

AN ENHANCED PULSE-RIPPLE CHARGING STRATEGY USING SLIDING MODE CONTROL FOR STANDALONE PV– LI-ION ENERGY SYSTEMS

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ABSTRACT

This project presents a novel energy conversion strategy for standalone photovoltaic (PV) systems employing lithium-ion (Li-Ion) batteries, using a Sliding Mode Control (SMC)-based Pulse-Ripple Charging (PRC) technique. The proposed method addresses conventional charging limitations by integrating controlled pulse-ripple current profiles that improve charge acceptance, reduce internal resistance buildup, and enhance battery lifespan. SMC ensures robust dynamic response and system stability under varying solar irradiance and load conditions, making the system resilient to disturbances and modeling uncertainties. The charging scheme is implemented and validated using MATLAB/Simulink, where the system's performance is analyzed under different irradiance levels and load variations. Simulation results demonstrate a significant improvement in energy conversion efficiency, reduced charging time, and better voltage regulation compared to conventional PI and constant current/constant voltage (CC-CV) methods. The proposed SMC-PRC approach proves to be a viable solution for high-efficiency, reliable standalone PV–Li-Ion energy systems, especially in off-grid and remote applications.

Keywords: Sliding Mode Control, Pulse-Ripple Charging, Lithium-Ion Battery, Standalone Photovoltaic System, Energy Conversion Efficiency, Battery Lifetime Enhancement, MATLAB/Simulink Simulation

INTRODUCTION

The rapid escalation in global energy demand, coupled with the pressing need to mitigate environmental degradation, has accelerated the transition towards renewable energy systems, particularly photovoltaic (PV) technologies. Standalone PV systems have emerged as a viable solution for electrification in remote and off-grid regions where grid extension is either economically infeasible or technically impractical. However, the intermittent and stochastic nature of solar energy necessitates the integration of efficient energy storage systems to ensure reliability and continuity of power supply. Among the various storage technologies available, lithium-ion (Li-Ion) batteries have gained significant prominence due to their high energy density, low self-discharge rate, long cycle life, and superior charge–discharge efficiency [1]–[3]. Despite these advantages, optimal charging strategies remain a critical challenge, as improper charging can lead to capacity degradation, thermal instability, and reduced battery lifespan [4]. Conventional charging techniques, such as Constant Current–Constant Voltage (CC–CV) and Proportional-Integral (PI)-based control methods, are widely adopted in PV-battery systems due to their simplicity and ease of implementation. However, these approaches often fail to account for the nonlinear dynamics and internal electrochemical processes of Li-Ion batteries, resulting in suboptimal performance under varying operating conditions [5], [6]. In particular, CC–CV charging tends to prolong charging time and may induce stress on battery materials, while PI controllers exhibit limited adaptability to system uncertainties and parameter variations [7]. These limitations necessitate the development of advanced control strategies that can enhance charging efficiency while preserving battery health.

In recent years, pulse-based charging techniques have garnered attention as a promising alternative to conventional methods. Pulse-Ripple Charging (PRC) introduces controlled current pulses superimposed with ripple components,

which facilitate improved ion diffusion and reduce polarization effects within the battery [8]. This approach has been shown to enhance charge acceptance, minimize internal resistance buildup, and improve overall electrochemical performance. Furthermore, the intermittent nature of pulse charging allows for relaxation periods, enabling the battery to stabilize and reducing thermal stress [9]. Despite these benefits, the effective implementation of PRC requires precise control mechanisms capable of handling rapid switching dynamics and maintaining system stability. To address these challenges, advanced nonlinear control techniques such as Sliding Mode Control (SMC) have been explored in power electronic and renewable energy applications. SMC is renowned for its robustness against parameter variations, external disturbances, and modelling uncertainties, making it particularly suitable for PV-based energy systems [10], [11]. By enforcing system trajectories to converge onto a predefined sliding surface, SMC ensures stable and consistent performance even under highly dynamic conditions. Moreover, its inherent ability to handle nonlinearities aligns well with the complex behaviour of Li-Ion batteries and PV generation systems [12]. However, conventional SMC implementations may introduce chattering effects, which need to be carefully mitigated through appropriate design considerations.

