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CLOSE LOOP BUCK CONVERTER INTEGRATED WITH PSO MPPT DESIGN FOR PV-FED FAST EV CHARGING

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ABSTRACT

This paper describes a photovoltaic PV powered fast charging of electric vehicles (EV) batteries employing a closed loop buck converter integrated with a Particle Swarm Optimization (PSO) maximum power point tracking (MPPT) controller. The research is conducted under standard test conditions with constant irradiance of 1000 W/m² and temperature of 25°C in order to ensure operation at the maximum power capability of the PV array. The PSO algorithm continuously optimizes the operating point of the PV system, enabling rapid convergence to the global maximum power point with minimal steady-state oscillations. The extracted power is processed through a high-efficiency buck converter that provides regulated charging current, low output ripple, and a stable DC supply suitable for fast battery charging applications. A buck converter optimized for high currents is developed to allow low ripple current, control of the charging current and maintenance of a smooth and stable DC source suitable for fast charging of the EV batteries. The complete system was modelled and verified in the MATLAB/Simulink format, including the detailed dynamics of the PV, converter and batteries. Simulation results demonstrate effective maximum power point tracking, im-proved power extraction efficiency, stable converter operation, and reliable battery charging performance while maintaining voltage and current within safe operating limits. The findings validate the effectiveness of the proposed PSO-based charging architecture for efficient, reliable, and sustainable solar-powered fast charging of electric vehicles, supporting the integration of renewable energy resources into future transportation systems.

Keyword: **-** *Photovoltaic (PV),[1] MPPT[2], Particle Swarm Optimization (PSO)[3], MATLAB[4] ,Buck Converters[5]*

1. INTRODUCTION

The rapid expansion of electric vehicles (EVs) has inevitably increased the demand for reliable, efficient and sustainable charging infrastructures. Among the many renewable sources, photovoltaic (PV) systems present a clean and locally available energy option for EV charging, which decreases dependency on the grid and reduces the overall GHG emissions [1]. In order to achieve reliable fast charging using PV systems, robust power management and capable maximum power extraction and efficient DC-DC conversion is required to ensure the safe and stable charging of the EV batteries. Among the available renewable energy technologies, solar photovoltaic (PV) systems have received significant attention for EV charging applications because of their abundant availability, modular structure, silent operation, low maintenance requirements, and environmental compatibility. Maximum power point tracking (MPPT) represents a key role in maximizing the energy utilization of PV arrays. Extensive research has been conducted on advanced MPPT techniques and control strategies to improve their tracking accuracy and quality of power for the charging of EV [1],[2]. The incorporation of MPPT to grid-assisted and/or standalone EV charging systems has yielded significant potential for improving charge availability and system efficiency under varying conditions of operation [1],[3]. In a standalone configuration this represents an additional design challenge associated with power balancing and reliable charging without grid support [2].

Integrated power conversion and control techniques with modern switching have also been suggested to improve efficiency and operational stability with PV and battery hybrid [4]. Now that the efficiency of chargers for EVs has begun to be significant, buck-based and buck-boost converter systems continue to be of interest because of their simplicity, their high efficiency and their appropriateness to fast charging operation [5], [6]. Recent literature has indicated the importance of the optimized converter design, intelligent control algorithms employed, the proper co-ordination of MPPT and battery management systems to give adequate results with regard to the PV-driven fast charging [5], [7]. Various MPPT algorithms such as Perturb and Observe (P&O), Incremental Conductance (INC), fuzzy logic control, artificial neural networks, and optimization-based intelligent techniques, have been proposed in the literature to improve photovoltaic energy extraction capability. System approach studies have shown that a good robust converter design and suitable control methods will go a long way towards improving power extraction, charging performance and reliability possessed in a stand-alone solar-powered EV charging stations [7]. Further, hybrid PV-based chargers of the 4 kW and above category have shown good results in medium power EV charging applications with safety of battery voltage and current limits being of utmost concern [8].

