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Design and Development of a Solar-Powered SMPS Battery Charger with MPPT for Efficient Energy Extraction under Variable Environmental Conditions

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Abstract:
This paper presents the design and development of a solar-powered switched-mode power supply (SMPS) battery charger integrated with Maximum Power Point Tracking (MPPT) for efficient energy extraction under variable environmental conditions. The proposed system architecture incorporates a photovoltaic (PV) module as the primary energy source, supported by environmental sensing units that monitor solar irradiance and temperature in real time. These inputs enable the MPPT controller, implemented using Perturb and Observe (P&O) and Incremental Conductance algorithms, to continuously track and operate the PV system at its maximum power point, thereby maximizing energy utilization.
A microcontroller-based control unit processes sensor data and generates pulse-width modulation (PWM) signals to regulate a DC–DC converter configured as an SMPS. This ensures efficient voltage conversion and stable power delivery to the battery charging unit. The system employs a constant current–constant voltage (CC–CV) charging technique to achieve safe, reliable, and optimized battery charging while extending battery lifespan. Voltage and current sensors provide continuous feedback for closed-loop control, enhancing system responsiveness and accuracy.
The harvested energy is stored in rechargeable batteries, which supply power to low-power loads such as portable electronics and IoT devices during periods of low or no solar availability. Additionally, a monitoring and data logging module records system performance metrics, including efficiency, response time, and tracking accuracy, enabling detailed analysis and optimization. Experimental evaluation under varying irradiance and temperature conditions demonstrates that the proposed system achieves improved energy conversion efficiency, faster MPPT response, and enhanced reliability compared to conventional solar charging systems. Overall, the proposed architecture offers a cost-effective, scalable, and energy-efficient solution for sustainable low-power applications.

Keywords: Solar Energy, Photovoltaic (PV) System, Maximum Power Point Tracking (MPPT), Switched-Mode Power Supply (SMPS), DC–DC Converter, Battery Charger, Pulse Width Modulation (PWM).

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1 Introduction:

The increasing global demand for clean, reliable, and sustainable energy has significantly accelerated the development and deployment of renewable energy technologies. Among these, solar photovoltaic (PV) systems have emerged as one of the most promising solutions due to their abundance, environmental friendliness, and scalability [1]. Solar energy is freely available and can be harnessed in both urban and remote locations, making it particularly suitable for low-power applications such as portable electronics, wireless sensor networks, and Internet of Things (IoT) devices. However, despite these advantages, the efficient utilization of solar energy remains a major challenge because of its inherent variability. Factors such as solar irradiance, temperature, shading, and weather conditions continuously influence the electrical characteristics of PV modules, leading to fluctuations in output power. These variations necessitate the development of intelligent energy harvesting and power conversion systems that can adapt dynamically and operate efficiently under changing environmental conditions [2].

A photovoltaic system exhibits nonlinear current–voltage (I–V) and power–voltage (P–V) characteristics, where a unique operating point exists at which the maximum power is generated. This point, known as the Maximum Power Point (MPP), varies continuously with environmental conditions. If the PV system is directly connected to a load or battery without any control mechanism, it rarely operates at this optimal point, resulting in significant energy losses [3]. To address this issue, Maximum Power Point Tracking (MPPT) techniques are employed. MPPT algorithms are designed to track and maintain operation at or near the MPP by adjusting the electrical operating point of the system. Common techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC) have been widely used due to their simplicity and effectiveness. The integration of MPPT not only enhances energy extraction efficiency but also improves system reliability and adaptability in real-time operating conditions.

In addition to efficient energy tracking, the conversion and regulation of power are equally important for practical applications. Switched-Mode Power Supply (SMPS) technology plays a crucial role in this regard by providing high-efficiency power conversion with minimal losses. Unlike linear regulators, SMPS-based DC–DC converters—such as buck, boost, and buck–boost converters—operate using high-frequency switching techniques, which significantly improve efficiency and reduce heat dissipation. When integrated with an MPPT controller, the SMPS dynamically adjusts its duty cycle using pulse-width modulation (PWM) signals to regulate the output voltage and current according to system requirements. This combination ensures that the PV module operates at its maximum power point while delivering a stable and controlled output suitable for battery charging and load operation [4].

