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Energy Management Approaches for Enhanced Performance in Grid-linked Solar PV System with Battery Storage

Pranati Katyal[1], Rajesh Katyal[2], K.Premkumar[3]

[1]Professor, EEE, Misrimal Navajee Munoth Jain Engineering college, Thoraipakkam, Chennai.

[2]Director General, National institute of Wind Energy, Chennai.

[3]Associate Professor, Department of EEE, Rajalakshmi Engineering College, Chennai

Email id : Pranati.kat@gmail.com[1], Katyal.niwe@nic.in[2], premkumar.k@rajalakshmi.edu.in[3]

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Abstract

This research delves into advanced energy management approaches aimed at optimizing the performance of grid-linked PV systems integrated with battery storage, featuring bidirectional converters. The incorporation of bidirectional converters enables seamless energy flow between the PV schemes, batteries, and the grid, presenting a dynamic framework for enhanced energy utilization. Our study explores strategies to efficiently manage the charging and discharging cycles of the battery storage system, aligning them with the varying solar irradiance levels. By implementing intelligent control algorithms, we aim to achieve optimal energy utilization, ensuring a reliable and sustainable power supply to the grid. The bidirectional converter plays a pivotal role in facilitating bidirectional power flow, allowing for energy exchange between the solar PV system and the battery storage unit. Key focus areas include the development of real-time monitoring and control systems to adaptively manage the energy flow, addressing the intermittency of solar power generation. Additionally, we investigate the impact of bidirectional converter efficiency on overall system performance and propose measures for its optimization. Our findings aim to contribute valuable insights into the seamless integration of bidirectional converters in grid-linked solar PV systems with battery storage, advancing the field of energy management for sustainable and resilient power supply.

Keywords: Energy Management, Grid-linked Solar PV Systems, Battery Storage, Bidirectional Converter, Sustainable Power Supply.

I. Introduction

Non Conventional energy sources (RES) are preferable to traditional energy sources because of their minimal environmental effect and cleanliness. The wind, the sun, the biomass, the water, and the geothermal heat are all examples of renewable energy sources (RES) that may be found in plenty in the natural world. This electrical gadget, known as a solar photovoltaic (PV) cell, is responsible for transforming the chemical energy of sunshine into direct current (DC) power. Multiple cells,

panels, and an array make up a photovoltaic system. Electricity generated at these massive PV facilities is sent into the grid and utilized to power homes and businesses. In most cases, a DC-to-AC converter/inverter and photovoltaic panels make up such a system. A maximum power point (MPP) and data storage devices are two more components that might be part of such a system. The power may be stored for later use, used on-site, or added to regional or national power networks. The output voltage, current, or power, as determined by the interconnections of the panels or array, is a variable that is affected by the amount of available sunlight. The importance of an energy storage system in system balancing or energy management is given in [1]

The fundamental structure of a solar PV system, whether connected to the grid or operating independently, involves the utilization of a utility, with the PV array serving as the primary energy source. Additionally, storage devices are incorporated as external regulators, responsible for absorbing or supplying power to maintain equilibrium in the primary energy source and accommodate varying loads. Therefore, power flow management is essential for controlling the bidirectional converter linked to the battery in order to charge or drain the battery from a variety of different sources. The battery's charge level serves as the basis for the controller that manages power flow.

Energy storage systems are beneficial because they lower electricity costs and improve power grid dependability. Storage (zinc–bromine) system size and control are offered for wind power systems [2]. The storage device in the grid-linked hybrid system controls the appropriate power movement in the system to decrease the total cost at the point of common connection [3]. For more efficient energy storage management, it is important to position additional distributed generating inside the current distribution network in conjunction with the energy storage device. Using an evolutionary algorithm, it is possible to maximize a number of different criteria at once [4]. Numerous renewable energy sources are used to generate electricity in the distribution system, with the probabilistic approach used to allocate these sources helping to reduce power system losses [5]. The optimal planning of solar photovoltaic (PV) and battery storage systems for the grid-linked residential sector is explored in the paper referenced as [6]. The main findings include the importance of considering various factors such as load demand, solar resource, and battery characteristics in the planning process. The review also highlights the challenges associated with optimal planning, such as the uncertainty in load demand and solar resources, and the need for new perspectives in addressing these challenges. It provides a general overview of the topic and does not delve into specific methodologies or case studies for ideal planning of PV and battery storage arrangements. The paper indexed as [7] delves into the stochastic performance analysis and robust design optimization of a grid-linked photovoltaic (PV) system incorporating battery storage and hydrogen storage. The main findings include the importance of considering uncertainties in factors such as solar resource, load demand, and battery and hydrogen storage capacities in the design optimization process. Additionally, a technique for unpredictable performance analysis is presented in the study to assess the system's performance in different situations. Its main emphasis is on optimizing the design and performance analysis of a particular hydrogen storage system; however, its applicability to others linked to the grid photovoltaic and battery storage systems may be limited. Under uncertainty, the best time to schedule a microgrid powered by renewable energy sources while considering a PV

system and battery energy storage [8]. The significance of incorporating uncertainties in load demand, solar resource, and battery state of charge during the scheduling process has been highlighted in the key findings. A mathematical model and an optimization algorithm are introduced in the paper to identify the optimal scheduling of the PV system and battery energy storage. Emphasis is placed on the optimal scheduling of a microgrid, acknowledging that its applicability to planning in the grid-connected residential sector may be indirect. The determination of optimal battery capacity for grid-connected PV-battery systems, accounting for battery degradation, is also addressed in the paper [9]. In determining the optimal battery capacity to ensure the long-term performance and economic viability of the system, the main findings underscore the significance of accounting for battery degradation. The paper introduces a mathematical model and an optimization algorithm dedicated to determining the optimal battery capacity. The focal point is specifically on optimal battery capacity, taking into account battery degradation, and the planning process does not incorporate other factors such as load demand and solar resource. The optimal schedule for grid-connected residential PV generation systems with battery storage under time-of-use and step tariffs is explored, emphasizing the importance of considering tariff structures and load demand patterns in optimizing the schedule for maximizing economic benefits. The paper also presents a mathematical model and an optimization algorithm for determining the optimal schedule. It focuses specifically on the optimal schedule considering time-of-use and step tariffs and does not consider other factors such as solar resource and battery characteristics in the planning process.