Inspired by these developments, the present work is aimed at the design and simulation of a PV-fed fast EV charging system with a closed loop buck converter integrated with a Particle Swarm Optimization (PSO) MPPT algorithm, connected with a high efficiency buck DC-DC converter under standard test conditions. The aim of this work is to deliver stable output DC, improved MPPT performance and efficient battery charging suitable for sustainable EV charging infrastructures.

2. SYSTEM DESCRIPTION

The charging configuration suggested as shown in Figure 1 considers a photovoltaic array, maximum power point tracking controller and high efficiency buck converter. The maximum power point tracking algorithm constantly monitors both voltage and current of the photovoltaic cell to ascertain the maximum power operating point at which voltage and current give maximum power. Particle Swarm Optimization (PSO) is an intelligent optimization technique inspired by the collective social behaviour observed in bird flocking and fish schooling phenomena. In photovoltaic systems, PSO-based Maximum Power Point Tracking (MPPT) has emerged as an efficient optimization method capable of improving tracking accuracy, convergence speed, and dynamic response under varying atmospheric conditions.

The PSO algorithm operates through a group of particles moving within a multidimensional search space. In the proposed work, each particle represents a candidate duty ratio of the DC-DC converter corresponding to a possible photovoltaic operating point. The particles continuously adjust their positions based on their own experience and the experience of neighbouring particles in order to identify the global optimum operating condition corresponding to the maximum photovoltaic power. The PSO algorithm continuously evaluates the photovoltaic power corresponding to different converter duty ratios and updates particle velocities and positions iteratively until the global maximum power operating point is reached. Once the optimum duty ratio is identified, it is supplied to the PWM-controlled DC-DC converter for efficient photovoltaic power extraction and stable battery charging operation.

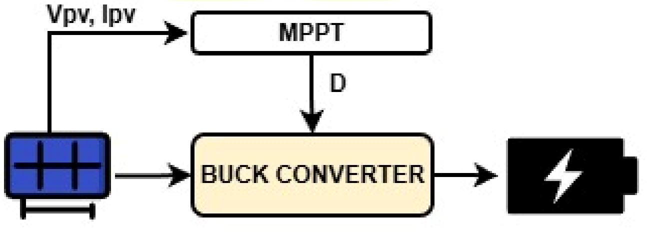

Figure 1 PV-fed EV charging system using Closed Loop PSO MPPT-controlled buck converter

2.1 PV MODULE

Particle Swarm Optimization (PSO) is an intelligent optimization technique inspired by the collective social behaviour observed in bird flocking and fish schooling phenomena. In photovoltaic systems, PSO-based Maximum Power Point Tracking (MPPT) has emerged as an efficient optimization method capable of improving tracking accuracy, convergence speed, and dynamic response under varying atmospheric conditions. In the proposed standalone photovoltaic-assisted electric vehicle charging system, the PSO algorithm is employed to enhance photovoltaic power extraction capability and overcome the limitations associated with conventional MPPT techniques.

Photovoltaic systems exhibit nonlinear current-voltage and power-voltage characteristics that continuously vary with solar irradiance and operating temperature. Consequently, the location of the maximum power point changes dynamically under environmental variations. Conventional MPPT methods such as PSO often suffer from steady-state oscillations around the maximum power point and may exhibit reduced performance under rapidly changing irradiance conditions.

2.2 MPPT CONTROL

The function depicted in Figure 3 determines the duty cycle of the buck converter using a Particle Swarm Optimization (PSO)-based Maximum Power Point Tracking (MPPT) algorithm. The output power, which acts as the fitness function for the optimization process, is determined by continuously measuring the photovoltaic (PV) voltage and current. A potential duty cycle that corresponds to a potential PV operating point is represented by each particle in the swarm. Particles update their positions and velocities during each iteration according to the swarm's global best position (G_{best}) and their own personal best position (P_{best}). In order to reach the operating point that produces the highest power production, the algorithm continuously assesses PV power and modifies the duty cycle. While memory variables preserve prior particle information to maintain continuity between subsequent iterations, duty-cycle restrictions are added to guarantee safe converter operation. This enables rapid convergence to the maximum power point with improved tracking accuracy and reduced steady-state oscillations, resulting in efficient photovoltaic power extraction and stable EV battery charging.