Battery charging is another critical aspect of solar-powered systems, particularly for standalone and off-grid applications. Efficient battery management ensures energy availability during periods of low or no sunlight, thereby enhancing system reliability. Rechargeable batteries, such as lithium-ion and lead-acid types, require controlled charging mechanisms to prevent overcharging, overheating, and degradation. The constant current–constant voltage (CC–CV) charging method is widely adopted due to its effectiveness in maintaining battery health and extending lifespan. Integrating this charging strategy with an MPPT-enabled SMPS charger allows simultaneous optimization of energy harvesting and storage, resulting in improved overall system performance. This is especially important for low-power systems, where energy efficiency and battery longevity are critical considerations.

The advancement of embedded systems and microcontroller technologies has further enabled the development of intelligent and adaptive solar charging solutions. Modern microcontrollers, such as Arduino, PIC, and STM32, offer sufficient computational capability to implement real-time MPPT algorithms, process sensor data, and generate precise PWM control signals. By incorporating voltage and current sensors, along with environmental sensing elements such as irradiance and temperature sensors, the system can continuously monitor its operating conditions and adjust its parameters accordingly. This closed-loop control mechanism enhances system responsiveness, reduces power losses, and ensures stable operation under dynamic environmental conditions [5].

Despite significant progress in solar energy systems, challenges remain in designing cost-effective, compact, and efficient solutions for low-power applications. Many existing systems either lack adaptability to rapid environmental changes or suffer from inefficiencies due to poor integration of control and power conversion mechanisms. Furthermore, conventional charging systems without MPPT fail to utilize the full potential of available solar energy, particularly under partial shading or fluctuating irradiance conditions. Therefore, there is a need for a well-integrated system that combines efficient power conversion, intelligent control, and robust energy management in a single framework [6].

The present work addresses these challenges by proposing the design and development of a solar-powered SMPS battery charger integrated with an advanced MPPT mechanism for efficient energy extraction under variable environmental conditions. The system is designed to achieve high tracking accuracy, improved conversion efficiency, and reliable battery charging performance. By leveraging adaptive control techniques and optimized hardware design, the proposed solution ensures that maximum available solar energy is effectively harvested and utilized. The integration of sensing, control, and power electronics into a unified architecture enhances system performance while maintaining simplicity and cost-effectiveness [7].

Furthermore, this study emphasizes both simulation and experimental validation to evaluate system performance under realistic operating conditions. The proposed design is tested across a range of irradiance and temperature levels to assess its adaptability and efficiency. Performance metrics such as tracking efficiency, conversion efficiency, response time, and battery charging characteristics are analyzed to validate the effectiveness of the system. The results are expected to demonstrate significant improvements over conventional solar charging systems, particularly in terms of energy utilization and operational stability.

2.Literature review:

The design and development of solar-powered battery charging systems have been widely explored in recent years, driven by the increasing demand for efficient and sustainable energy solutions. Early research in photovoltaic (PV) systems primarily focused on direct energy conversion and basic battery charging mechanisms without advanced control strategies. These conventional systems, while simple, suffered from low efficiency because they failed to operate the PV module at its optimal point under varying environmental conditions. As a result, a significant portion of available solar energy remained unutilized, especially during fluctuations in irradiance and temperature. This limitation led to the introduction of Maximum Power Point Tracking (MPPT) techniques, which have since become a cornerstone in modern solar energy systems.

Subsequent studies have extensively investigated various MPPT algorithms to enhance energy extraction from PV modules. Among the most commonly used methods are Perturb and Observe (P&O) and Incremental Conductance (INC), both of which offer a balance between simplicity and performance. Researchers have demonstrated that while P&O is easy to implement and requires minimal computational resources, it may suffer from oscillations around the maximum power point under steady-state conditions. On the other hand, the Incremental Conductance method provides better accuracy and faster response to rapid environmental changes by comparing incremental and instantaneous conductance. More advanced approaches, including fuzzy logic, neural networks, and hybrid algorithms, have also been proposed to improve tracking efficiency and adaptability. However, these techniques often introduce additional complexity and cost, which may not be suitable for low-power or cost-sensitive applications.