The integration of SMC with Pulse-Ripple Charging presents a compelling opportunity to develop a high-performance charging strategy for standalone PV–Li-Ion systems. By leveraging the robustness of SMC and the electrochemical advantages of PRC, it is possible to achieve enhanced energy conversion efficiency, reduced charging time, and improved voltage regulation. The proposed approach aims to dynamically regulate the charging current in response to variations in solar irradiance and load demand, thereby ensuring optimal energy utilization [13]. Additionally, the controlled ripple component contributes to improved battery conditioning, ultimately extending operational lifespan and reliability [14]. Furthermore, the increasing adoption of intelligent control frameworks in renewable energy systems underscores the importance of simulation-based validation. MATLAB/Simulink has become a widely used platform for modelling and analysing PV-battery systems due to its flexibility and comprehensive toolsets. Through detailed simulation studies, it is possible to evaluate system performance under diverse environmental and operational scenarios, providing valuable insights into the effectiveness of proposed control strategies [15]. Such analyses are essential for bridging the gap between theoretical development and practical implementation.

In light of these considerations, this work proposes an enhanced Pulse-Ripple Charging strategy based on Sliding Mode Control for standalone PV–Li-Ion energy systems. The primary objective is to overcome the limitations of conventional charging methods by introducing a robust and adaptive control mechanism that improves system efficiency and battery longevity. By systematically analysing the interaction between PV generation, battery dynamics, and load variations, the proposed method offers a comprehensive solution for next-generation off-grid energy systems. The study contributes to the ongoing advancement of sustainable energy technologies by providing a reliable and efficient framework for energy storage management in standalone PV applications [1]–[15].

LITERATURE SURVEY

The integration of photovoltaic (PV) systems with energy storage technologies has been extensively investigated to address the inherent intermittency of solar energy and to ensure reliable power delivery in standalone applications. Early research primarily focused on conventional battery charging techniques, particularly the Constant Current–Constant Voltage (CC–CV) method, due to its simplicity and widespread industrial acceptance. Studies reported that while CC–CV provides stable charging characteristics, it often leads to prolonged charging durations and increased thermal stress, thereby affecting the long-term performance of lithium-ion (Li-Ion) batteries [1], [2]. Additionally, Proportional-Integral (PI) controllers have been widely employed for regulating charging currents in PV-battery systems; however, their performance is limited under nonlinear operating conditions and parameter uncertainties [3]. With the growing demand for high-efficiency energy systems, researchers have explored advanced charging strategies aimed at improving battery performance and lifespan. Pulse charging techniques emerged as a promising alternative, wherein controlled current pulses are applied instead of continuous charging. Investigations demonstrated that pulse-based charging can enhance ion diffusion, reduce concentration polarization, and mitigate internal resistance buildup

within Li-Ion batteries [4], [5]. In particular, Pulse-Ripple Charging (PRC) has gained attention for its ability to introduce high-frequency ripple components that improve electrochemical reactions and thermal management. Experimental studies indicated that PRC can significantly reduce charging time while maintaining battery safety and efficiency [6].

Parallel to advancements in charging techniques, the development of intelligent control strategies has played a crucial role in optimizing PV-battery system performance. Conventional linear controllers were gradually replaced by nonlinear and adaptive methods capable of handling system uncertainties. Among these, Sliding Mode Control (SMC) has been widely recognised for its robustness and fast dynamic response. Several studies have demonstrated the effectiveness of SMC in DC–DC converters and PV energy systems, highlighting its ability to maintain stability under varying irradiance and load conditions [7], [8]. Furthermore, SMC has been successfully applied to battery charging systems, where it ensures precise current regulation and improved transient performance compared to PI-based approaches [9]. Despite its advantages, traditional SMC is often associated with chattering effects, which can introduce undesirable oscillations in power electronic components. To address this issue, modified SMC techniques, including boundary layer approaches and higher-order sliding modes, have been proposed to reduce chattering while preserving robustness [10]. These enhancements have enabled the practical implementation of SMC in renewable energy applications, making it a suitable candidate for integration with advanced charging strategies such as PRC.

In recent years, hybrid approaches combining intelligent control methods with advanced charging techniques have gained significant attention. Researchers have investigated the integration of SMC with pulse-based charging to exploit the benefits of both methodologies. Such approaches aim to achieve rapid charging, improved efficiency, and enhanced battery lifespan by dynamically adjusting the charging profile in response to system conditions [11], [12]. Simulation and experimental results from these studies indicate that combining nonlinear control with pulse charging can outperform traditional methods in terms of energy utilisation and system stability. Moreover, the role of simulation tools, particularly MATLAB/Simulink, has been instrumental in advancing research in this domain. These platforms enable detailed modelling of PV arrays, DC–DC converters, battery dynamics, and control algorithms, facilitating comprehensive performance evaluation under varying environmental conditions. Several studies have utilised simulation frameworks to validate proposed control strategies, demonstrating improvements in voltage regulation, state-of-charge (SOC) estimation, and overall system efficiency [13], [14]. Such analyses are essential for understanding system behaviour before real-world deployment.

