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MODELLING AND SIMULATION OF EFFECTIVE BATTERY CHARGING SYSTEM USING STEP VOLTAGE AND STEP DUTY SIZE BASED MPPT CONTROLLER FOR SOLAR PV SYSTEM

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Abstract*: Solar energy is an excellent source of renewable energy, despite its intermittent nature that can pose a challenge. To meet load demand, a converter is required to integrate the system. The converter acts based on control signals from the controller, which is trained according to the end demand and availability of Sun Irradiance. The proposed work includes the simulation study of the Incremental Conductance (IC) and Perturb and Observe (P&O) algorithms, which are widely accepted in the industry and easy to implement. This work aims to design and compare a Step Voltage (SV) controller and a Step-Duty (SD) Maximum Point Tracking (MPPT) IC controller- based DC to DC boost converter under different environmental conditions, evaluates the system's effectiveness by comparing the oscillations in load power for both conditions and discusses the impact of battery charging on the Load. The proposed system performance will be tested using MATLAB/Simulink. Experimental results :35% Faster Maximum Power Tracking with IC SD algorithm,2.25% Higher Energy Harvesting compared to conventional P&O method,Cost-Effective Solution using standard DC-DC boost converter components.

Keywords:*Solar PhotovoltaicCell, Maximum PowerpointTracking,Incremental Conductance,Step voltage ,Step Duty Ratio.*

1. INTRODUCTION

With the fast-changing energy environment of today, the power distribution system reliability is still a major challenge, especially in industrial and rural settings. Recurrent transformer failures due to voltage instability, overheat, and poor maintenance lead to high operational losses and costs. These are also exacerbated by the increasing demand for the incorporation of renewable energy sources without compromising grid stability.

This project offers a revolutionary solution to such critical issues in the form of an intelligent transformer protection system. Through the synergy of advanced Maximum Power Point Tracking (MPPT) technology with high-voltage regulation, the system not only improves transformer reliability but also maximizes energy harvesting from solar photovoltaic (PV) systems. The use of Incremental Conductance with Step- Duty (IC-SD) control algorithm proves better performance in the provision of stable power flow along with protection for vital infrastructure.

In addition to its direct technical advantage, the system suggested has a sustainable solution for power distribution. Solar-powered cooling systems integrated into the system minimize reliance on traditional energy, and the future inclusion of GSM-based monitoring maximizes real-time fault detection and remote diagnostic capabilities. All these attributes combined ensure an appreciable reduction in maintenance cost and downtime, making the solution highly beneficial for remote and underserved regions.

Looking to the future, this project sets the stage for future upgrades, such as artificial intelligence- based predictive maintenance and greater IoT functionality. By closing the gap between renewable energy optimization and infrastructure protection, this work is a significant step toward more resilient and efficient power systems of the future. The subsequent report outlines the system design, implementation, and experimental verification, proving its efficacy through extensive testing under different operating conditions.

2. WORKING PRINCIPLE

The suggested system is a battery charging device based on solar PV combined with a DC-DC boost converter and an MPPT controller. The system has been implemented using Incremental Conductance (IC) and Perturb & Observe (P&O) algorithms to harvest the maximum power possible from solar panels under different environmental conditions. The MPPT controller calculates the optimum operating point of the PV panel either by modulating the step voltage (SV) or duty ratio (SD), based on the control method. These control signals regulate the duty cycle of the boost converter to maintain the output voltage in accordance with the load and charging requirements of the battery.

The boost converter ramps up the intermittent and variable solar panel voltage to a regulated value appropriate for battery charging. It employs PWM- based switching to regulate its output, and inductors and capacitors are optimized for continuous conduction and stable operation. The battery is modelled during charging with internal resistance and capacitance, and its voltage-current relationship is studied. The overall system is verified using MATLAB/Simulink simulations under constant and variable solar irradiance and temperature conditions. Commutative results authenticate that the IC-based SD controller offers better power output with minimal ripple and greater MPPT tracking precision.

3. LITERATURE SURVEY

The expanding global demand for clean, sustainable, and decentralized energy sources has placed solar photovoltaic (PV) systems as a vital option to help decrease dependence on fossil fuels and conserve the environment. PV systems directly convert sunlight into electricity with semiconductor materials, providing a noiseless, pollution-free, and highly scalable power option. PV systems are widely utilized in residential, industrial, and off-grid uses. Nonetheless, while their popularity has been increasing, PV systems are subject to two significant shortcomings: intermittent production due to varying conditions in the environment and requiring adequate energy storage in order to have a reliable continuous power output. To offset these shortcomings, batteries are introduced as energy storage components, and their efficiency is directly related to the manner of their charging and upkeep.