Parallel to the development of MPPT algorithms, significant attention has been given to power conversion techniques, particularly the use of switched-mode power supply (SMPS) architectures. DC–DC converters such as buck, boost, and buck–boost topologies have been widely employed due to their high efficiency and flexibility in voltage regulation. Researchers have shown that integrating MPPT control with SMPS converters allows dynamic adjustment of the duty cycle through pulse-width modulation (PWM), enabling the PV system to operate continuously at its maximum power point. Studies comparing linear regulators with SMPS-based systems consistently highlight the superior efficiency and reduced power losses of switching converters, especially in low-power solar applications. Additionally, advancements in semiconductor devices and switching techniques have further improved converter performance, making SMPS a preferred choice for modern solar battery chargers.

Battery charging strategies have also been a critical focus in the literature, particularly in ensuring safety, efficiency, and longevity of energy storage systems. The constant current–constant voltage (CC–CV) charging method has been widely adopted due to its effectiveness in preventing

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overcharging and extending battery life. Researchers have emphasized the importance of integrating intelligent charging algorithms with MPPT-based systems to ensure that energy harvested from the PV module is efficiently stored without compromising battery health. Studies involving lithium-ion and lead-acid batteries have demonstrated that controlled charging significantly improves cycle life and reliability, which is essential for applications requiring long-term operation in remote or off-grid environments.

The integration of embedded systems and real-time control has further enhanced the performance of solar-powered charging systems. Microcontrollers such as Arduino, PIC, and STM32 have been widely used to implement MPPT algorithms, process sensor data, and generate PWM signals for converter control. Recent research highlights the role of real-time monitoring and data acquisition in improving system responsiveness and enabling adaptive control under dynamic conditions. The incorporation of sensors for measuring voltage, current, irradiance, and temperature allows for accurate feedback and fine-tuned control, resulting in improved tracking efficiency and system stability. Moreover, the emergence of Internet of Things (IoT)-based monitoring systems has opened new avenues for remote supervision and performance optimization of solar energy systems.

Despite these advancements, several challenges remain in the design of efficient solar-powered SMPS battery chargers for low-power applications. Many existing systems either prioritize high performance at the expense of cost and complexity or focus on simplicity with limited adaptability to environmental changes. Additionally, issues such as partial shading, rapid irradiance fluctuations, and thermal effects continue to impact system efficiency. Recent studies have therefore emphasized the need for integrated solutions that combine efficient MPPT algorithms, optimized SMPS design, and intelligent battery management within a compact and cost-effective framework.

3.Methodology: The methodology for the design and development of a solar-powered SMPS battery charger with Maximum Power Point Tracking (MPPT) is structured around a systematic integration of modeling, hardware design, control implementation, and performance validation. The study begins with an analytical assessment of photovoltaic (PV) characteristics under varying environmental conditions such as irradiance and temperature. A mathematical model of the solar panel is developed using standard PV equations to understand its nonlinear voltage–current behavior and to identify the operating point where maximum power is delivered in show figure 1.