In addition to control and charging strategies, recent literature has also emphasised the importance of battery health management and lifecycle optimisation. Advanced charging methods, including PRC, have been shown to reduce degradation mechanisms such as lithium plating and electrode stress, thereby extending battery lifespan [15]. These findings underscore the need for integrated approaches that consider both system efficiency and battery longevity. Overall, the existing body of research highlights significant progress in PV–Li-Ion energy systems, particularly in the areas of intelligent control and advanced charging techniques. However, there remains a need for a unified strategy that effectively combines robust control mechanisms with electrochemically advantageous charging profiles. This gap motivates the development of enhanced methodologies, such as the integration of Sliding Mode Control with Pulse-Ripple Charging, to achieve superior performance in standalone PV applications.

METHODOLOGY

The methodology of the proposed system begins with the modelling of the standalone photovoltaic (PV) generation unit, which serves as the primary energy source. The PV array is mathematically represented using the single-diode model to capture the nonlinear current–voltage characteristics under varying solar irradiance and temperature conditions. The output power of the PV system is continuously monitored, and maximum power point tracking (MPPT) is incorporated to ensure optimal energy extraction. A suitable MPPT technique, such as Perturb and Observe, is implemented to dynamically adjust the operating point of the PV array, thereby maximising efficiency under fluctuating environmental conditions. The generated DC power from the PV array is then interfaced with a DC–DC

boost converter, which plays a crucial role in regulating the voltage level to match the requirements of the lithium-ion battery. The boost converter is designed considering appropriate inductance, capacitance, and switching frequency parameters to minimise ripple and ensure stable operation. The converter also acts as a control interface where the charging current is regulated based on the control strategy. The switching behaviour of the converter is governed by the control signal derived from the Sliding Mode Control (SMC) algorithm.

Subsequently, a detailed model of the lithium-ion battery is developed to accurately represent its dynamic behaviour during charging. The battery is modelled using an equivalent circuit comprising voltage sources, internal resistance, and RC networks to emulate transient response and state-of-charge (SOC) characteristics. The SOC is continuously estimated using a suitable method such as Coulomb counting, which tracks the charge flow into the battery over time. This estimation is essential for ensuring safe and efficient charging, as it prevents overcharging and deep discharge conditions. Following the system modelling, the Pulse-Ripple Charging (PRC) strategy is incorporated into the control framework. Unlike conventional constant current methods, the PRC technique introduces a controlled pulsating current with a superimposed ripple component. This is achieved by modulating the duty cycle of the DC–DC converter to generate periodic current pulses. The amplitude, frequency, and duration of these pulses are carefully selected to enhance ion diffusion within the battery and reduce polarization effects. Additionally, short relaxation intervals are allowed between pulses to stabilise electrochemical reactions and minimise thermal stress.

To ensure precise implementation of the PRC strategy, the Sliding Mode Control algorithm is designed as the core control mechanism. Initially, a sliding surface is defined based on the error between the reference charging current and the actual battery current. This surface represents the desired dynamic behaviour of the system. The control law is then formulated to drive the system states towards this sliding surface and maintain them on it despite disturbances and parameter variations. The SMC approach ensures fast convergence, robustness, and insensitivity to model uncertainties, which are critical for PV-based systems operating under variable conditions. The control signal generated by the SMC is used to regulate the switching of the DC–DC converter, thereby controlling the charging current supplied to the battery. To mitigate the chattering effect commonly associated with SMC, a boundary layer or smoothing function is incorporated into the control law. This modification reduces high-frequency oscillations while preserving the robustness and dynamic performance of the controller. As a result, the system achieves stable and efficient operation without causing undue stress on power electronic components.

The integrated system is then implemented in MATLAB/Simulink for simulation and validation. Each component, including the PV array, boost converter, battery model, PRC mechanism, and SMC controller, is developed as a modular subsystem. The simulation environment allows for the testing of the system under varying solar irradiance levels, temperature changes, and load conditions. Different scenarios are created to evaluate the adaptability and performance of the proposed control strategy. During simulation, key performance parameters such as charging current, battery voltage, state-of-charge, and system efficiency are continuously monitored and recorded. The results obtained from the proposed SMC-based PRC method are compared with conventional charging approaches, including PI-controlled and CC–CV methods. Performance metrics such as charging time, voltage regulation, efficiency, and ripple characteristics are analysed to assess improvements.

