications .[46]

1.4 Innovation and Unique Features

The proposed project introduces a hybrid power conversion system that combines solar photovoltaic generation, battery energy storage, and grid support within a unified architecture. An innovative Incremental Conductance (INC) MPPT algorithm is employed to achieve accurate maximum power extraction under changing environmental conditions. The system utilizes a PI-controlled DC–DC boost converter for effective voltage regulation and improved conversion efficiency. A bidirectional buck–boost converter enables intelligent battery charging and discharging, enhancing energy management. The common DC-link structure allows seamless power flow among the PV source, battery, and utility grid. Automatic grid support ensures uninterrupted power supply during low solar generation or high load demand. The proposed control strategy is simple, cost-effective, and suitable for practical implementation. These features improve system stability, reliability, and overall energy utilization efficiency.

2 Methodolgy

2.1. System Design and Modeling

The proposed hybrid energy system is designed using MATLAB/Simulink to integrate a Solar Photovoltaic (PV) array, lithium-ion battery, and utility grid through a common DC-link. The PV array serves as the primary energy source, while the battery provides energy storage and backup support. A DC–DC boost converter is used to regulate and increase the PV output voltage. The battery is connected through a bidirectional buck–boost converter to enable charging and discharging operations. An AC–DC converter interfaces the utility grid with the DC-link. PI controllers are implemented for voltage and current regulation, and an Incremental Conductance (INC) MPPT algorithm is employed to maximize solar power extraction. The entire system is modeled and simulated under different operating conditions to evaluate its performance and reliability.

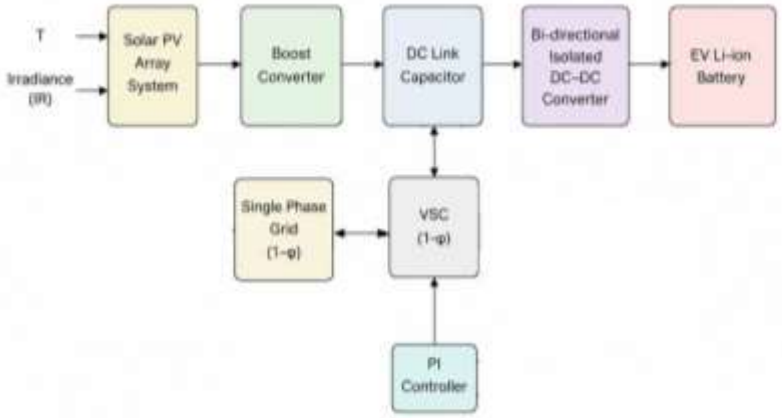


FIGURE 1: BLOCK DIAGRAM

2.2 Components Used

1. Solar Photovoltaic (PV) Array
2. DC–DC Boost Converter
3. Incremental Conductance (INC) MPPT Controller
4. Lithium-Ion Battery
5. Bidirectional Buck–Boost Converter

6. PI Controller
7. AC–DC Rectifier
8. Utility Grid
9. DC-Link Capacitor.

2.2.1 Solar Photovoltaic (PV) Array

FIGURE 2: SOLAR PHOTOVOLTAIC (PV) ARRAY

The Solar Photovoltaic (PV) Array is the primary source of energy in the proposed hybrid system. It converts solar radiation directly into DC electrical power through the photovoltaic effect. The output of the PV array depends on solar irradiance and temperature conditions. In the proposed model, the PV array generates approximately 325 V DC and delivers around 2 kW of power under standard operating conditions. Since the PV output varies with environmental conditions, an Incremental Conductance (INC) MPPT controller is employed to extract maximum available power. The generated power is supplied to the DC-link through a DC–DC boost converter for voltage regulation. The PV array helps reduce dependence on conventional energy sources and promotes clean, renewable energy utilization.