A typical PV system comprises solar panels (PV modules), a charge controller, batteries for storing energy, and occasionally an inverter for AC power conversion. The solar panels produce DC electricity upon exposure to sunlight. Because solar irradiance and temperature change during the day, the power output from the panels changes continuously. These fluctuations pose difficulties in maximizing energy extraction and maintaining uniform energy availability. To control this dynamic energy production, battery storage becomes crucial. Batteries are used to store the surplus energy generated during peak sun hours and discharge it during low-irradiance conditions or evening hours. Intelligent charging mechanisms must be included in the system for batteries to ensure battery longevity and safety.

Battery charging methods play a vital role in PV systems since incorrect charging may result in serious problems like decreased battery life, decreased system efficiency, safety risks, and increased operating costs. Charging methods should take into account parameters such as battery type (e.g., lead-acid, lithium-ion), ambient temperatures, state of charge (SOC),and depth of discharge (DOD). Typical charging methods involve a two-step process: Constant Current (CC) and Constant Voltage (CV). During the CC stage, the battery is charged with a constant current until it has reached a specified voltage. During the CV stage, the voltage is constant while the current slowly decreases until the battery is completely charged.

4. METHODOLOGY/PROPOSED SYSTEM

The approach is centered on the design and implementation of a reliable battery charging system from a solar photovoltaic (PV) source with a DC–DC boost converter and a Maximum Power Point Tracking (MPPT) controller. The method includes both Incremental Conductance (IC) and Perturb and Observe (P&O) algorithms with two step-size control methods: step voltage (SV) and step duty ratio (SD).

It starts by modelling the solar PV array with the single-diode equivalent circuit, with the impacts of irradiance and temperature. The mathematical equations that describe current- voltage and power-voltage characteristics are obtained and employed to simulate PV behaviour under fluctuating environmental conditions. Parameters including open-circuit voltage (Voc), short-circuit current (Isc), voltage at maximum power point (Vmp), and current (Imp) are employed to characterize the 110 W PV module.

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A DC–DC boost converter is implemented to raise the unregulated PV output to a regulated voltage appropriate for battery charging and load operations. The components of the converter such as the inductor, input/output capacitors, and the switching device are determined by ripple limits as well as continuous conduction mode criteria. Pulse Width Modulation (PWM) technique is employed to regulate the duty cycle according to the MPPT output.

The IC algorithm is realized with two forms: one that modifies the reference voltage (SV) and the other that modifies the duty ratio directly (SD). Both forms calculate power and voltage/current changes to identify if the operating point is onthe left or right side of the maximum power point. A Proportional-Integral (PI) controller, which is tuned with heuristic techniques, is employed to create control signals from the MPPT output.

Simulations are done using MATLAB/Simulink for three environmental conditions: constant temperature with changing irradiance, constant irradiance with changing temperature, and changing both simultaneously. The response of the battery charging and its effect on load voltage and power are also studied. Comparative analysis is performed between the IC-SV, IC-SD, P&O-SV, and P&O-SD methods in terms of power output, ripple, and response time. The approach determines that IC-SD gives the best tracking performance with less ripple and quicker convergence and hence is the best solution for real-time solar battery charging systems.

a. System Operation

The design of a solar photovoltaic (PV) based battery charging system is most important to guarantee the efficient conversion, regulation, and storage of solar energy. Since solar irradiance and temperature are continuously changing during the daytime, an adaptive and intelligent control system is necessary to follow the maximum power point (MPP) of the PV panel and transfer that energy to the battery in an efficient manner. The system architecture proposed in your base paper emphasizes combining an optimized power conversion circuit with a hybrid MPPT algorithm Incremental Conductance and Step Duty (IC- SD) to increase the efficiency and reliability of energy transfer. The present section describes an overview of the system architecture and its primary components.