Table 1. Comparison of Energy managements methods of Grid connected PV system

References	Main Findings	Focus	Limitations
[6]	Importance of considering load demand, solar resource, and battery characteristics in planning. - Highlights challenges and uncertainties in load demand and solar resources.	Ideal planning for the residential sector linked to the grid.	potential limitations in addressing challenges.
[7]	Emphasizes the importance of uncertainties in solar resource, load demand, and storage capacities in design optimization. - Presents a methodology for stochastic performance analysis.	Performance evaluation and design optimization of a particular hydrogen storage system. May not be universally applicable to all grid-connected PV and battery storage systems.	It may not work with every grid-linked PV scheme and battery storage solution.
[8]	Stresses the importance of considering uncertainties in load demand, solar resource, and battery state of charge in scheduling. - Introduces a mathematical model and optimization algorithm for optimal scheduling.	Optimal scheduling of a microgrid.	May not directly apply to grid-connected residential sector planning

[9]	Focuses on taking battery deterioration into account when calculating the ideal battery capacity for long-term use and financial feasibility. outlines an optimization process and mathematical model for figuring out the ideal battery capacity. Maximum battery capacity taking into account battery deterioration.	Optimal battery capacity considering battery degradation.	Does not consider other factors like load demand and solar resource in planning.
[10]	- Highlights the importance of considering tariff structures and load demand patterns in determining the optimal schedule for economic benefits. - Presents a mathematical model and optimization algorithm for determining the optimal schedule.	Optimal schedule considering time-of-use and step tariffs.	Does not consider other factors such as solar resource and battery characteristics in the planning process.

A. Problem Statement

The literature review highlights several aspects of renewable energy systems, particularly focusing on PV and battery storage systems for grid-linked residential sectors. While there has been substantial progress in understanding and implementing these technologies, there are evident challenges and gaps that warrant further investigation. The problem can be articulated as follows:

Inadequate Integration of Renewable Energy Sources (RES)

The literature emphasizes the importance of RES, especially solar PV and battery storage, in reducing environmental impact and enhancing grid reliability. However, there is a lack of detailed insights into the effective integration of various RES components and their impact on overall system performance.

Limited Comprehensive Planning Methodologies

Although the ideal planning of solar PV and battery storage systems is acknowledged as crucial, there is a research gap in the development of comprehensive planning methodologies. The existing literature provides a general overview but lacks specific methodologies or case studies for effective planning in grid-connected residential sectors.

Uncertainties and Challenges in System Design

The papers [6], [7], [8], and [9] highlight the significance of considering uncertainties in factors such as load demand, solar resource, and battery characteristics. However, there is a need for more focused research on addressing these uncertainties and challenges in the system design phase to ensure robust and adaptable renewable energy systems.

Limited Exploration of Additional Distributed Generation

Energy storage systems are acknowledged for lowering electricity costs and enhancing power grid dependability. However, there is a research gap in exploring the integration of additional distributed generation within the current distribution network in conjunction with energy storage devices for more efficient energy storage management.

Optimization Algorithms and Multi-Criteria Maximization

The literature briefly mentions the use of evolutionary algorithms to maximize multiple criteria simultaneously in [4]. However, there is a lack of in-depth exploration of optimization algorithms and their application to maximize efficiency, reliability, and economic benefits in renewable energy systems.

B. Research Gap

The identified problem areas lead to the formulation of the following research gap:

Despite the growing importance of renewable energy systems, particularly solar PV and battery storage, there exists a research gap in developing comprehensive planning methodologies, addressing uncertainties and challenges in system design, exploring the integration of additional distributed generation, and optimizing renewable energy systems using advanced algorithms. The existing literature provides valuable insights but lacks detailed methodologies and case studies to bridge these gaps effectively. Further research is needed to develop practical and adaptable solutions for the successful implementation of renewable energy systems in grid-connected residential sectors.

II. Proposed Topology

The Block Diagram of the proposed system is presented in Figure 1. It consists of PV array, Bidirectional converter, Boost converter, DC bus and an inverter connected to the AC grid.

A. PV System Mathematical Modelling

Figure 2 illustrates the mathematical model of a PV cell, featuring the current source Iph representing the photocurrent of the cell. The cell encompasses intrinsic shunt (Rsh) and series (Rs) resistances, although, in most cases, Rsh possesses a considerably large value, and Rs exhibits a very small value. Consequently, these resistances are often disregarded to streamline the analysis. In practical applications, PV cells are organized into more extensive units known as PV modules. These modules are subsequently interconnected in series or parallel configurations to form PV arrays, which serve as the foundation for generating electricity in PV generation systems