2.2.2 DC–DC Boost Converter

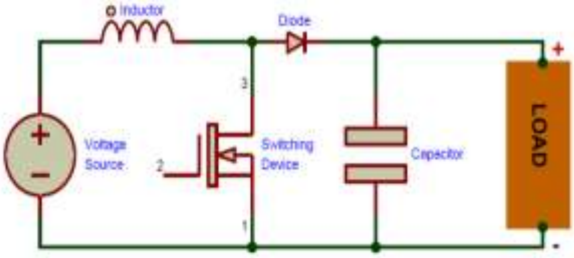


FIGURE 3: DC–DC BOOST CONVERTER

The DC–DC Boost Converter is used to increase the variable output voltage of the solar PV array to the required DC-link voltage level. In the proposed system, it steps up the PV voltage from approximately 325 V to 400 V DC. The converter ensures a stable and regulated output voltage despite changes in solar irradiance and temperature. It operates under the control of a Proportional–Integral (PI) controller, which continuously adjusts the converter duty cycle based on voltage error. The Incremental Conductance (INC) MPPT algorithm works together with the boost converter to extract maximum power from the PV array. The converter also supports the DC-link by maintaining voltage stability and improving overall energy conversion efficiency. Its fast response and reduced steady-state error contribute to reliable system operation.

2.2.3. Incremental Conductance (INC) MPPT Controller

The Incremental Conductance (INC) MPPT Controller is used to track the Maximum Power Point (MPP) of the solar photovoltaic array and maximize energy extraction. It continuously monitors the PV array voltage and current and determines the optimal operating point under changing weather conditions. The INC method compares the incremental conductance (dI/dV)(dI/dV)(dI/dV) with the instantaneous conductance (I/V)(I/V)(I/V) to identify the maximum power point. When the condition dI/dV=−I/VdI/dV = -I/VdI/dV=−I/V is satisfied, the PV system operates at maximum power. The controller adjusts the duty cycle of the DC–DC boost converter to maintain operation at the MPP. Compared to conventional methods, INC MPPT provides higher accuracy, faster response, and reduced oscillations around the operating point. This improves the overall efficiency and performance of the hybrid energy system.

2.2.4. Lithium-Ion Battery

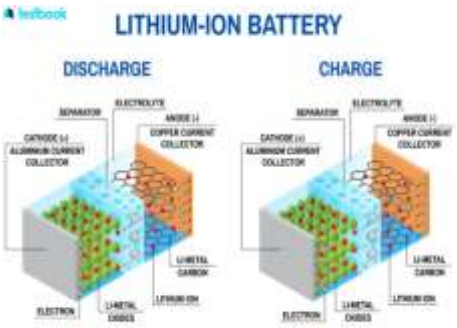


FIGURE 4: LITHIUM-ION BATTERY

The Lithium-Ion Battery serves as the energy storage component in the proposed hybrid energy system. It stores excess solar energy generated during periods of high irradiance and supplies power when solar generation is insufficient. The battery used in the system has a rated voltage of 250 V and is connected to the DC-link through a bidirectional buck–boost converter. During charging mode, surplus energy from the PV array is stored in the battery, while during discharging mode, the stored energy is supplied to the load. Lithium-ion batteries are preferred due to their high energy density, long cycle life, fast charging capability, and low maintenance requirements. The battery improves system reliability, enhances energy utilization, and ensures continuous power supply during low solar generation or nighttime operation.

2.2.5. Bidirectional Buck–Boost Converter

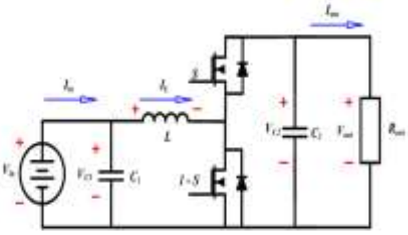


FIGURE 5: BIDIRECTIONAL BUCK–BOOST CONVERTER

The Bidirectional Buck–Boost Converter connects the lithium-ion battery to the common DC-link and enables two-way power flow. It operates in **buck mode** during battery charging by reducing the DC-link voltage from 400 V to 250 V. During battery discharging, it operates in **boost mode** by increasing the battery voltage from 250 V to 400 V. The converter allows efficient charging and discharging of the battery according to system requirements. A PI controller is used to regulate the charging and discharging currents, ensuring stable and smooth operation. The converter maintains DC-link voltage stability and supports power balance between the PV system, battery, and load. Its bidirectional capability improves energy management, system efficiency, and reliability in the hybrid energy system.

2.2.6 PI Controller

The Proportional–Integral (PI) Controller is used to regulate voltage and current in the proposed hybrid energy system. It continuously compares the reference value with the actual output value and generates an error signal. The proportional component provides a fast response to changes, while the integral component eliminates steady-state error. In the proposed system, PI controllers are employed in the DC–DC boost converter, bidirectional buck–boost converter, and grid-side converter. They ensure stable DC-link voltage regulation, controlled battery charging/discharging, and efficient power transfer. The PI controller improves system stability, reduces voltage fluctuations, and provides smooth dynamic performance under varying load and solar conditions. Due to its simplicity and effectiveness, it is widely used in renewable energy applications.