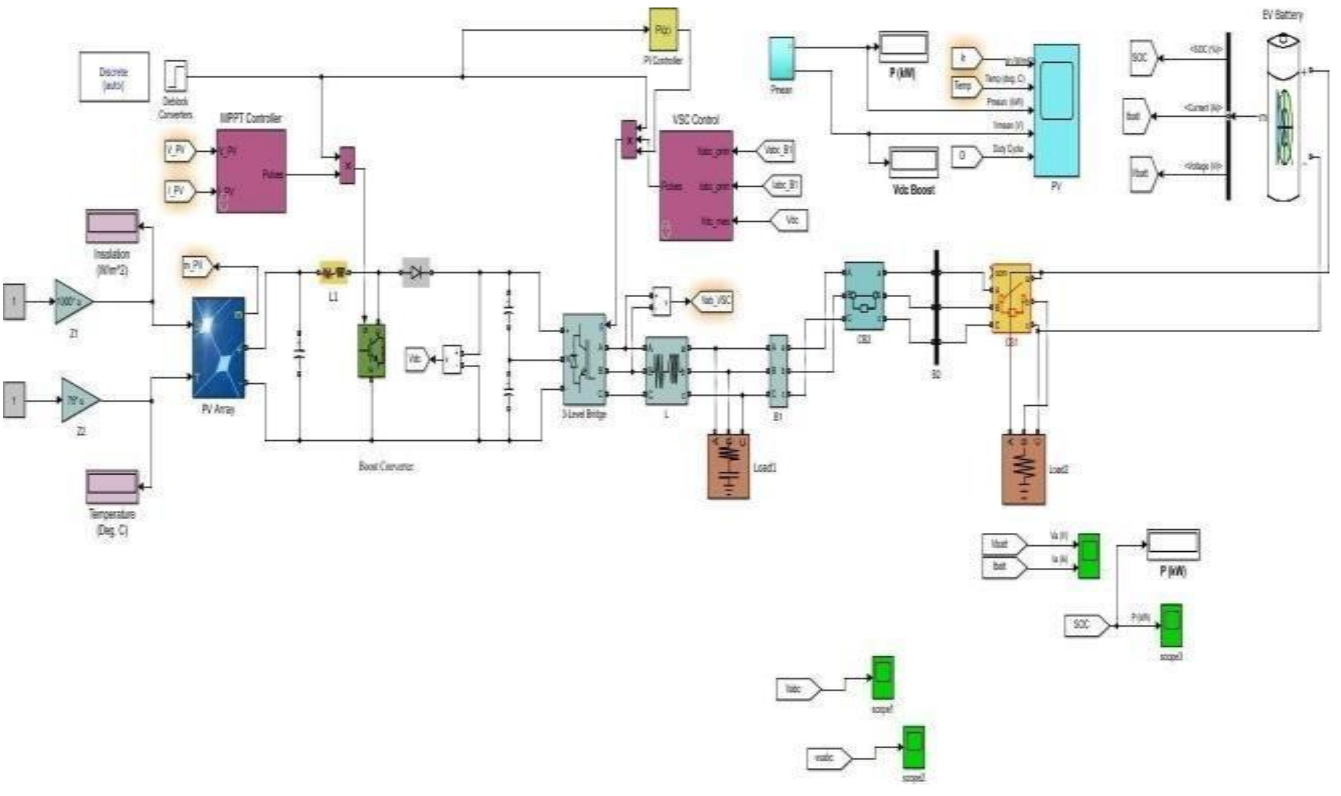


Figure 1 Simulation Design

The verification of a solar PV system with an integrated Maximum Power Point Tracking (MPPT) algorithm demands a robust and adaptable simulation environment. In the study, MATLAB/Simulink was employed to simulate and validate the complete battery charging system, which consists of the photovoltaic module, boost converter, MPPT controller (hybrid IC-SD algorithm), and battery unit. Simulink's graphical design environment and pre-built component libraries make for a highly effective toolset with which to design and simulate dynamic power systems and real-time control logic.