$$I_{ph} = [I_{sc} + K_i(T - 298)] * I_r/1000 \quad (1)$$

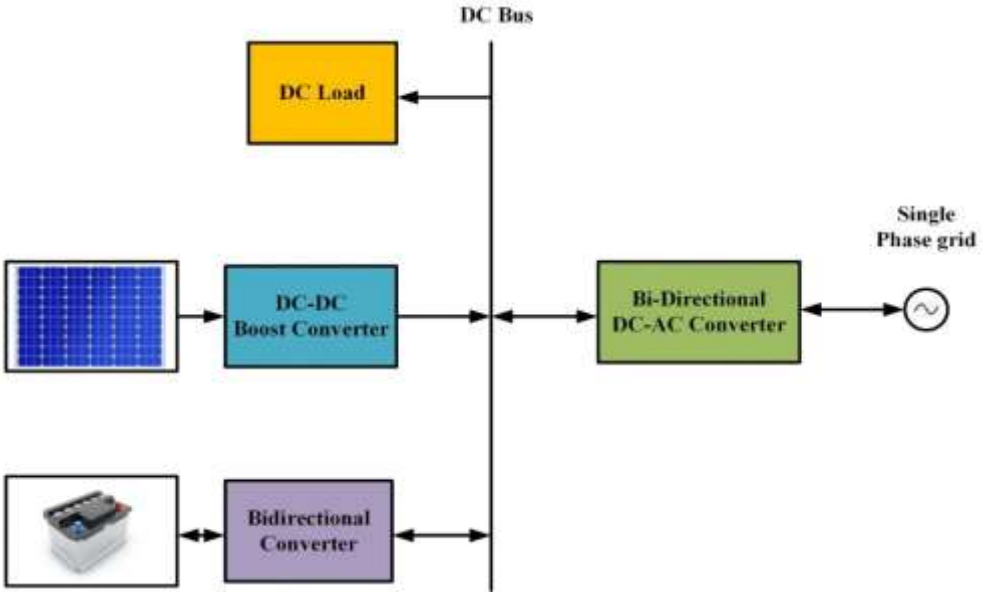


Figure 1. Block diagram of the Proposed system

Here, Iph represents the photo-current in amperes (A), while Isc denotes the short-circuit current in amperes (A). Ki signifies the short-circuit current of the cell at 25°C and 1000 W/m2. T corresponds to the operating temperature measured in kelvins (K), and Ir stands for solar irradiation measured in watts per square meter (W/m2). The module's reverse saturation current is denoted as Irs.

$$I_{rs} = I_{sc}/[\exp\left(\frac{qV_{oc}}{N_s knT}\right) - 1] \quad (2)$$

Here, The electron charge (q) is equal to 1.6 × 10^−19 coulombs (C). The open circuit voltage (Voc) is denoted in volts (V). Ns represents the number of cells connected in series. The ideality factor of the diode is represented by 'n'. Boltzmann's constant (k) is valued at 1.3805 × 10^−23 joules per kelvin (J/K).

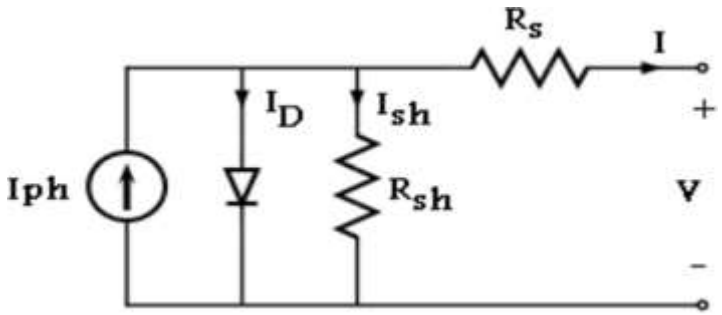


Figure 2. Mathematical model of PV cell

B. Incremental conductance method-MPPT

By employing this method, small alterations in current and voltage are observed by the controller to predict the consequences of a voltage shift. While this approach necessitates additional computations on the part of the controller, it exhibits the capability to respond to changing scenarios with greater speed compared to P&O. Power generation experiences minimal fluctuations. The calculation of the change in power concerning voltage (dP/dV) involves assessing the incremental conductance (dI/dV) of the solar array.

Involving the incremental conductance technique for determining the maximum power point (MPP) necessitates a comparison between the array conductance (I/V) and the incremental conductance (I/V). When equality is achieved (I/V = I/V), the MPP voltage is identified. This voltage is subsequently kept constant by the controller until alterations in irradiation prompt the repetition of the procedure. The incremental conductance approach is grounded on recognizing that both P=IV and dP/dV=0 hold true at the maximum power point (MPP). Expressing the array's current as a function of voltage involves the representation: P=I(V)V..

$$\frac{dP}{dV} = v\frac{dI}{dV} + I(v) \tag{3}$$

$$\frac{dI}{dV} = -I(v)v \tag{4}$$

As a result, the maximum power point (MPP) is attained when the negative value of the instantaneous conductance equals the incremental conductance. When the voltage descends below the MPP, conformity with the characteristic power-voltage curve is maintained.,

$$\frac{dP}{dV} > 0 \tag{5}$$

$$\frac{dP}{dV} > \frac{-I}{v} \tag{6}$$

when the voltage is bigger than MPP,

$$\frac{dP}{dV} < 0 \tag{7}$$

or

$$\frac{dI}{dV} > \frac{-I}{v} \tag{8}$$

The determination of its position on the power-voltage curve can be made by calculating the correlation between the change in current/voltage and the current voltage themselves.