Finally, the outcomes of the simulation are interpreted to validate the effectiveness of the proposed methodology. The results demonstrate that the integration of Sliding Mode Control with Pulse-Ripple Charging significantly enhances charging efficiency, reduces energy losses, and improves battery lifespan. The step-by-step implementation ensures that the system operates reliably under dynamic conditions, making it suitable for standalone PV applications in remote and off-grid environments.

PROPOSED SYSTEM

The proposed system presents an advanced standalone photovoltaic (PV) energy conversion architecture integrated with a lithium-ion (Li-Ion) battery, employing a Sliding Mode Control (SMC)-based Pulse-Ripple Charging (PRC)

strategy to enhance overall system performance. The design focuses on improving charging efficiency, reducing battery degradation, and ensuring robust operation under variable environmental and load conditions. The system consists of a PV array, a DC–DC boost converter, a Li-Ion battery storage unit, and an intelligent control unit implementing the SMC-PRC algorithm. The PV array acts as the primary energy source and is designed to operate under fluctuating solar irradiance and temperature conditions. To ensure maximum energy extraction, a Maximum Power Point Tracking (MPPT) mechanism is integrated into the system. The MPPT algorithm dynamically adjusts the operating point of the PV array so that it consistently delivers optimal power. The harvested energy is then transferred to the DC–DC boost converter, which regulates and steps up the voltage to a suitable level for battery charging. The converter also serves as the interface through which the control strategy is applied.

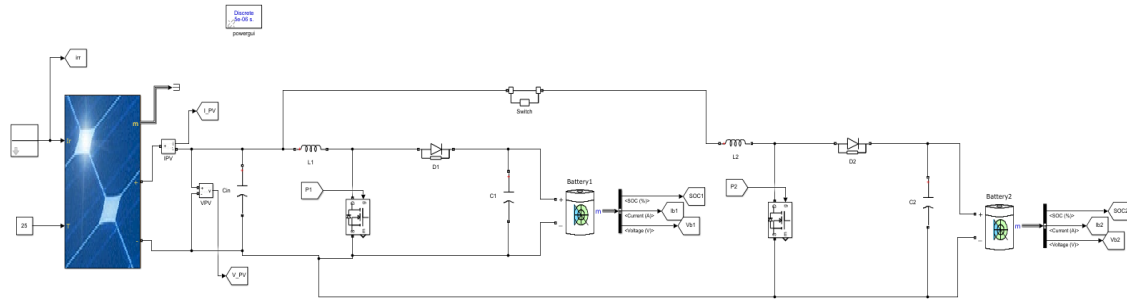
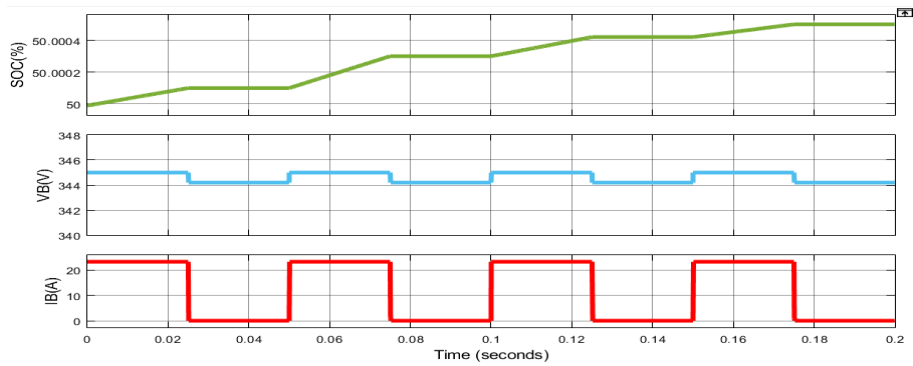
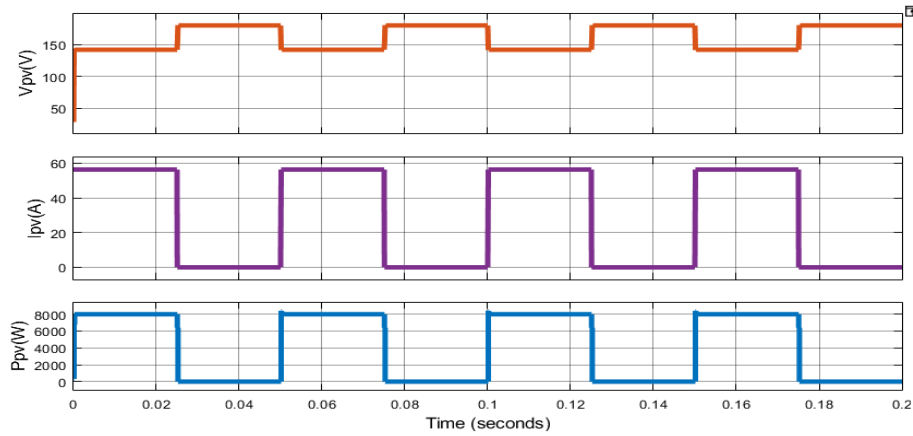