2.2.7 AC–DC Rectifier

The AC–DC Rectifier is used to connect the utility grid to the common DC-link in the proposed hybrid energy system. It converts the single-phase AC supply (230 V, 50 Hz) from the grid into a regulated 400 V DC output. The rectifier acts as a backup power interface when solar generation and battery energy are insufficient to meet load demand. It ensures a continuous and reliable power supply during nighttime operation, low solar irradiance conditions, or battery depletion. The rectifier maintains stable DC-link voltage and supports efficient power transfer to the load. It is designed to minimize harmonic distortion and improve overall power quality. The integration of the AC–DC rectifier enhances the reliability, flexibility, and stability of the hybrid energy system.

2.2.8 Utility Grid

FIGURE 6: UTILITY GRID

The Utility Grid serves as a backup power source in the proposed hybrid solar–battery–grid system. It provides electrical energy whenever the solar PV system and battery storage are unable to satisfy the load demand. The grid operates at a single-phase voltage of 230 V and a frequency of 50 Hz. Through an AC–DC rectifier, grid power is converted into a regulated 400 V DC supply and delivered to the DC-link. The utility grid ensures uninterrupted power supply during nighttime operation, low solar irradiance conditions, battery depletion, or sudden load increases. It also helps maintain DC-link voltage stability and improves overall system reliability. The integration of the utility grid enhances the flexibility and continuous operation of the hybrid energy system.

2.2.9 DC-Link Capacitor

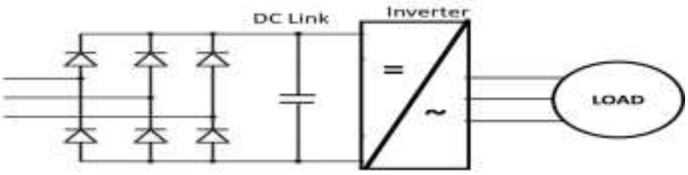


FIGURE 7:DC-LINK CAPACITOR

The DC-Link Capacitor is an essential component that connects the power converters, battery storage system, and utility grid through a common DC bus. Its primary function is to maintain a stable DC-link voltage of 400 V by storing and releasing energy whenever required. The capacitor reduces voltage ripples and smooths fluctuations caused by variations in solar generation, load demand, and converter switching operations. It acts as a temporary energy buffer, ensuring continuous power flow between different subsystems. The DC-link capacitor also improves system stability, enhances power quality, and supports the dynamic performance of the converters. By maintaining a constant DC voltage level, it enables efficient energy transfer and reliable operation of the hybrid solar–battery–grid system.

2.3 SOLAR SYSTEM

Solar energy is one of the most abundant and environmentally friendly renewable energy sources available today. A Solar Photovoltaic (PV) system converts sunlight directly into electrical energy through the photovoltaic effect. Due to its clean operation, low maintenance requirements, and unlimited availability, solar energy has become an important component of modern power generation systems.

2.4 Working Principle of Solar PV System

The Solar Photovoltaic (PV) System converts solar energy directly into electrical energy through the photovoltaic effect. When sunlight falls on the PV cells, photons excite electrons within the semiconductor material, generating a DC voltage and current. The output power produced by the PV array varies according to solar irradiance and temperature conditions. To ensure maximum energy extraction, the Incremental Conductance (INC) MPPT algorithm continuously tracks the maximum power point of the PV array. The generated DC power is then supplied to a DC–DC boost converter, which increases the voltage from approximately 325 V to the required DC-link voltage of 400 V. A PI controller regulates the converter output to maintain stable voltage levels. The regulated power is delivered to the DC-link, from where it can supply the load, charge the battery, or support the grid-connected system. This process ensures efficient utilization of solar energy and reliable operation of the hybrid power system