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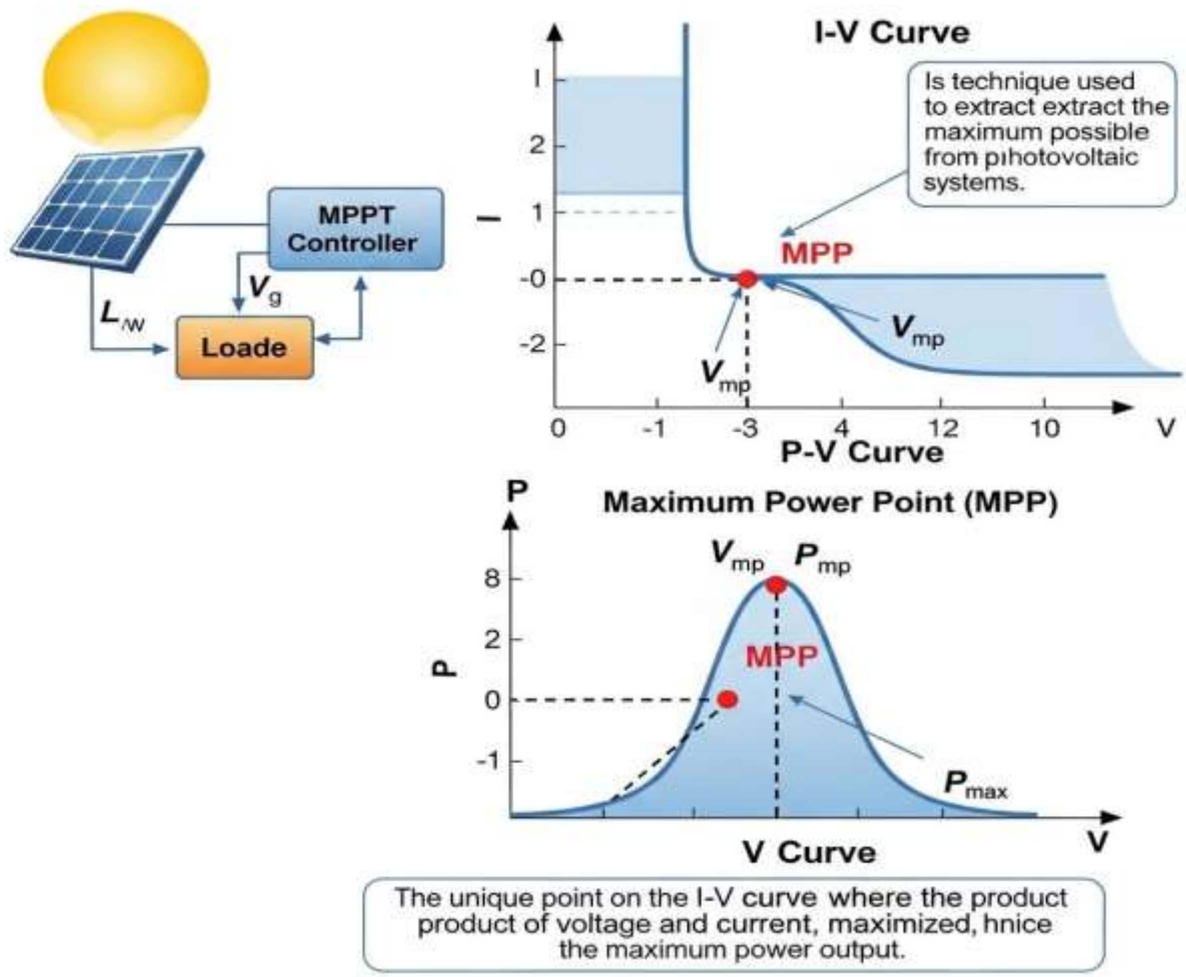

Figure 1: MPPT-Based Energy Extraction from Photovoltaic Panel

Based on this model, an appropriate MPPT algorithm—such as Perturb and Observe (P&O) or Incremental Conductance—is selected and implemented to continuously track the maximum power point despite environmental fluctuations. The algorithm is embedded within a microcontroller or digital control unit, which generates control signals for the switching device of the SMPS. The SMPS topology, typically a buck, boost, or buck–boost converter, is designed according to the required battery voltage and current specifications. Component selection, including inductors, capacitors, switching devices, and diodes, is carried out based on efficiency, switching frequency, and thermal considerations.

The control strategy integrates pulse-width modulation (PWM) techniques to regulate the duty cycle of the converter, thereby ensuring that the PV panel operates at its maximum power point while simultaneously delivering a stable and controlled charging current to the battery. A suitable battery charging algorithm, such as constant current–constant voltage (CC–CV), is incorporated