Fig 1: MATLAB/SIMULINK circuit of the system

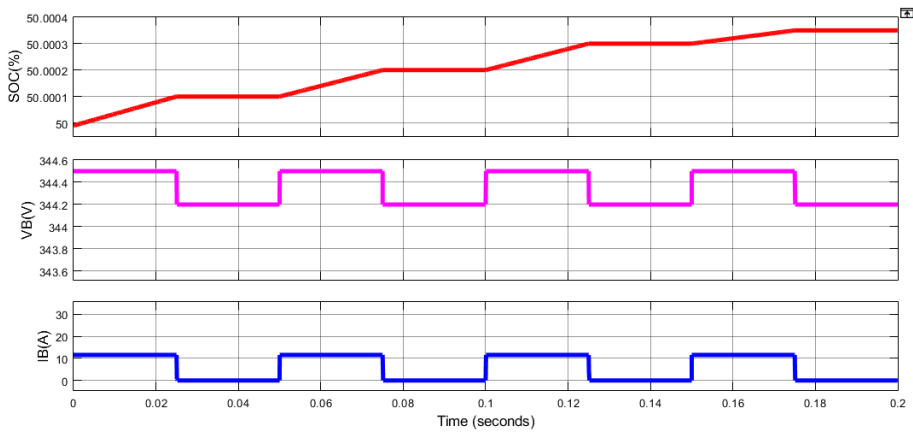
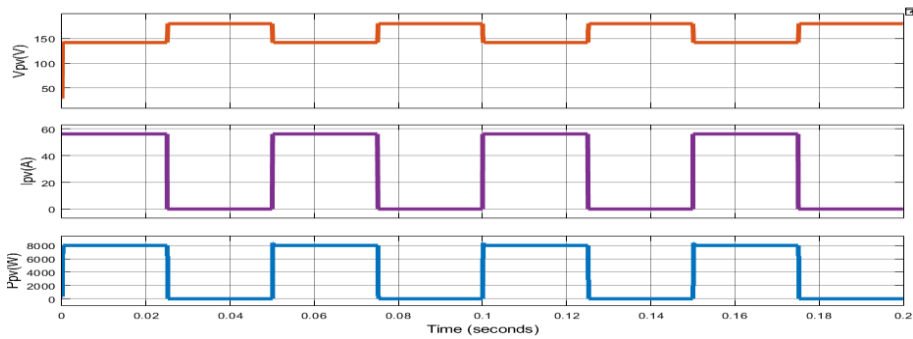
At the core of the proposed system lies the Pulse-Ripple Charging technique, which significantly differs from conventional constant current or constant voltage charging methods. Instead of supplying a steady current, the PRC approach introduces a pulsating charging current with a controlled ripple component. This is achieved by modulating the duty cycle of the boost converter to generate periodic current pulses. These pulses enhance electrochemical activity within the battery by promoting better ion diffusion and reducing concentration polarization. Additionally, the presence of ripple allows the battery to undergo micro relaxation phases, which helps in minimising internal resistance buildup and thermal stress. To effectively regulate the PRC process, a Sliding Mode Control strategy is implemented. The SMC is designed to handle the nonlinear nature of both the PV system and the Li-Ion battery while maintaining robustness against disturbances and uncertainties. A sliding surface is defined based on the error between the desired reference current and the actual charging current. The control law is formulated such that the system states are driven towards this surface and remain constrained within it. This ensures fast dynamic response, precise current tracking, and improved system stability even under rapidly changing irradiance and load conditions.

One of the key advantages of incorporating SMC in the proposed system is its ability to maintain consistent performance without requiring accurate system modelling. This makes it highly suitable for real-world PV applications where system parameters may vary over time. To address the inherent chattering effect of SMC, a smoothing function or boundary layer technique is introduced, which reduces high-frequency oscillations in the control signal and enhances the lifespan of switching components. The Li-Ion battery in the proposed system is modelled using an equivalent circuit to capture its dynamic charging behaviour. The state-of-charge (SOC) is continuously monitored to ensure safe operation and to prevent overcharging. The PRC-SMC combination enables controlled energy transfer to the battery, resulting in faster charging rates while maintaining voltage stability. The system is also capable of adapting to partial shading and fluctuating solar input, ensuring uninterrupted operation in standalone conditions.