2.5 Characteristics of Solar PV System

2.5.1 Current–Voltage (I–V) Characteristics

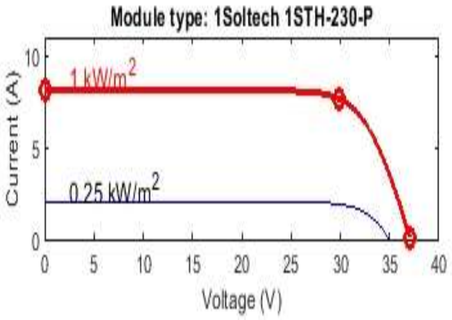


FIGURE 8: CURRENT-VOLTAGE CHARACTERISTICS

The Current–Voltage (I–V) characteristic curve represents the relationship between the output current and output voltage of a solar photovoltaic (PV) array. It is an important parameter used to evaluate the performance of PV modules under different operating conditions. At short-circuit conditions, the current reaches its maximum value while the voltage is zero. Conversely, at open-circuit conditions, the voltage reaches its maximum value while the current becomes zero. As the voltage increases, the output current remains nearly constant up to a certain point and then decreases rapidly. The knee point of the I–V curve corresponds to the Maximum Power Point (MPP), where the PV array delivers maximum power. Changes in solar irradiance mainly affect the output current, while temperature variations primarily influence the output voltage. The I–V characteristics are used by MPPT controllers to determine the optimal operating point for maximum energy extraction from the PV system.

2.5.2 Power–Voltage (P–V) Characteristics

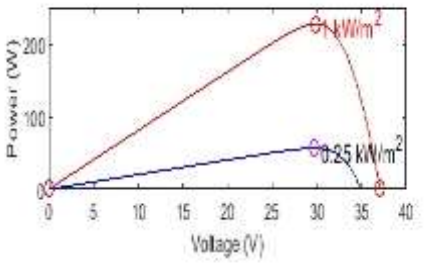


FIGURE 8: POWER-VOLTAGE CHARACTERISTICS

The **Power–Voltage (P–V) Characteristics** represent the operational behavior and electrical power output of a solar photovoltaic (PV) array at varying voltage levels. Under uniform weather conditions, the P–V curve exhibits a non-linear relationship where the output power initially ascends as the operating voltage increases. This rising curve continues up to a distinct peak known as the Maximum Power Point (MPP). At this specific peak point, the solar array operates at maximum efficiency, delivering the absolute highest possible electrical power to the system. Beyond the Maximum Power Point, any further increase in operating voltage causes the output power to drop sharply toward zero, eventually reaching the open-circuit voltage condition. Because the entire P–V curve dynamically shifts and fluctuates based on shifting environmental variables such as solar irradiance and cell temperature, real-time tracking is necessary. Advanced tracking methods, such as the Incremental Conductance (INC) MPPT technique, are deployed to continuously evaluate the mathematical condition ($\frac{dI}{dV} = -\frac{I}{V}$).This algorithm adjusts the converter's duty cycle on the fly, locking the system onto the peak of the P–V curve to guarantee optimal energy extraction under rapidly changing environmental conditions.

2.6 BATTERY STORAGE SYSTEM

Battery Energy Storage Systems (BESS) play a vital role in modern renewable energy systems by storing excess electrical energy and supplying it when required. In hybrid solar–battery–grid systems, the battery acts as an energy buffer that compensates for the intermittent nature of solar power generation. It improves system reliability, enhances energy utilization, and ensures continuous power supply during periods of low solar irradiance or increased load demand.

2.6.1 Battery Integration in the Proposed System

The proposed system uses a **250 V lithium-ion battery** connected to the DC-link through a bidirectional buck–boost converter.