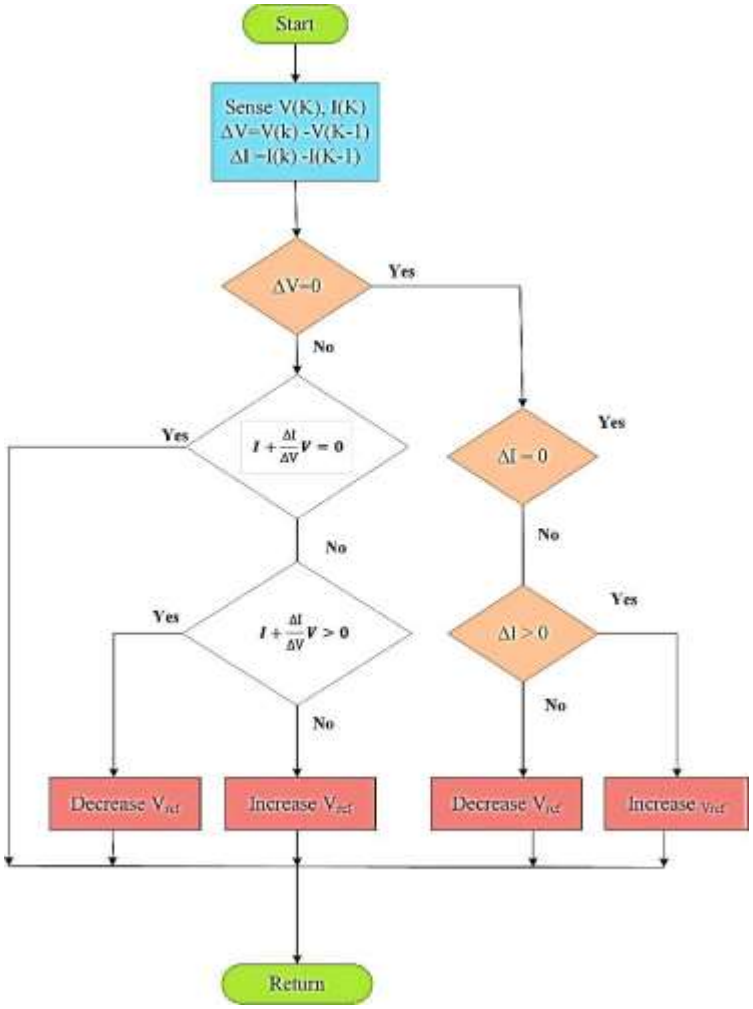


Figure 3. Flow Chart of Incremental conductance algorithm

C. Boost converter

Utilizing a boost converter, recognized as a step-up DC/DC converter, is a method employed to raise the solar voltage to meet the specified output voltage based on load demands. The configuration, as depicted in Fig. 5, encompasses a DC input voltage Vin, an inductor L, a switch S, a diode D1, a filter capacitor C, and a load resistance R. In the ON state of switch S, energy from the input voltage source is stored in the boost inductor, while the charged capacitor sustains a consistent load current. During the OFF state of switch S, both the input voltage and the stored inductor voltage are applied across the load, resulting in an elevation of the load voltage. Consequently, the state of switch S (ON or OFF) determines the load voltage, influencing the duty ratio D. The output DC voltage is contingent upon the duty ratio D of the switch.

$$\frac{V_0}{V_S} = \frac{1}{1-D} \quad (9)$$

$$D_{max} = 1 - \frac{V_{in_min}}{V_o} \times \eta \quad (10)$$

$$D_{min} = 1 - \frac{V_{in_max}}{V_o} \times \eta \quad (11)$$

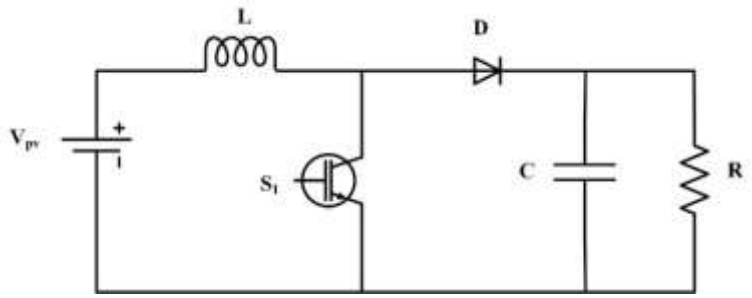


Fig.4.Circuit Diagram of Boost converter

D. Bidirectional DC-DC Converter

To govern the charge and discharge activities of the Li-ion battery, a bidirectional DC/DC converter is employed. The use of small inductor values in this converter serves to improve the switching operation, resulting in reduced input current ripple. This leads to heightened dynamics and safety in the Energy Storage System (ESS), along with increased efficiency in the conversion process. Fig.5 displays the schematic representation of the converter

By overseeing the output currents and comparing them with the reference value and IB,ref, the necessary duty cycle for the converter is generated by the Energy Management System (EMS), thereby regulating the battery. The analysis of the two-phase bidirectional converter can also involve its two operating modes: buck mode and boost mode. In the case of buck mode operation, the input battery voltage (Vin) is delivered to the inductor, and the inductance can be calculated as follows:

$$L = \frac{V_{in}(1-d)}{\Delta i_L f_{sw}} \quad (12)$$

The alteration in inductor current is denoted by ΔiL. In this scenario, the duty ratio will vary between dmin and dmax, where dmin and dmax represent the minimum and maximum duty cycles, depending on the required DC link voltage value. The converter regulates the DC-link voltage, keeping it constant at a reference value. Furthermore, in the event of the converter being employed in boost mode, the relationship concerning the input voltage and the DC-link voltage can be stated as follows:

$$V_{dc,link} = \frac{V_{in}}{(1-d)} \tag{13}$$

$$L = \frac{V_{in}d}{\Delta i_L f_{sw}} \tag{14}$$

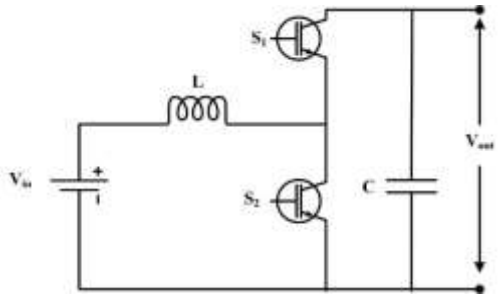


Fig.5. Circuit Diagram of Bidirectional converter

The voltage control of a bidirectional DC-DC converter is a critical aspect in power electronic systems, particularly in applications where energy needs to flow bidirectionally between two voltage levels. One commonly employed method for achieving precise voltage regulation is through closed-loop control with a Proportional-Integral (PI) controller. A pivotal role in sustaining the desired output voltage is undertaken by the PI controller, as it consistently compares the reference voltage with the actual output voltage. The instantaneous error is addressed by the proportional term of the controller, while accumulated past errors are managed by the integral term, thereby ensuring stability and minimizing steady-state deviations. This dynamic feedback system enables the bidirectional DC-DC converter to seamlessly transition between buck and boost modes, adjusting the duty cycle of the switching signal through Pulse Width Modulation (PWM) to regulate the energy transfer and achieve the desired voltage at the output.In practical terms, the PI controller receives feedback from voltage sensors monitoring the output voltage, and it computes the error signal by comparing this feedback with the reference voltage. The controller then adjusts the duty cycle of the converter's switching signal, effectively controlling the energy flow and output voltage. This closed-loop control with a PI controller ensures that the bidirectional DC-DC converter can adapt to varying load conditions, input voltages, and bidirectional power flow requirements, providing a reliable and stable voltage regulation mechanism in diverse applications such as renewable energy systems and electric vehicles.