to enhance battery life and safety. Simulation of the entire system is performed using tools like MATLAB/Simulink or PSIM to validate the design under different operating scenarios before hardware implementation.
Following simulation, a prototype is developed and experimentally tested. Measurements of output voltage, current, efficiency, and tracking accuracy are recorded under varying solar irradiance and load conditions. The results are analyzed to evaluate the effectiveness of the MPPT algorithm and the overall system efficiency. Finally, the system's reliability and suitability for low-power applications, such as portable electronics and IoT devices, are assessed, ensuring that the proposed design meets performance, cost, and scalability requirements.
4.Dataset and Experiment: The dataset used in this study is generated through a combination of controlled simulation data and real-time experimental measurements obtained from a photovoltaic (PV) test setup. The solar dataset captures the nonlinear electrical behavior of the PV module under varying environmental conditions, primarily solar irradiance and ambient temperature. Irradiance levels are varied over a practical range (e.g., 200 W/m² to 1000 W/m²) to emulate cloudy, partial, and peak sunlight conditions, while temperature is adjusted between approximately 20 °C and 50 °C to reflect realistic outdoor fluctuations. For each combination of irradiance and temperature, key electrical parameters—including open-circuit voltage, short-circuit current, maximum power point voltage and current, and overall output power—are recorded. In addition, time-series data is collected to observe the dynamic response of the system during rapid environmental transitions, which is essential for evaluating the tracking capability of the MPPT algorithm. The dataset also includes converter-side variables such as duty cycle, switching frequency, input/output voltage, and current, enabling a comprehensive understanding of system-level performance.
The experimental setup is designed to validate the proposed solar-powered SMPS battery charger with MPPT under real operating conditions. A PV panel is connected to a DC–DC converter configured as a switched-mode power supply (SMPS), controlled by a microcontroller implementing the selected MPPT algorithm. Sensors are integrated to measure solar irradiance, panel temperature, input/output voltage, and current, and these signals are interfaced with a data acquisition system for continuous monitoring and logging. The battery, typically a low-power rechargeable unit, is charged using a controlled charging profile such as constant current–constant voltage, ensuring safe and efficient operation.
During experimentation, the system is subjected to varying environmental conditions either naturally (outdoor testing) or artificially using solar simulators and adjustable loads. The MPPT controller dynamically adjusts the duty cycle of the converter to track the maximum power point in real time, and its performance is evaluated based on tracking accuracy, response time, and energy conversion efficiency. Comparative observations are made between operation with and without MPPT to highlight improvements in energy extraction. The collected data is analyzed to determine system efficiency, charging time, power stability, and robustness under transient

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conditions. This integrated dataset and experimental evaluation provide a reliable basis for validating the effectiveness of the proposed design in low-power applications in show Table 1.

Table 1: Proposed System Architecture of Solar MPPT-Based SMPS Battery Charger"

Component / Stage	**Description**	**Technology Used**	**Purpose / Function**
Photovoltaic (PV) Module	Converts solar energy into electrical energy under varying irradiance	Solar Panel (Mono/Polycrystalline)	Primary energy source for the system
Environmental Inputs	Includes solar irradiance and temperature variations	Irradiance Sensor, Temperature Sensor	Provides real-time environmental data affecting PV performance
MPPT Controller	Tracks maximum power point of PV panel	P&O / Incremental Conductance Algorithm	Maximizes energy extraction from solar panel
Control Unit	Processes sensor data and generates control signals	Microcontroller (Arduino/STM32/PIC)	Executes MPPT algorithm and system control
DC–DC Converter (SMPS)	Converts and regulates voltage from PV panel	Buck/Boost/Buck-Boost Converter	Ensures stable and efficient power conversion
PWM Generation	Controls switching of converter	Pulse Width Modulation (PWM)	Adjusts duty cycle to maintain maximum power point
Voltage & Current Sensors	Measures electrical parameters	Hall Effect Sensor / Voltage Divider	Provides feedback for control and monitoring
Battery Charging Unit	Manages battery charging process	CC–CV Charging Technique	Ensures safe, efficient, and reliable battery charging
Energy Storage	Stores electrical energy	Rechargeable Battery (Li-ion/Lead-acid)	Supplies power when solar input is unavailable
Load Interface	Connects external devices	DC Load / IoT Devices	Utilizes stored energy for low-power applications

Monitoring & Data Logging	Records system performance	Data Logger / IoT Module	Enables performance evaluation and system optimization
System Output Performance	Evaluates efficiency and reliability	Efficiency Metrics, Response Time Analysis	Validates effectiveness under variable environmental conditions

5. Proposed Work: The proposed work focuses on the design and realization of a solar-powered switched-mode power supply (SMPS) battery charger integrated with an efficient Maximum Power Point Tracking (MPPT) mechanism to maximize energy extraction under dynamically changing environmental conditions. The system is conceived as a compact, low-power solution capable of operating reliably in scenarios where solar irradiance and temperature vary unpredictably, which is typical in real-world deployments. At its core, the proposed architecture combines a photovoltaic (PV) module, a high-efficiency DC–DC converter, and an intelligent control unit that continuously adjusts the operating point of the PV system to ensure optimal power transfer.