2.6.2 Current Discharging Characteristics

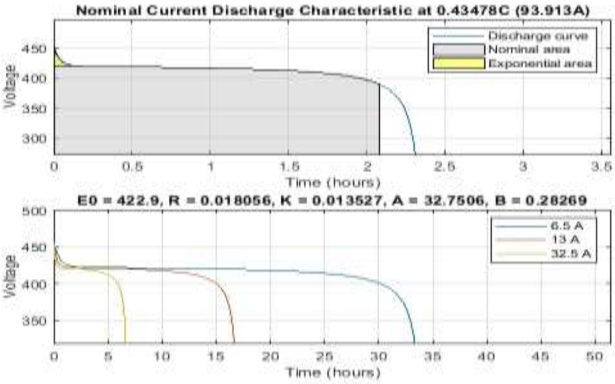


FIGURE 9: CURRENT DISCHARGING CHARACTERISTICS

The provided block diagram illustrates the architectural layout and power distribution network of a **Solar Power-Based Electric Vehicle (EV) Charging Station** integrated with a battery backup. At the front end, a Photovoltaic (PV) array captures solar energy and transfers it through a step-up Boost Converter, which uses a Maximum Power Point Tracking (MPPT) system to dynamically extract the maximum available power under changing weather conditions. To handle the intermittent nature of solar energy, a Battery Storage system is integrated into the network via a Bidirectional DC-DC Converter; this allows the battery to absorb surplus energy when generation exceeds demand or discharge energy back into the system during periods of low sunlight or high demand. Both renewable sources feed into a centralized DC Bus, which serves as the core power distribution link. This DC Bus is connected to a standard three-phase AC Grid (50 Hz) through a Bidirectional Three-Phase Inverter, enabling a two-way power flow where energy can be imported from the utility grid during deficits or injected back into it during periods of excess generation. Ultimately, the regulated power from this central network is supplied directly to the EV Charging Load to power electric vehicles, with the entire interconnected operation being synchronized by a Centralized Controller that manages the switching states of the power converters to ensure system balance and efficiency.

3. Simulation Results

3.1 The Proposed Hybrid Energy System

The Proposed Hybrid Energy System introduces the core simulation model used to evaluate the performance of an integrated power network. This configuration evaluates a multi-stage power electronic architecture that interconnects a renewable solar photovoltaic (PV) array, a lithium-ion battery storage unit, and a single-phase utility grid (230V, 50Hz) through a centralized 400Vcommon DC-link node. In this network, the solar PV array serves as the primary energy source, utilizing a step-up DC-DC boost converter governed by an Incremental Conductance (INC) MPPT algorithm to optimize energy extraction under fluctuating weather conditions. To mitigate the intermittent nature of solar generation, a 250V lithium-ion battery is integrated using a PI-controlled bidirectional buck-boost converter, which automatically operates in buck mode to absorb surplus energy or boost mode to discharge and support the common bus. Finally, the utility grid is tied via an AC-DC rectifier to provide immediate backup power during periods of prolonged cloud cover, battery depletion, or nighttime operations, ensuring a highly reliable and continuous electricity supply to the connected load.