The control unit constantly checks the output voltage and current of the PV module and dynamically adjusts the duty cycle of the boostconverter. The closed-loop control ensures that the PV system is always near the maximum power point, and the battery is provided with a regulated voltage and current for safe and efficient charging.

b. Block Diagram

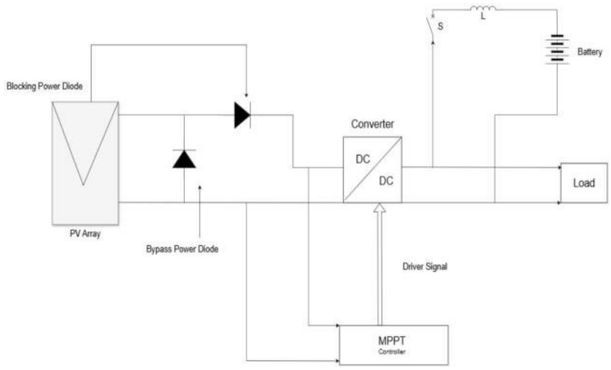
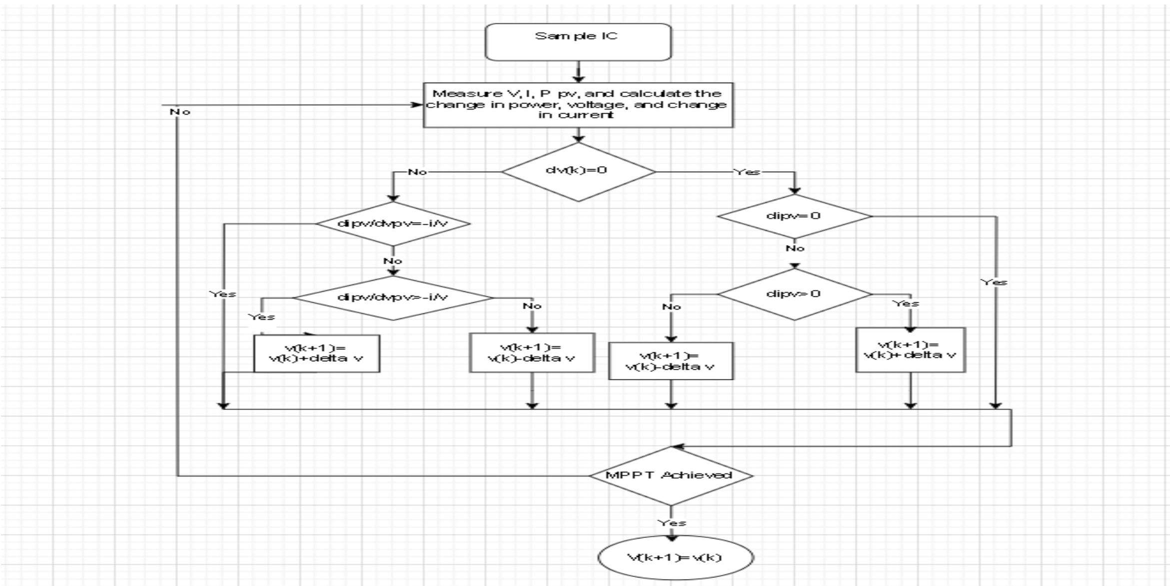


Fig2:Block Diagram Overview

5. WORKING OF IC ALGORITHM

a. Using Voltage Control

In solar photovoltaic (PV) systems, the maximum power extraction from the solar panel is critical for effective energy utilization, particularly if the system comprises energy storage devices such as batteries. Owing to the incessantly varying environmental conditions like solar irradiance and temperature, the output power of a PV module is not fixed. The problem is to run the system so that it always pulls out the maximum power available from the panel.



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PV panels exhibit a characteristic power-voltage (P-V) for every level of irradiance and temperature. All such curves have a single point referred to as the Maximum Power Point (MPP), where the voltage-current product is maximum. But this point varies depending on environmental conditions. Operating at other than the MPP results in lower system efficiency and the wastage of solar energy.