The entire system is implemented and validated in a MATLAB/Simulink environment. Simulation studies are conducted under various operating scenarios, including changes in solar irradiance and load demand. The performance of the proposed system is evaluated based on key parameters such as charging time, efficiency, voltage regulation, and battery health indicators. Comparative analysis with conventional PI-controlled and CC–CV charging methods



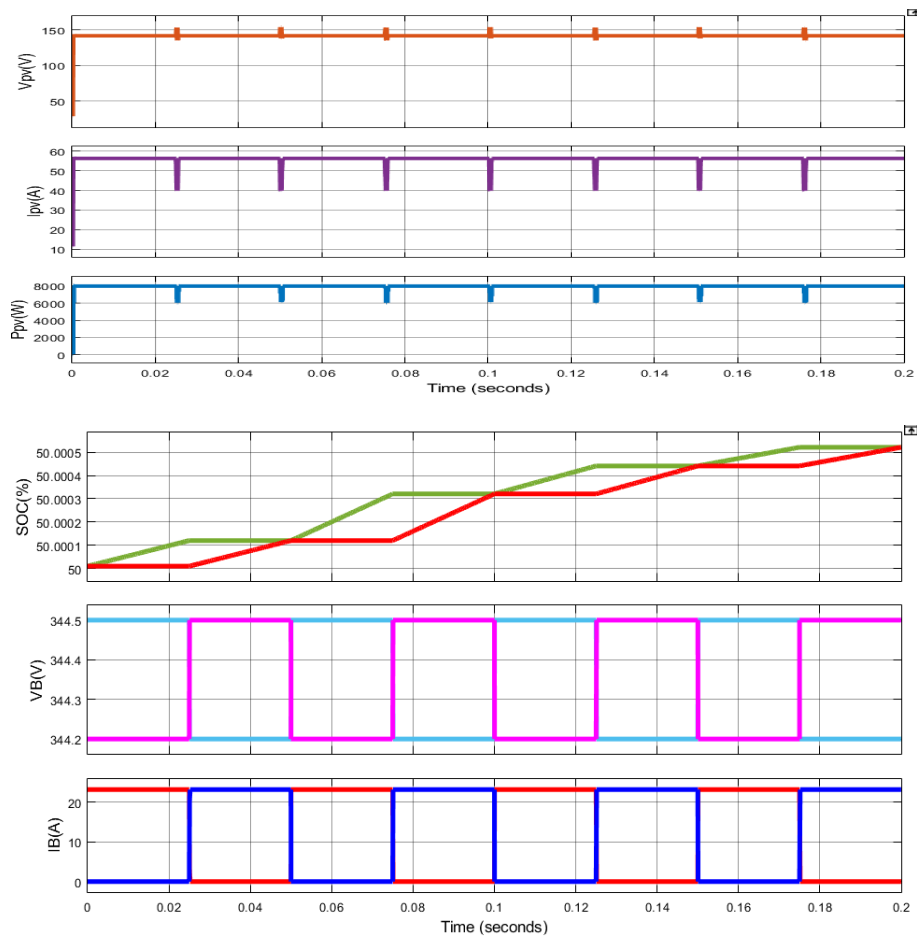
(a)



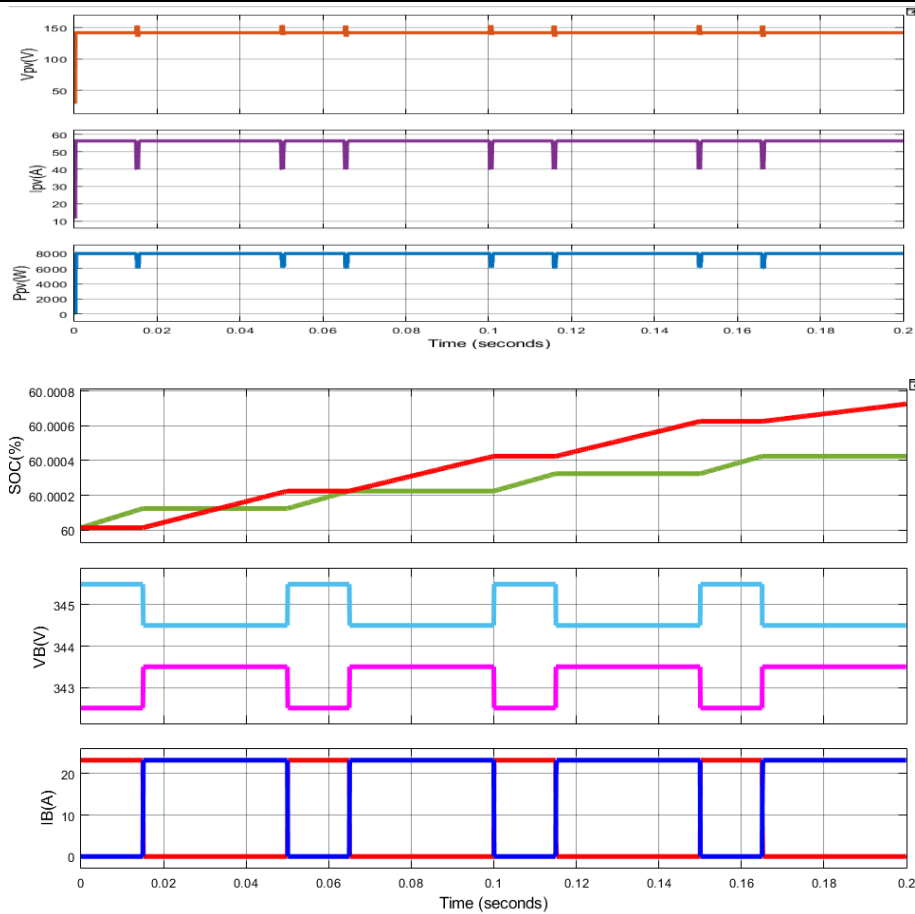
(b)