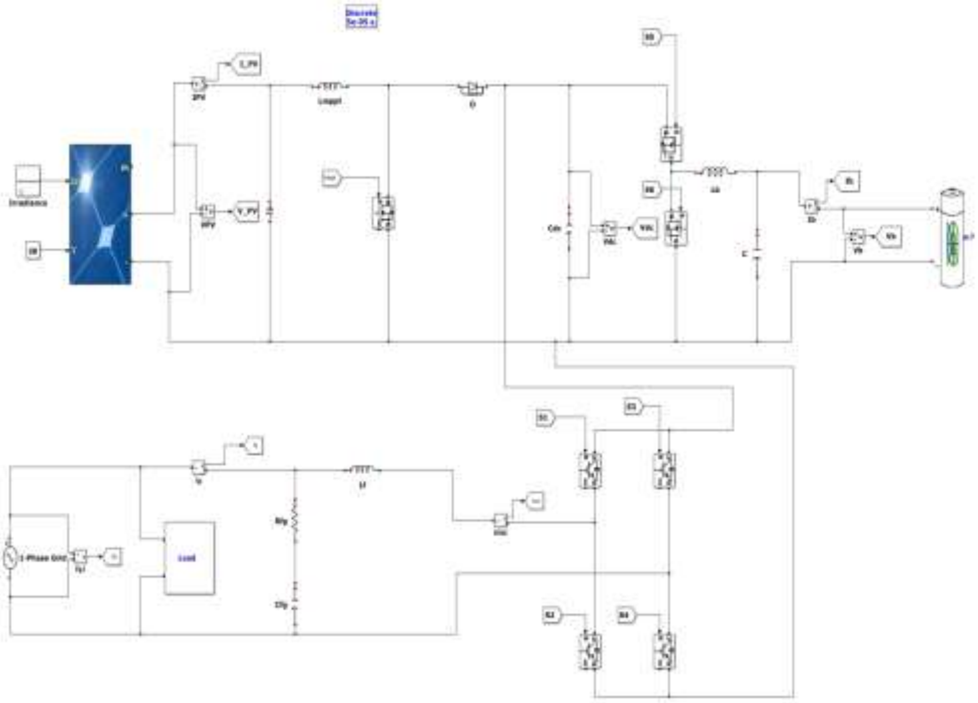


FIGURE 10: MATLAB/SIMULINK circuit of the Proposed system hybrid EV charger

3.2 Table 1: Test System Parameters

Name of the parameter	Values
Grid	2.3kW, 230V,50Hz
PV module	Vmp = 418.6 V, Imp = 7.65 A, Voc = 519.4 V, Isc = 8.18 A, Ns = 14, Np = 1, Pmax = 5 kW.
Boost converter	Rb = 0.01Ω, Lb = 20mH, Cout = 0.625μF,
PI controller	Kp = 8, Ki = 20
Electric vehicle battery	Type: Lithium Ion, Pnom = 84.24kWh, Vnom = 390V, Capacity = 216Ah.

3.3 Performance of the DC–DC boost Converter

Performance of the DC–DC Boost Converter details the evaluation and key functionalities of the system's step-up conversion stage. Because the initial output voltage from the solar photovoltaic array sits at a variable 325V, the boost converter is utilized to step up and stabilize this power to meet the central 400V DC-link requirement. The converter's switching operations are managed via a Proportional–Integral (PI) controller that continuously maps the real-time output against a set reference voltage to dynamically adjust the switch's duty cycle. Simulation results confirm that this control strategy enables the converter to maintain a steady 400V bus supply while showing excellent dynamic traits, including a fast transient response, minimal overshoot, and reduced steady-state error. Furthermore, the converter successfully handles dual roles by providing steady DC-link support and working alongside the Incremental Conductance MPPT algorithm to ensure optimal energy extraction during solar fluctuations.

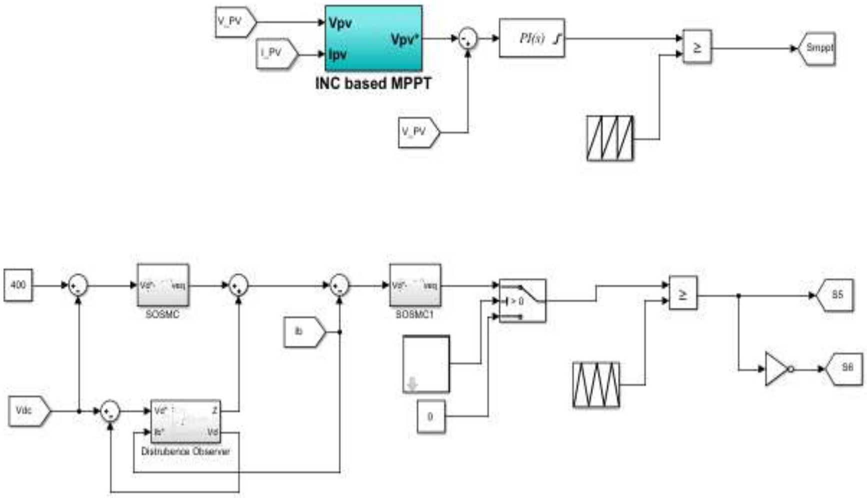


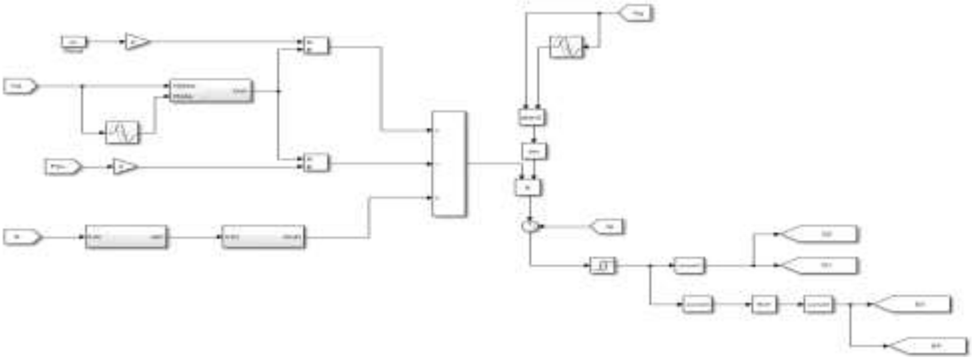
FIGURE 11:Control system for Boost and DC/DC Converter with PI controller