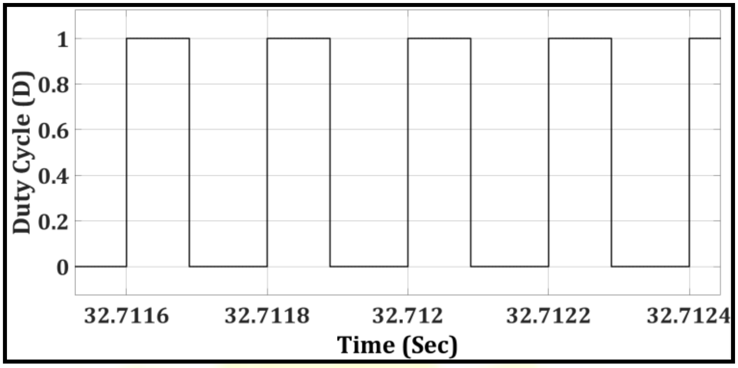

Figure 2 Duty-cycle waveform generated by the MPPT controller during steady-state operation

The duty cycle variation to the buck converter as applied by the MPPT algorithm is detailed in figure 2. The oscillogram shows the periodic switching from high to low levels which is representative of stable tracking, demonstrating a consistent control effort in the constant state operating interval.

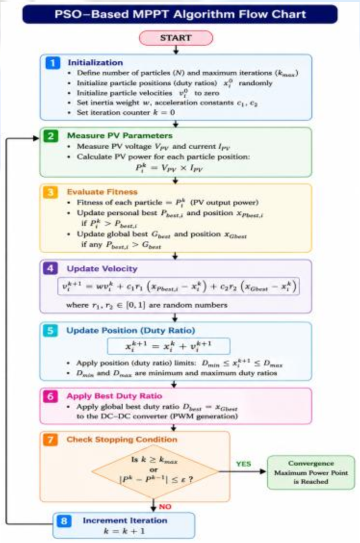

Figure 3 Flow chart of Particle Swarm Optimization (PSO)-based MPPT algorithm for photovoltaic maximum power extraction and converter duty ratio optimization.

2.3 DC-DC CONVERTER

The buck converter topology, detailed in figure 4, will consist of a switching device, freewheeling diode, inductor and output capacitor. The converter operates to lower the PV voltage and give a DC regulated output suitable for EV battery charging applications. The main design parameters for the buck converter DC-DC system design are detailed in table 1. This is shown in figure 3 and incorporated into the proposed PV fed EV charging system. To ensure continuous conduction and minimize current ripple during the charging process, a 25 mH output inductor is incorporated into the converter. This component captures energy when the switch is activated and releases it when the switch is deactivated, allowing for a consistent flow of current to the electric vehicle battery. Input and output filter capacitors of 5000 µF are employed to attenuate the voltage ripple on both the PV side and battery side, this maintains a stable direct current voltage profile and reliable charging performance.

Table 1 Buck converter parameters used for the PV-fed EV battery charging system.

Parameter	Value
Switching Frequency (f_{sw})	5 kHz
Inductor (L)	25 mH
Input Capacitor (C_{in})	5000 µF
Output Capacitor (C_{out})	5000 µF