A. 2.5 Inverter

A DC to AC converter, commonly known as an inverter, is an electrical device responsible for transforming direct current (DC) into alternating current (AC). This conversion is essential in various scenarios where AC power is required for end-use or grid infrastructure, but the available power source generates DC energy. The core of the DC to AC converter is the inverter stage, utilizing power semiconductor components such as transistors or insulated gate bipolar transistors (IGBTs). These components facilitate the generation of a series of pulses mimicking the sinusoidal waveform

characteristic of AC power through the switching of the DC input. The control circuitry, typically powered by microcontrollers or digital signal processors, manages the switching process to ensure synchronization with the grid's frequency and voltage.

Inverter control with current reference generation using d-q control and a Proportional-Integral (PI) controller is a common technique employed in AC motor drives and other applications requiring precise control of the current supplied by the inverter to the motor. The d-q control method is based on the transformation of three-phase quantities into two orthogonal components: the direct (d) component aligned with the rotor flux and the quadrature (q) component perpendicular to the rotor flux. The control system then operates in the d-q reference frame, simplifying the control strategy.

The PI controller in this context is responsible for generating the appropriate voltage references for the inverter to achieve the desired current response. The process begins with the specification of the desired current in the d-q frame. The PI controller compares the actual current feedback from sensors with the desired current and generates control signals. The proportional term of the PI controller responds to the instantaneous error, while the integral term addresses accumulated past errors, ensuring steady-state accuracy and stability.

The output of the PI controller signifies the reference voltage in the d-q frame, which is then transformed back to the three-phase reference frame. This reference voltage is used to modulate the inverter switches using techniques like Space Vector Modulation (SVM) to generate the necessary switching signals for the inverter. As a result, the inverter supplies the motor with the required current to achieve the desired performance.

III. SOLAR PHOTOVOLTAIC SYSTEM & ENERGY STORAGE MANAGEMENT

Achieving a continuous power supply on the grid involves the storage of excess energy. Essential roles in the electrical power system are played by various energy storage technologies, including batteries, flywheels, ultra-capacitors, and fuel cells. For instance, applications in solar photovoltaic generation involve batteries, wind turbine shafts incorporate flywheels, and ultra-capacitors are deployed on transmission lines to mitigate electrical losses. The utilization of energy storage is primarily influenced by the level of charge in the battery, with its utilization being influenced by the load and power source. The battery management relies significantly on the level of charge in the battery, with the utilization being influenced by the load and power source. A key metric in battery management is the "state of charge" (SOC), which represents the proportion of usable capacity relative to the total capacity. Decisions regarding the selection between a grid-linked electrical network and a stand-alone or islanding electrical network are heavily influenced by the state of charge (SOC) of the battery. The lack of state-of-charge measurements in many existing battery chargers hinders the adjustment of charging current based on SOC, a feature that has the potential to prolong the battery's lifespan. The outlined procedures for battery charging and discharging in the provided MATLAB code highlight the significance of SOC for improving battery performance and extending its longevity. In this system, lead-acid serves as the storage device, facilitating optimized

energy management between the source and the load. Charging and discharging activities take place when solar generation is insufficient or during peak demand.

IV. SIMULATION RESULTS & DISCUSSIONS

The Simulation results of the proposed system are discussed as follows. Figure 6 shows the simulation circuit of the proposed system.