3.4 Incremental Conductance MPPT Performance

In addition to voltage regulation, the system incorporates a Maximum Power Point Tracking (MPPT) algorithm to maximize energy extraction from the PV source. The Incremental Conductance (INC) method is used for this purpose due to its accuracy and effectiveness under varying environmental conditions. The INC algorithm operates by comparing the incremental conductance (dI/dV) with the instantaneous conductance (I/V) of the PV module. At the maximum power point, the condition dI/dV = –I/V is satisfied. The algorithm continuously monitors changes in voltage and current and adjusts the operating point of the PV system accordingly. The PI controller works in conjunction with the MPPT algorithm to ensure that the boost converter operates at the optimal duty cycle, thereby maintaining the PV system at its maximum power point. This combination of MPPT and PI control results in efficient energy utilization and improved system performance.

3.5 Battery Energy Storage System Performance

The energy storage component of the system is a 250 V lithium-ion battery, which plays a crucial role in maintaining power balance and ensuring continuous supply. The battery is connected to the DC link through a bidirectional buck–boost converter, which allows energy to flow in both directions. This converter operates in two modes depending on system conditions: buck mode and boost mode. During periods of high solar generation, when the PV system produces more power than the load demand, the excess energy is used to charge the battery. In this case, the bidirectional converter operates in buck mode, stepping down the DC link voltage from 400 V to 250 V to match the battery charging requirements. The charging process is controlled using a PI controller, which regulates the charging current and ensures safe and efficient operation of the battery.



FIGRUE 12: BATTERY ENERGY STORAGE SYSTEM PERFORMANCE

3.6 DC-Link Voltage Regulation Analysis

The DC link, maintained at 400 V, serves as the central node of the system, interconnecting all energy sources and converters. It acts as a common platform for energy exchange, allowing seamless power transfer between the PV system, battery, and grid. Maintaining a stable DC link voltage is critical for the proper operation of the entire system. Any fluctuations in the DC link voltage can affect the performance of connected converters and lead to instability. Therefore, the control strategies implemented in the system are primarily focused on regulating the DC link voltage and ensuring balanced power flow.