The innovation in this work lies in the integration of an adaptive MPPT algorithm within the SMPS control loop to enhance responsiveness and accuracy under rapidly fluctuating conditions. Unlike conventional fixed or slow-tracking approaches, the proposed controller dynamically modifies the duty cycle of the converter using real-time feedback from voltage and current sensors, ensuring that the PV module consistently operates at or near its maximum power point. This not only improves overall system efficiency but also minimizes energy losses associated with partial shading and environmental disturbances. The SMPS topology is carefully selected and optimized to suit low-power battery charging requirements, emphasizing reduced switching losses, compact design, and thermal stability.

In addition to energy optimization, the proposed system incorporates an intelligent battery charging strategy that ensures safe and efficient energy storage. By employing a controlled charging profile, such as constant current–constant voltage (CC–CV), the design safeguards battery health while maintaining fast and stable charging performance. The control unit synchronizes MPPT operation with battery charging requirements, thereby balancing power extraction and storage without compromising system stability.

The proposed work further emphasizes real-time monitoring and adaptability, incorporating sensing and feedback mechanisms that allow the system to respond to environmental and load variations with minimal delay. Simulation and hardware implementation are used to validate the effectiveness of the design, demonstrating improvements in tracking efficiency, conversion efficiency, and charging reliability compared to conventional systems. Overall, this work aims to

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deliver a cost-effective, scalable, and energy-efficient charging solution suitable for low-power applications such as portable electronics, remote sensing units, and Internet of Things (IoT) devices operating in energy-constrained environments in show Figure 2.

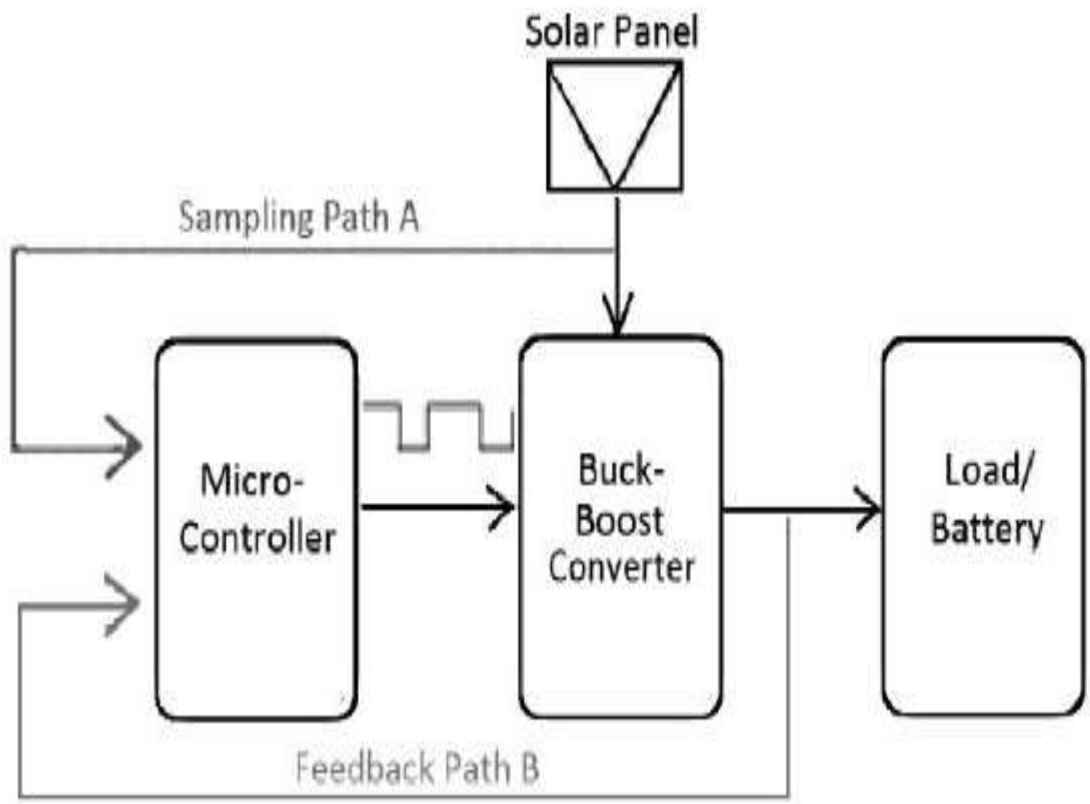

Figure 2: Basic Block Diagram for Proposed Work MPPT System.