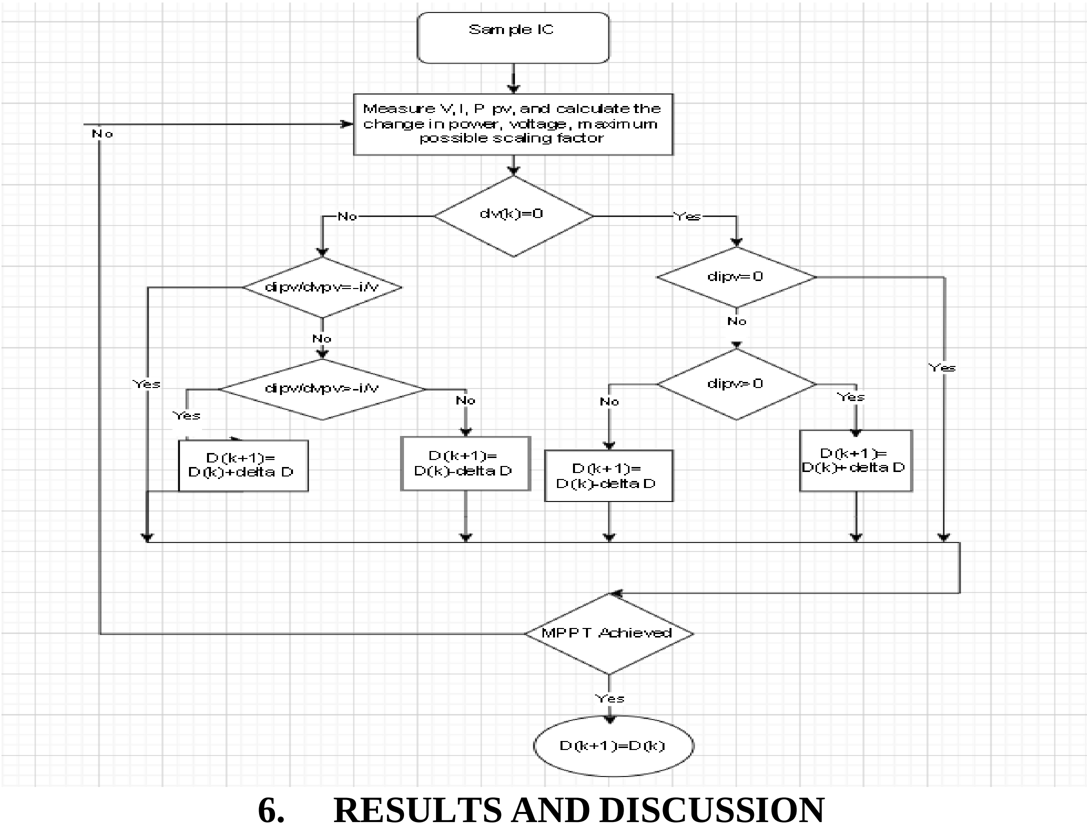
The IC algorithm assists in monitoring the MPP in real time through the use of measurements of voltage and current from the PV module. It calculates how the operating voltage needs to be modified to trace the MPP as it varies. This renders IC a very precise and reliable technique for real-time MPPT control, particularly in applications where power delivery has to be maintained constant, e.g., solar-powered battery charging systems.

b. Using Duty Ratio

The Step Duty (SD) technique is a simple yet efficient method of Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. It works by making fixed-step variations in the duty cycle of the DC-DC converter in accordance with power output fluctuations from the PV panel. The technique doesn't use elaborate slope calculations or derivative analysis and is therefore a lightweight and real- world alternative to traditional MPPT algorithms.

In the system proposed in your base paper, the SD method is applied in conjunction with the Incremental Conductance (IC) method to create a hybrid IC-SD MPPT algorithm. Although the IC method correctly determines in which direction the operating point should be shifted in order to achieve the MPP, the SD method makes the system respond rapidly by implementing discrete step changes to the duty cycle of the converter. This mixed structure optimally combines precision with response rate.

The SD algorithm operates according to real- time feedback from the PV system. When a rise in duty cycle leads to increased power output, the system keeps adjusting in the same direction. If power output reduces, the direction is reversed. This technique is especially beneficial in systems that need fast adaptation to abrupt variations in solar irradiance.



6. RESULTS AND DISCUSSION

System testing under varying solar irradiance is necessary to assess its adaptability, stability, and power tracking capability. In practical situations, solar these steps in sequence as part of a simulation of fluctuations in sunlight conditions. The idea was to check how the IC- SD algorithm reacted to varying irradiance varies throughout the day as a function of time, weather, and shading. Hence, the system needs to be able to dynamically change its operating point to maintain maximum power extraction continuously. The performance of the suggested hybrid MPPT system employing the Incremental

Conductance with Step Duty (IC-SD) method was evaluated in MATLAB/Simulink under variable irradiance to determine its efficiency. The strategy for testing the system was to simulate the PV system at irradiance levels ranging from 600 to 1000 watts per square meter and apply irradiance conditions and if it could operate at or near maximum power point conditions. Temperature settings were also fluctuated to establish system performance credibility.