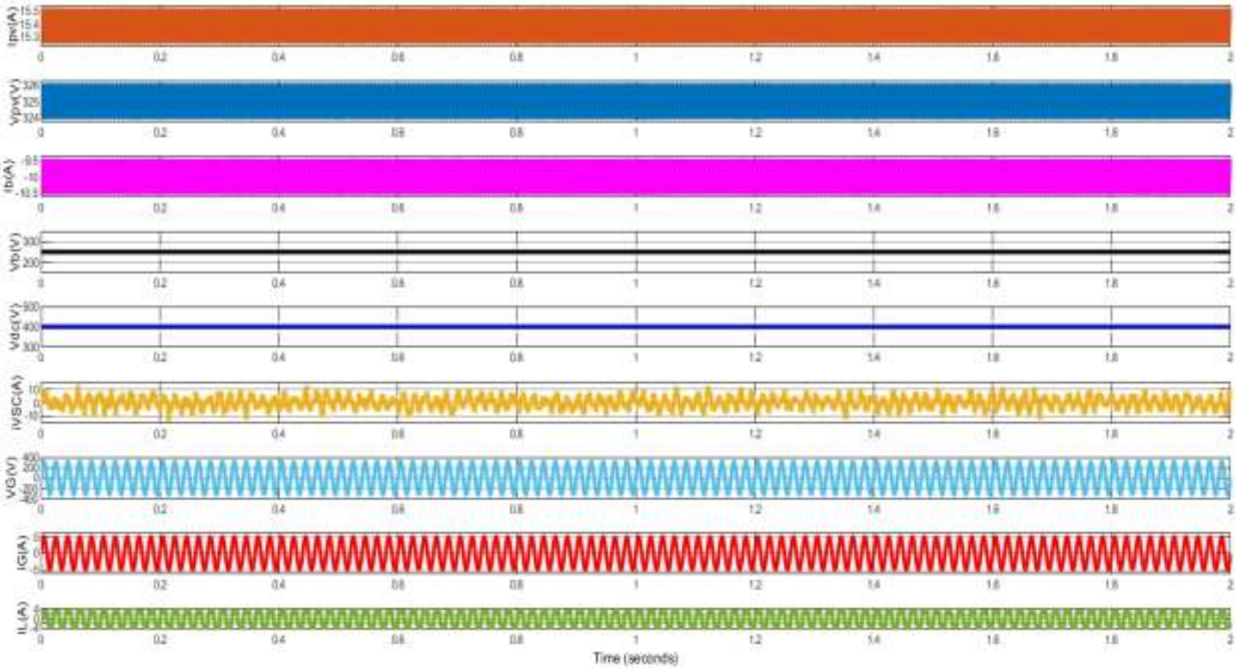


FIGURE 13: PROPOSED SYSTEM PARAMETERS

The overall control of the system is achieved using multiple PI controllers, each dedicated to a specific converter. The boost converter PI controller ensures maximum power extraction from the PV system by maintaining the desired operating point. The bidirectional converter PI controller manages battery charging and discharging while maintaining DC link stability. The grid-side rectifier ensures consistent DC output and supports the DC link during power deficits. The coordinated operation of these controllers ensures that the system responds effectively to changes in load demand and environmental conditions.

The system operates in different modes depending on the availability of solar energy and the state of the battery. In normal conditions, when solar energy is sufficient, the PV system supplies power to the load and charges the battery simultaneously. During partial solar availability, both the PV system and battery share the load demand. In the absence of solar energy, the battery and grid supply power to the load. If the battery is depleted, the grid becomes the primary source of power. These modes of operation ensure optimal utilization of available energy sources and minimize dependency on the grid.

From a performance perspective, the system demonstrates stable operation, efficient energy management, and reliable power supply. The use of PI controllers provides a simple yet effective control strategy, ensuring satisfactory dynamic response and minimal steady-state error. The implementation of the INC MPPT algorithm enhances the efficiency of the PV system by ensuring maximum power extraction under varying conditions. The bidirectional converter enables effective utilization of battery storage, improving overall system efficiency.

4. Conclusion

This work presented the design and implementation of a hybrid energy system integrating photovoltaic generation, battery storage, and grid support using conventional control techniques. The proposed system employed a multi-stage power conversion structure to ensure efficient energy transfer and stable operation under varying conditions. A proportional–integral (PI) controller was utilized to regulate the performance of the converters, providing reliable voltage and current control throughout the system. The incremental conductance MPPT algorithm was implemented to extract maximum available power from the photovoltaic source, ensuring efficient utilization of solar energy under changing environmental conditions. The bidirectional converter effectively managed the charging and discharging of the battery, maintaining power balance and supporting the DC link during fluctuations. Additionally, the grid interface acted as a backup source, ensuring continuity of power supply and enhancing overall system reliability. The results demonstrated that the PI-controlled system provides satisfactory dynamic response, acceptable steady-state performance, and stable operation. Overall, the study confirms that conventional control methods can offer a simple, cost-effective, and reliable solution for hybrid energy systems. The proposed approach is suitable for practical implementation and serves as a strong foundation for further improvements using advanced control strategies.

5. Future Scope

The future scope of this project focuses on transitioning the developed simulation framework into a scalable hardware prototype and introducing sophisticated smart grid technologies. A primary enhancement involves integrating internet-of-things (IoT) sensors and communication modules to enable continuous, real-time remote monitoring of solar array generation, battery state-of-health (SoH), and overall charging infrastructure efficiency. Furthermore, implementing advanced machine learning algorithms can optimize load forecasting, accurately predict peak demand periods, and enable adaptive power allocation among multiple connected vehicles simultaneously.

Another highly promising avenue is the integration of bidirectional Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) energy transfer protocols. This would transform parked electric vehicles into flexible, distributed energy storage assets capable of feeding power back into the local grid or residential loads during peak hours or supply deficits, thereby improving overall grid resilience. To maximize user convenience and system throughout, upgrading the converter topologies to support multi-port configurations and ultra-fast DC charging protocols would drastically minimize vehicle replenishment times.

Finally, the system's reliability can be enhanced by evolving it into a multi-source hybrid microgrid. Incorporating other complementary renewable generation sources, such as wind turbines or green hydrogen fuel cell systems alongside the existing solar PV arrays, would mitigate the intermittent nature of solar energy. This diversification, managed by an intelligent Energy Management System (EMS), ensures a fully sustainable, zero-emission, and entirely uninterrupted power supply capable of operating independently of the commercial utility grid under any environmental conditions.

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