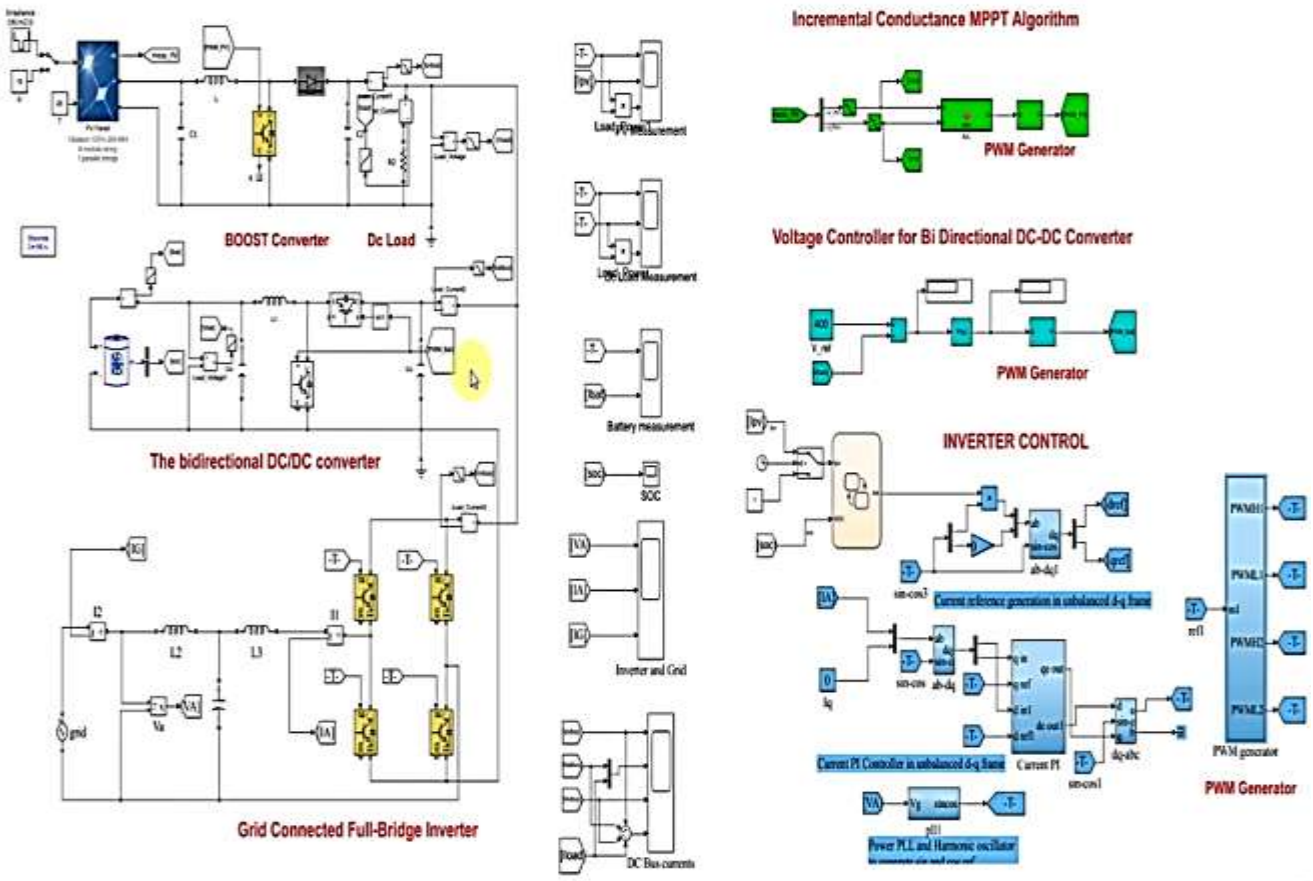


Figure 6. Simulation Circuit of the Proposed system

Focusing on a photovoltaic (PV) array with specific characteristics, comprising 15 series strings with two panels each. The maximum power point conditions reveal a power of 30.7 and a current of 8.15 amps.

The Voltage, Current & Power of the load is shown in Figure 6.Load power obtained is about 1KW. The load voltage & current remained constant. Figure 7 shows the battery voltage and current. The state of charge of the battery is represented in Figure 8. The SOC of the battery changes according to the change in input PV power. Hence the charging and discharging of the battery is done accordingly. The boost converter's inductance (L) and capacitance (C) values are then calculated using specified formulas. Subsequently, a bidirectional converter for the battery is designed. This converter, connecting to a 35-model, 48 Ah lithium-ion battery, is tailored for bidirectional power flow, allowing the battery to act as both a source and a load. The battery

converter is controlled using a voltage control algorithm. The voltage at DC bus is compared to a reference value (700 volts), and the controller adjusts the duty cycle accordingly to maintain the desired voltage.