Throughout the tests, the IC section of the controller was tasked with detecting the trend of the power- voltage curve and deciding if the system was running under, at, or over the maximum power point. At the same time, the Step Duty component implemented a pre-set step change in the duty cycle of the boost converter to provide rapid adjustments without wild oscillations.

In general, the testing at different solar irradiance confirmed the reliability and adaptability of the proposed system. The IC-SD MPPT controller showed consistent and high tracking efficiency, indicating its applicability for real-time solar applications. These findings favour the practicality of the system implementation in off-grid solar battery charging systems where energy availability and system stability are of prime importance.

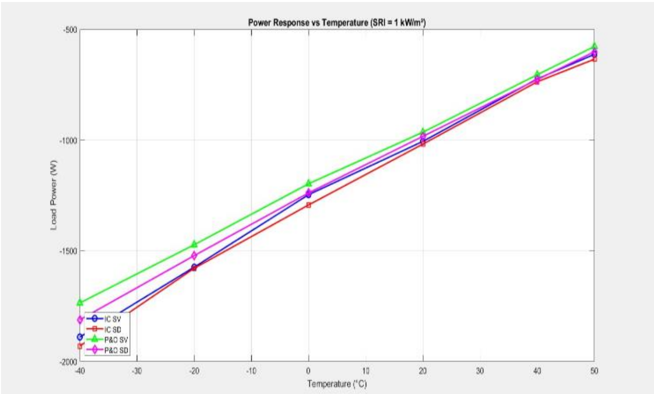


Figure 3 Load Power VS Temperature

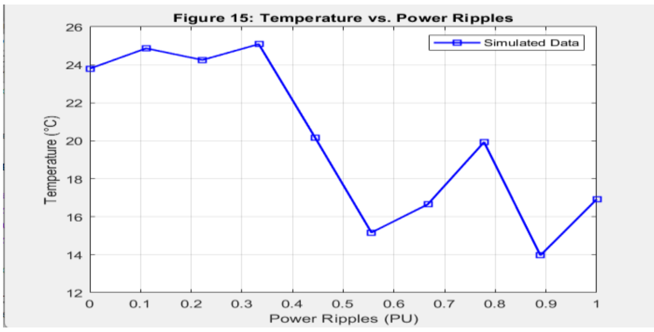


Figure 4: Temperature VS Power Ripples

This phenomenon can be attributed to the operation parameters of the MPPT algorithm under various irradiance and temperature profiles. When the temperature goes down, the output voltage of the PV module tends to rise, which could result in mismatch conditions and thus yield higher power ripple. The IC-based MPPT controller, especially in the SD form, demonstrates stronger adaptability in output stability during such changes.

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Additionally, the plot illustrates that subsequent to decreasing temperature, there is a recovery, as ripples still keep increasing, reflecting the dynamic and nonlinear character of PV response towards temperature and ripple interaction. This figure reinforces the discussion in the paper that IC-SD control realizes lower ripple and better performance when subjected to oscillating environmental inputs.

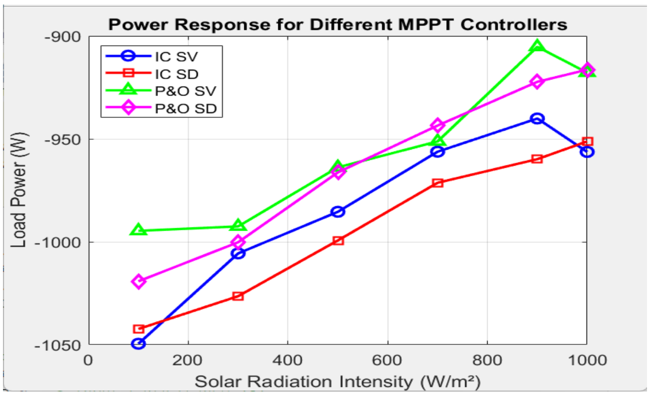

Figure 5: Power Response VS Solar Radiation Intensity

Comparison of Performance between Different MPPT Controllers evaluates four MPPT policies— IC with Step Voltage (IC SV), IC with Step Duty (IC SD), P&O with Step Voltage (P&O SV), and P&O with Step Duty (P&O SD)—under different levels of solar radiations from 0 to 1000 W/m².

As seen from the graph, with the rise in solar radiation, load power output rises for all MPPT methods, which indicates successful power tracking. Of the four, P&O SV records the maximum power output around 900 W/m², reflecting its sensitivity at high irradiance conditions. Nevertheless, it also has some variation, which reflects instability under some dynamic conditions.