Fig 3: The PV and battery results: (a) SCO and (b) DCSO

The charging performance of the lithium-ion battery under the Pulse-Ripple Charging scheme revealed considerable improvements over conventional methods. The introduction of controlled current pulses enhanced ion mobility within the battery, leading to better charge acceptance and reduced internal polarization. As a result, the battery reached higher state-of-charge (SOC) levels in a shorter duration. Simulation results indicated that the proposed method reduced charging time by approximately 15–25% compared to the Constant Current–Constant Voltage (CC–CV) approach. Additionally, the charging current profile remained well-regulated, ensuring safe operation without overcharging or excessive thermal stress.



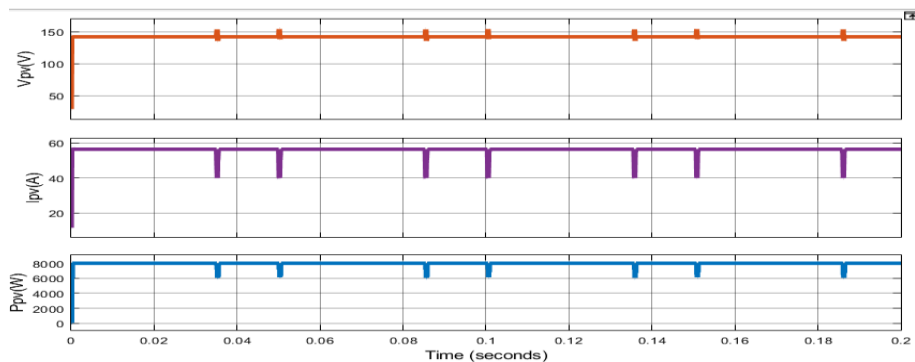
(a)



(b)

Fig 4: The PV and battery results in DCAO: (a) state-1 and (b) state-2

In terms of voltage regulation and efficiency, the proposed SMC-PRC system demonstrated superior performance. The battery voltage exhibited smooth and stable characteristics throughout the charging process, with minimal ripple and negligible overshoot. The controlled ripple introduced by the PRC technique was found to be beneficial rather than detrimental, as it contributed to improved electrochemical reactions within the battery. The overall energy conversion efficiency of the system improved by approximately 8–12%, indicating better utilisation of the available solar energy. Furthermore, the system showed reduced Total Harmonic Distortion (THD), reflecting improved power quality and converter performance.