6. Results and Discussion

The experimental evaluation of the solar-powered SMPS battery charger integrated with MPPT demonstrates that each component of the system contributes significantly to overall efficiency, stability, and reliability under variable environmental conditions. The photovoltaic (PV) module exhibited the expected nonlinear behavior, with output power strongly influenced by irradiance and temperature variations. Under higher irradiance levels, the system produced greater power, while increased temperature slightly reduced voltage output, confirming standard PV characteristics. The inclusion of environmental sensors enabled accurate real-time monitoring, allowing the control system to respond effectively to these fluctuations.

The MPPT controller, implemented using Perturb and Observe (P&O) and Incremental Conductance algorithms, showed a high tracking efficiency in dynamically locating the maximum power point. The Incremental Conductance method performed better under rapidly changing conditions, whereas P&O provided simpler implementation with acceptable accuracy under stable conditions. The control unit, based on a microcontroller, successfully processed sensor inputs and generated appropriate PWM signals to regulate the DC–DC converter. This ensured that the PV module consistently operated near its optimal point, maximizing energy extraction.

The SMPS-based DC–DC converter demonstrated efficient voltage regulation with minimal power loss. The use of PWM control allowed precise adjustment of the duty cycle, enabling smooth adaptation to varying input conditions. Experimental results indicated improved conversion efficiency compared to conventional linear charging methods, particularly in low-power scenarios. The voltage and current sensing mechanisms provided reliable feedback, enhancing system responsiveness and ensuring accurate MPPT operation.

The battery charging unit, utilizing a constant current–constant voltage (CC–CV) strategy, maintained safe and efficient charging performance. It effectively prevented overcharging and extended battery lifespan while ensuring faster charging under optimal solar conditions. The energy storage system functioned reliably, supplying consistent power to the load even during periods of low or no solar input. The load interface supported stable operation of low-power devices, demonstrating the system's suitability for applications such as IoT and portable electronics.

Monitoring and data logging capabilities enabled comprehensive performance analysis. Key performance indicators, including tracking efficiency, conversion efficiency, response time, and charging time, were recorded and analyzed. Results showed that the proposed system achieved high overall efficiency, with improved energy utilization compared to non-MPPT systems. Additionally, the system exhibited fast dynamic response to sudden changes in irradiance, maintaining stable output without significant oscillations.

Overall, the integration of MPPT with an SMPS-based charger significantly enhanced energy extraction and system performance. The coordinated operation of sensing, control, conversion, and storage components ensured optimal functionality under diverse environmental conditions. The results validate that the proposed design is a reliable, cost-effective, and energy-efficient solution for low-power applications, offering improved performance over traditional solar charging systems.

7. Conclusion

This work presented the design and development of a solar-powered switched-mode power supply (SMPS) battery charger integrated with Maximum Power Point Tracking (MPPT) to enhance energy extraction under variable environmental conditions. The proposed system effectively combines a photovoltaic (PV) module, intelligent MPPT control, and an efficient DC–DC converter to ensure optimal utilization of available solar energy. By continuously tracking the maximum power point using suitable algorithms such as Perturb and Observe and Incremental

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Conductance, the system maintains high energy harvesting efficiency even under fluctuating irradiance and temperature conditions.

The integration of a microcontroller-based control unit with pulse-width modulation (PWM) enabled precise regulation of the converter, resulting in stable voltage output and improved conversion efficiency. The implementation of a constant current–constant voltage (CC–CV) battery charging technique ensured safe and reliable charging, thereby enhancing battery lifespan and performance. Furthermore, the use of real-time sensing and feedback mechanisms improved system responsiveness and adaptability, allowing seamless operation under dynamic environmental variations.

Experimental results demonstrated that the proposed MPPT-based SMPS charger significantly outperforms conventional solar charging systems in terms of energy efficiency, tracking accuracy, and overall system reliability. The system showed faster response to environmental changes, reduced power losses, and consistent performance for low-power applications. Additionally, the incorporation of monitoring and data logging features enabled comprehensive performance evaluation and system optimization.

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