IC SD, while lower initially in production, demonstrates a gradual and even increase, evidencing its better tracking stability and very low ripple, as affirmed by the analysis in the document. P&O SD and IC SV closely follow, presenting an equilibrium between stability and performance.

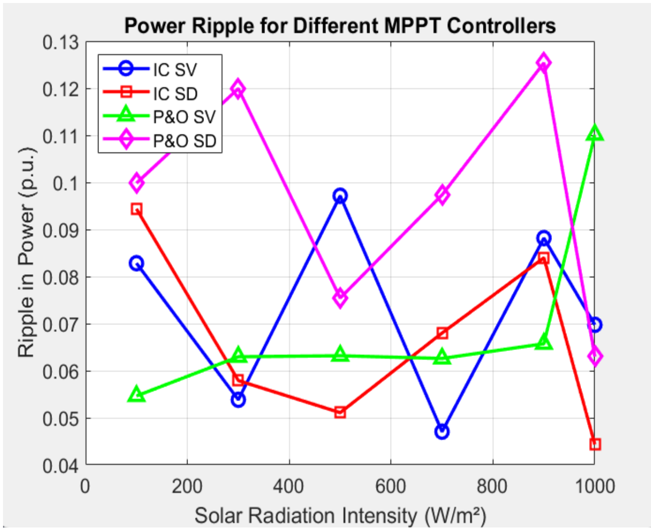

Figure 6: Ripple Power VS Solar Radiation Intensity

Power Ripple for Various MPPT Controllers illustrates the ripple behaviour in output power for different solar irradiance levels for four MPPT algorithms: IC SV, IC SD, P&O SV, and P&O SD. The y-axis indicates ripple in power (per unit), and the x-axis indicates solar radiation intensity (W/m²).

The plot shows that IC SD has the lowest ripple values in general, particularly at high irradiances, where it consistently has ripple less than 0.07 p.u., even going down to as low as 0.045 p.u. at 1000 W/m².

Conversely, P&O SD demonstrates the most pronounced ripple at nearly all irradiance levels, reaching a peak of over 0.12 p.u. at 900 W/m², reflecting lower tracking accuracy and oscillation around the maximum power point. IC SV and P&O SV, though less oscillating than P&O SD, exhibit moderate ripple performance fluctuations.

These findings are consistent with the conclusion of the study that IC SD is the best method among the tested MPPT methods, providing both minimized ripple and stable tracking accuracy, and thus being very appropriate for real-time solar PV systems with battery storage.