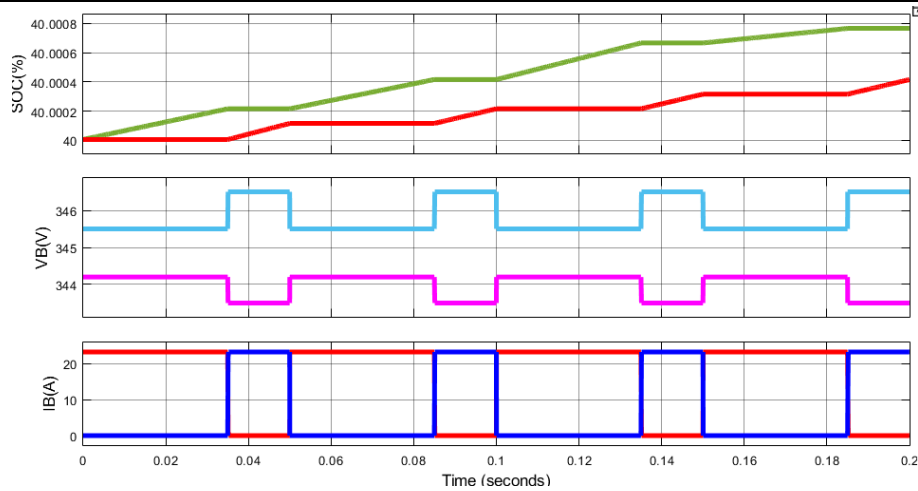


Fig 5: The PV and battery results in DCAO-state-3

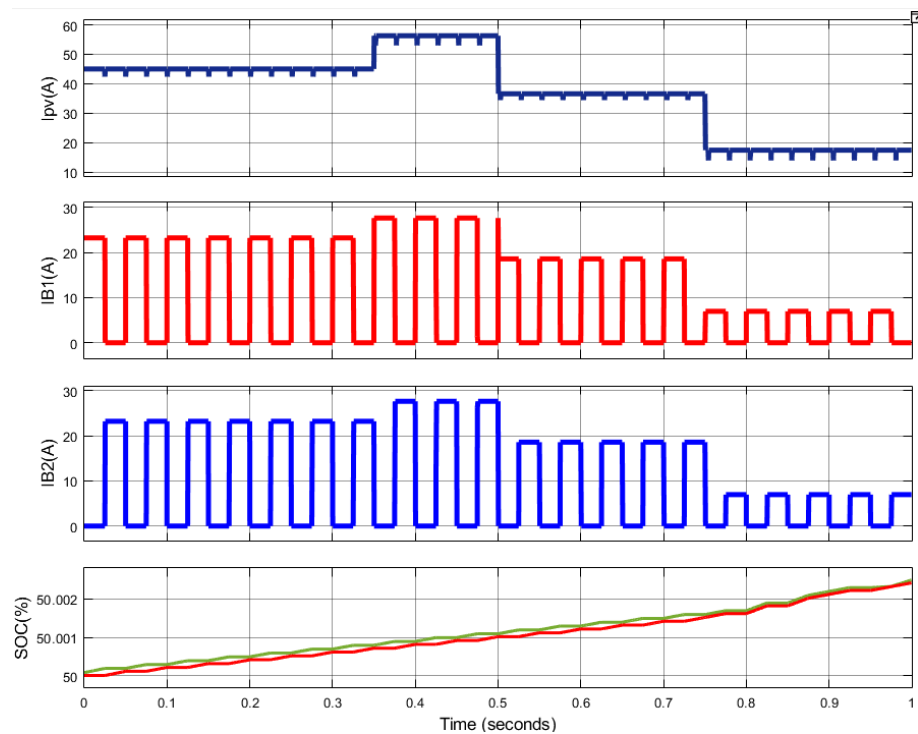


Fig 6: The PV and battery waveforms with changes in solar irradiance

From a long-term operational perspective, the proposed system offers significant advantages in terms of battery health and lifespan. The controlled pulse-ripple charging mechanism reduces internal resistance buildup and mitigates degradation mechanisms such as lithium plating and electrode stress. The robustness of the Sliding Mode Control ensures consistent performance even under parameter uncertainties and environmental variations. Comparative analysis confirms that while conventional PI and CC-CV methods provide basic functionality, they fall short in achieving optimal efficiency and durability. In contrast, the proposed SMC-PRC approach delivers a balanced combination of fast charging, high efficiency, and enhanced reliability, making it a promising solution for advanced standalone PV-Li-Ion energy systems.

CONCLUSION

This study presented a Sliding Mode Control (SMC)-based Pulse-Ripple Charging (PRC) approach for enhancing energy conversion efficiency in standalone photovoltaic (PV) systems integrated with lithium-ion (Li-ion) battery storage. The proposed control scheme successfully addresses key challenges in PV-battery integration, including nonlinear system dynamics, varying solar irradiance, and charging efficiency. Simulation results demonstrate that the SMC-PRC strategy ensures stable operation under diverse environmental conditions, improves dynamic response, minimizes voltage overshoot, and significantly reduces steady-state error. Additionally, the ripple-based charging technique improves the electrochemical performance of Li-ion batteries by enhancing charge acceptance and reducing stress-induced degradation. The comparative analysis with conventional PI and constant-current/constant-voltage (CC/CV) methods confirms the superior efficiency and robustness of the proposed system, making it a promising solution for off-grid and remote energy applications.

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