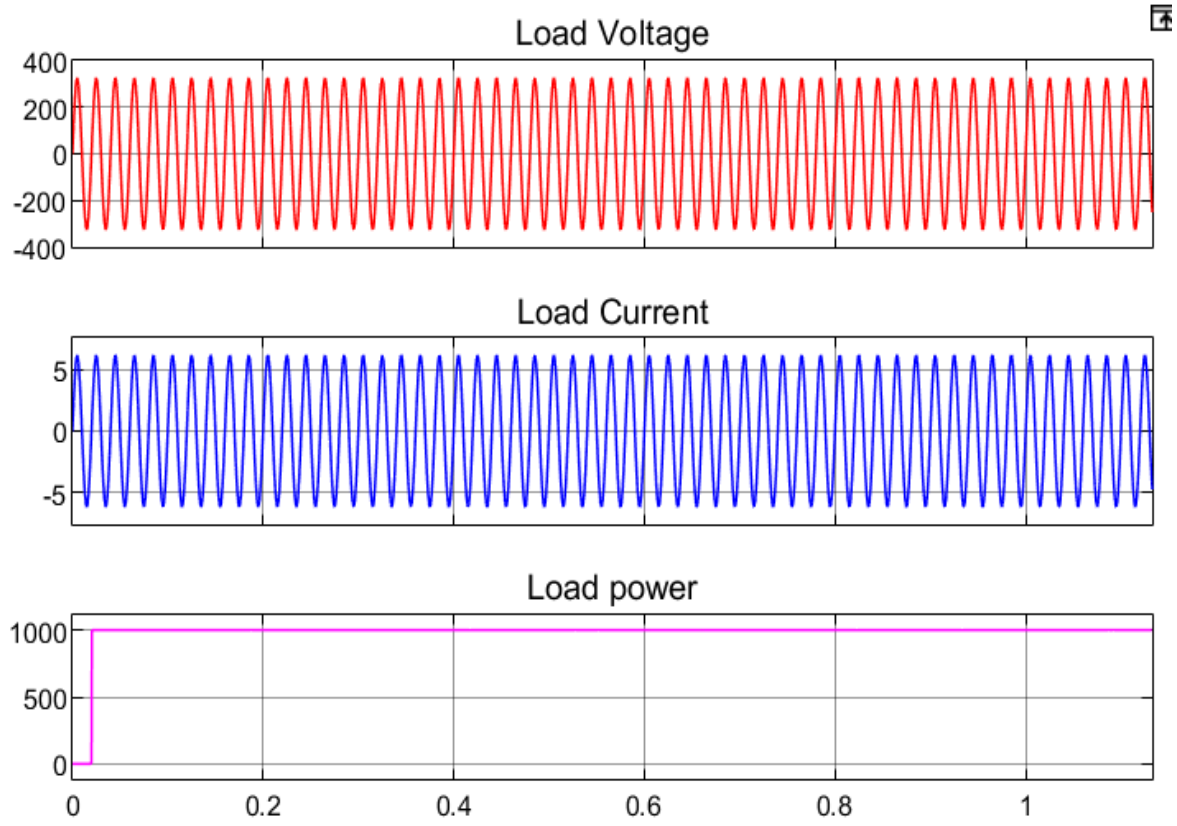


Figure 7. Voltage, Current & Power of the load

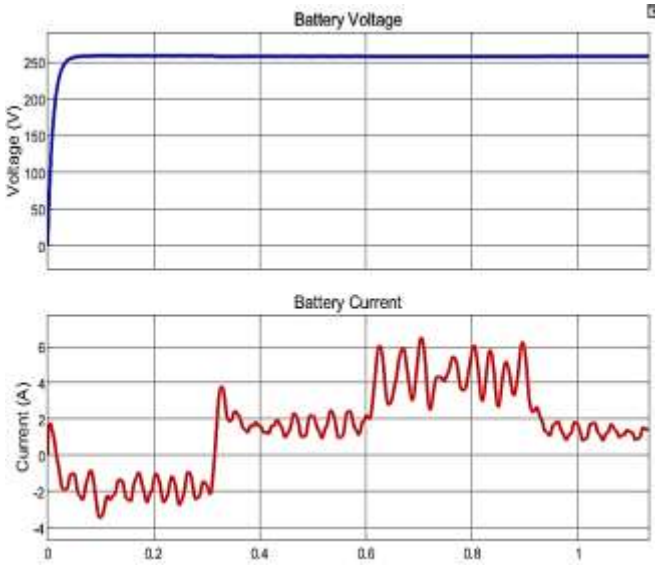


Figure 7. Battery Voltage & Current

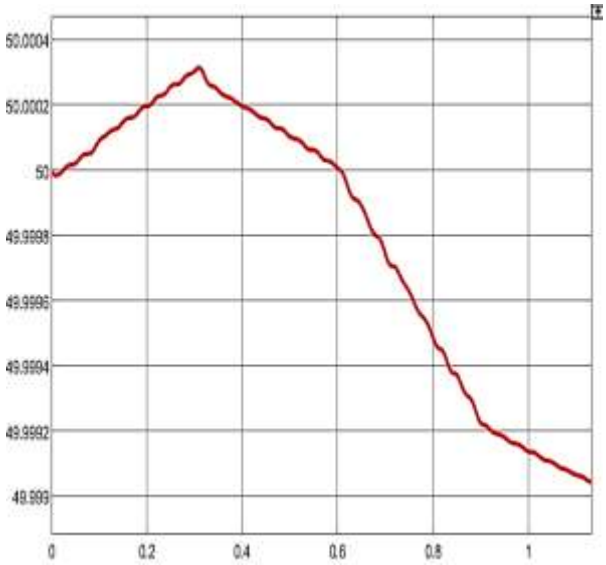


Figure 8. State of charge of the Battery

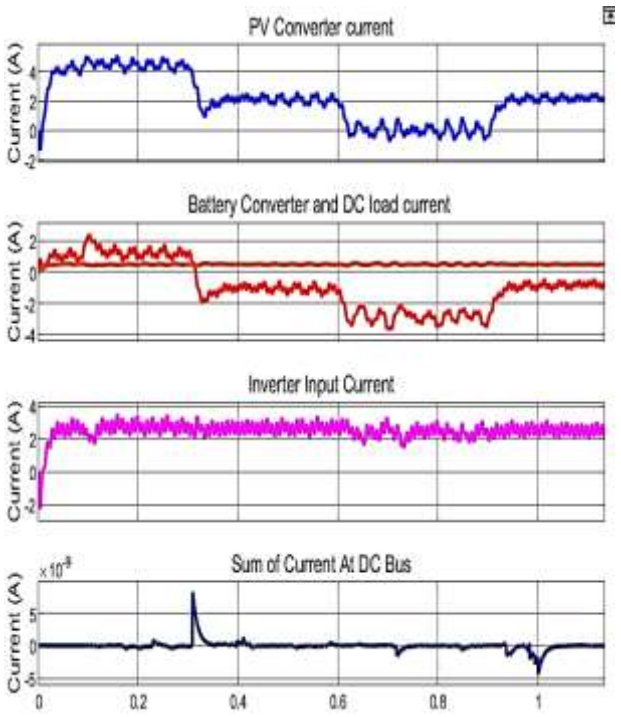


Figure 9. PV, Battery, DC load , Inverter & Sum of Current at DC bus

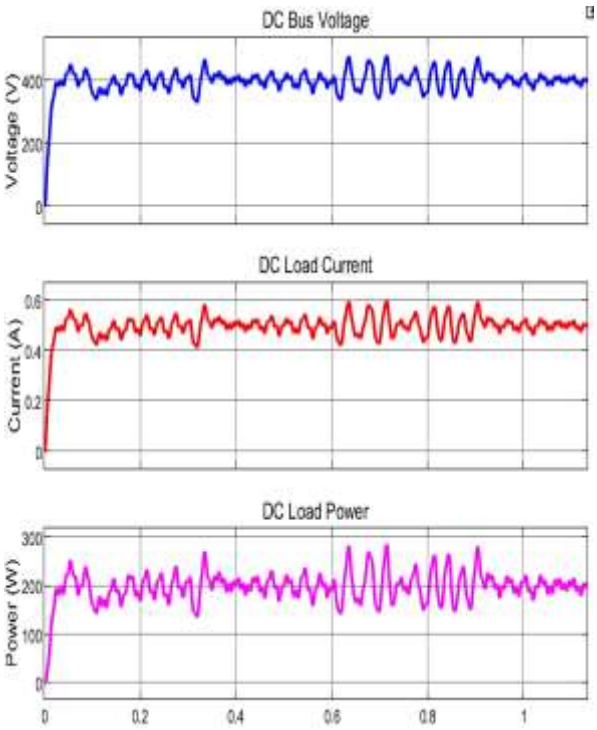


Figure 10. Voltage, Current & power of DC Load

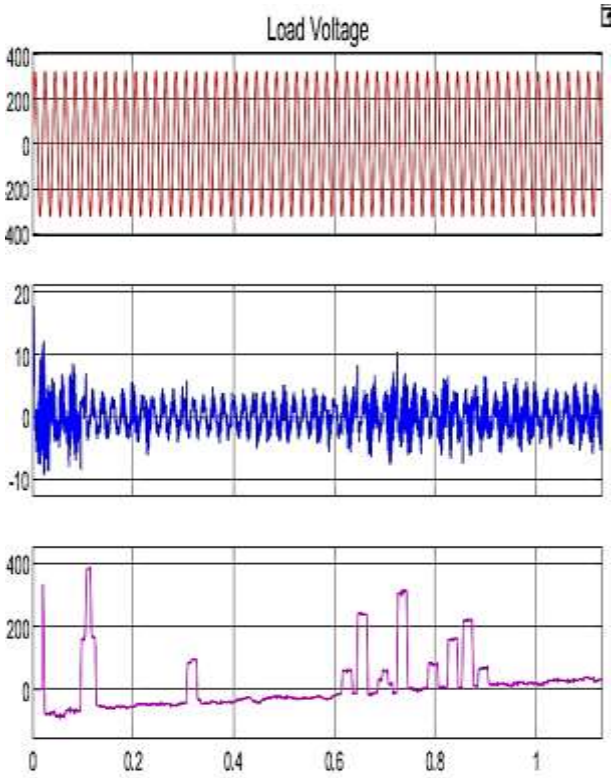


Figure 11. Grid Voltage & Power

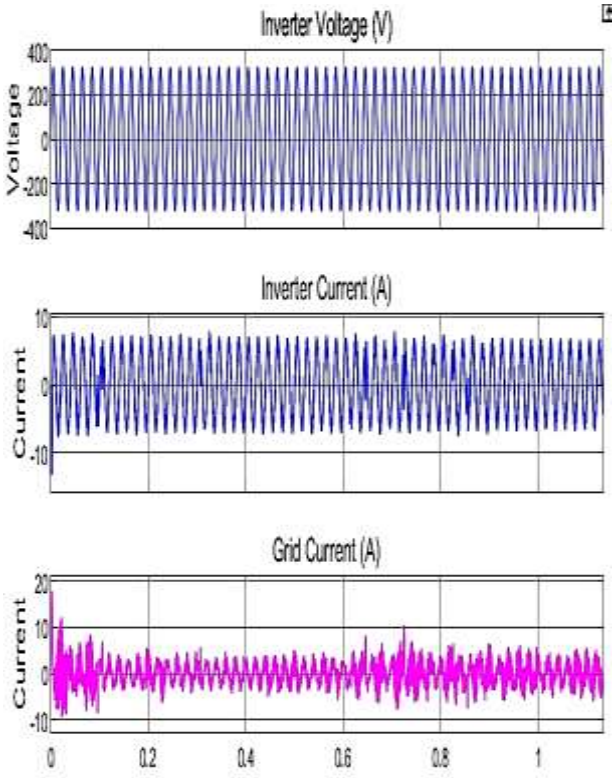


Figure 12. Inverter Voltage & Current and Grid Current

The Inverter voltage and current was shown in Figure 12. Voltage current and power of PV array is given in Figure 13.

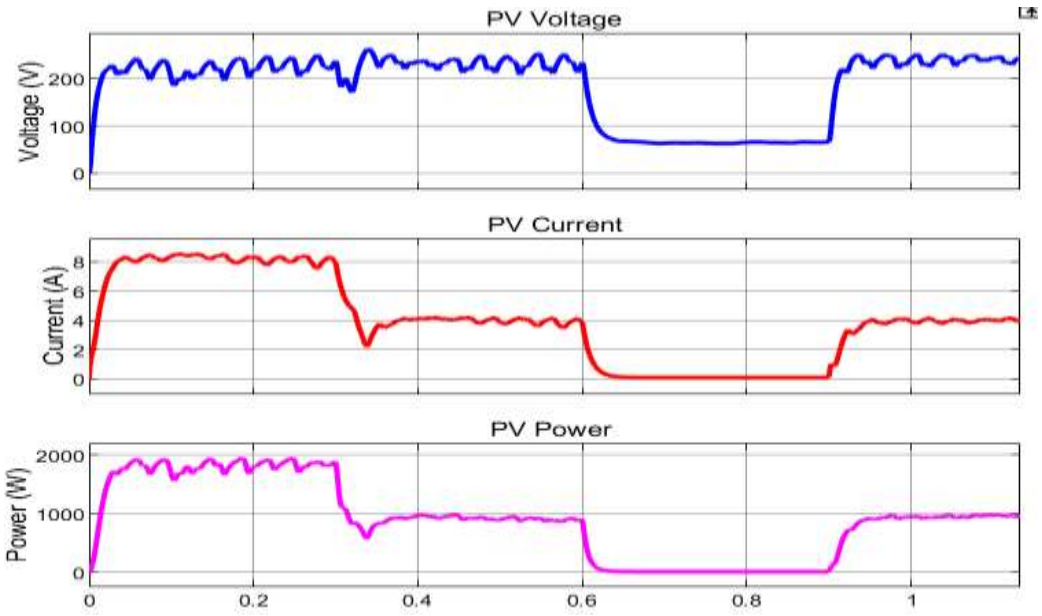


Figure 13. Voltage, Current & power of PV Array

PV, Battery, DC load, Inverter & Sum of Current at DC bus is shown in Figure 9.The inverter current changes according to the change in PV and battery current. Voltage, Current and power of DC load are given in Figure 10. Grid power and voltage are represented in Figure 11.

CONCLUSION

In conclusion, our research underscores the significance of advanced energy management strategies in optimizing the performance of grid-linked solar PV system integrated with battery storage and bidirectional converters. The incorporation of bidirectional converters enables dynamic energy flow between the PV system, batteries, and the grid, establishing a flexible framework for enhanced energy utilization. Through the implementation of intelligent control algorithms, our study aims to achieve optimal energy utilization by efficiently managing the charging and discharging cycles of the battery storage system, aligning them with varying solar irradiance levels. The bidirectional converter serves as a crucial component, facilitating bidirectional power flow and enabling seamless energy exchange between the solar PV system and the battery storage unit. Key focal points include the development of real-time monitoring and control systems to adaptively manage energy flow, addressing the inherent intermittency of solar power generation. Furthermore, our research delves into assessing the impact of bidirectional converter efficiency on overall system performance, proposing measures for its optimization. The insights gained from our findings contribute valuable knowledge to the seamless integration of bidirectional converters in grid-connected solar PV systems with battery storage. This advancement in energy management holds the

potential to foster sustainable and resilient power supply systems, flagging the way for a more efficient and reliable renewable energy future.

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