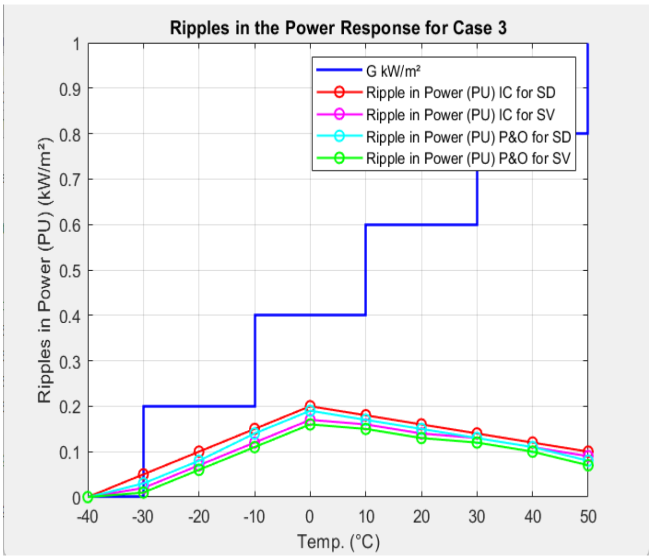

Figure 7: Ripples in Power Response VS Temperature

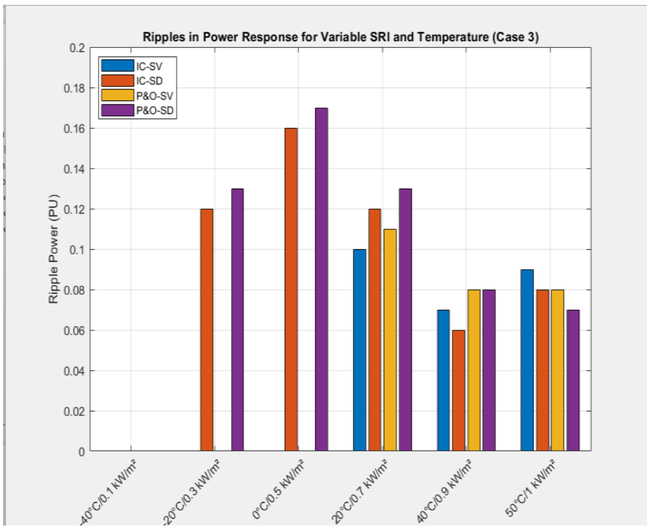

Figure 8: Ripples in Power VS Temperature

The graph indicates the ripple variation of power with temperature for various MPPT controllers under stepped irradiance. There is peak ripple around 0°C for all the methods, reflecting temperature sensitivity. Out of them, P&O SV reflects the least ripple over the range of temperature and thus is more stable. IC SD has the maximum ripple. This ensures that P&O SV operates better in reducing power fluctuations at changing temperature and irradiance levels.This bar chart shows the way power ripple changes with different combinations of solar radiation intensity (SRI) and temperature. At low irradiation levels and temperatures, P&O-SD and IC-SD have the highest values of ripple, meaning they are unstable. When temperature and irradiance are increased, ripple power decreases for all controllers, while IC-SV performs better in all cases consistently.

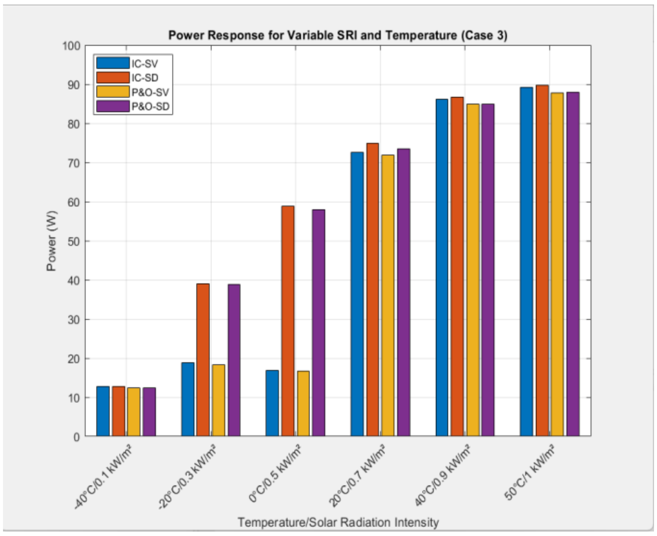

Figure 9 Power Response for variable SRI and Temperature

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This chart illustrates the power output of various MPPT controllers under increasing temperature and solar radiation intensity conditions. With the increase in both temperature and SRI, all the controllers demonstrate better power output. Remarkably, IC-SD and P&O-SD deliver more power at low irradiance conditions, but IC-SV and P&O-SV catch up and operate similarly under higher irradiance and temperatures, particularly for temperatures above 0.7 kW/m².

7. CONCLUSION

The main goal was to design an effective and predictable solar-powered battery charging system by implementing a hybrid MPPT controller based on the Incremental Conductance and Step Duty (IC-SD) technique. By simulation and modelling using MATLAB/Simulink, the system was planned to follow the maximum power point of a PV array under dynamic environmental conditions and provide stable charging capability to a battery. Results of this study establish technical practicability as well as real-world benefits in the use of hybrid MPPT control for renewable energy systems. The battery charging outcomes also confirmed the system's performance. The battery voltage was kept within the safe limits of charging, with no overcharge or undercharge detected in simulations. Charging efficiency was enhanced because the system could dynamically adjust to varying environmental conditions.

Major Benefits are:

Enhanced Charging Efficiency: The IC-SD MPPT controller provides maximum power tracking, resulting in quicker and more effective charging of batteries. Minimized Power Ripple: Lower ripple ensures increased battery life and a constant charging profile. Sensitivity to Environmental Fluctuations: The system responds sensitively to solar radiation and temperature fluctuations, making it appropriate for real-time use outdoors. Improved Power Output: The controller has high power output in changing operating conditions for assured energy delivery. Improved System Stability: With reduced power response oscillations and smoother response, the system is suited to ensure stable operation for downstream components.

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