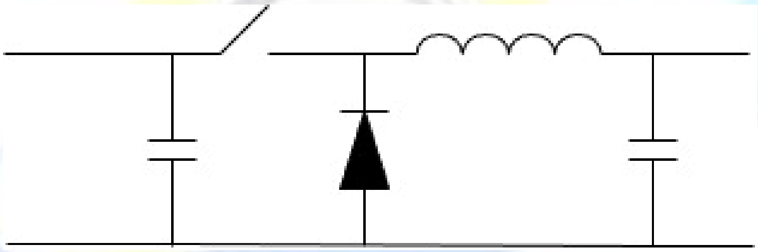

Figure 4 Circuit diagram of the DC-DC buck converter used in the charging system

2.4 LITHIUM-ION EV BATTERY

The selected battery parameters also enable the study of voltage stabilization at the DC bus level. Table 2 displays the major specifications of the lithium-ion battery which has been simulated for usage in the recommended PV fed charging system. The battery is rated 120 V, 10 Ah and with an initial state of charge of 50 %. This specification makes it possible to obtain an indication of the high efficiency DC charging available in a controlled manner. The parameters were selected to replicate a compact EV battery module suitable for fast charging work, and enable the evaluation of voltage stabilization, current control and SOC changes in operation governed by MPPT. It also facilitates detailed study of energy flow behaviour, converter interaction, and control system effectiveness under varying operating conditions. This makes the battery model a critical component in validating the proposed PV fed EV charging architecture and assessing its suitability for fast-charging applications in sustainable transportation systems.

Table 2. Electrical specifications of the lithium-ion EV battery used in the charging system

Parameter	Value
Nominal Voltage (V)	120 V
Rated capacity (Ah)	10 Ah
Initial SOC (%)	50 %
Battery Response Time	1 s

3. Result and Discussions

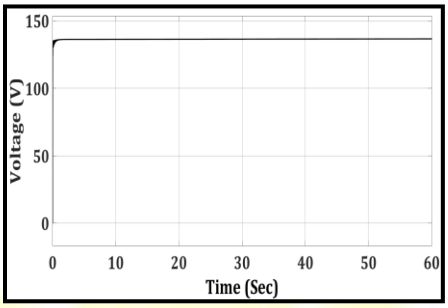

Figure 5 Battery terminal voltage response during photovoltaic- fed Closed-Loop PSO-MPPT Controlled Fast EV Charging System

Figure 5 shows the charging voltage characteristics are presented. Initially, the voltage exhibits a rapid transient rise due to converter startup and controller convergence. After this short transient interval, the voltage stabilizes near 135 V and remains almost constant throughout the remaining charging duration. The stable voltage response confirms the effectiveness of the closed-loop control strategy in maintaining appropriate charging conditions for the energy storage system.

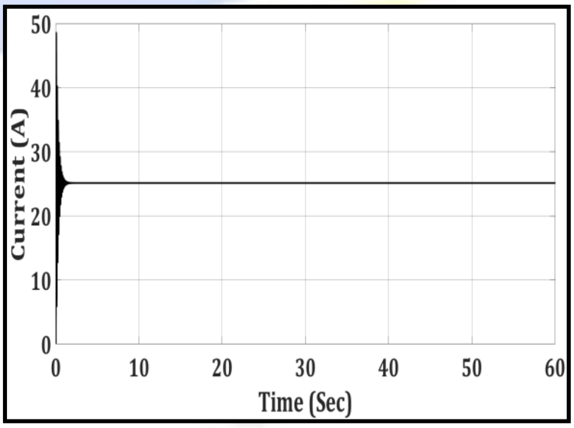

Figure 6 Battery charging current response under photovoltaic-fed Closed-Loop PSO-MPPT Controlled Fast EV Charging System

Figure 6 shows the performance of the battery during the MPPT-controlled charging of the battery. The the charging current response of the proposed system.

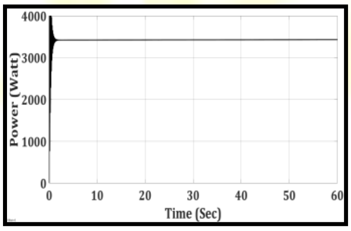

Figure 7 Battery-side charging power response of the photovoltaic-fed fed Closed-Loop PSO-MPPT Controlled Fast EV Charging System

During the initial stage of operation, the current experiences a transient overshoot caused by converter initialization and rapid convergence of the MPPT controller toward the maximum power operating point. Subsequently, the current stabilizes near 25 A and remains nearly constant throughout steady-state operation. The obtained current characteristics therefore validate the effectiveness of the proposed control strategy in achieving safe and efficient charging operation. Figure 7 shows the battery charging power and the efficiency of the converter during the PV presents the battery-side charging power response of the proposed PV fed closed-loop PSO-MPPT fast EV charging system. At start-up, a brief transient occurs due to converter switching and MPPT convergence dynamics. The charging power rapidly reaches the desired operating region with minimal oscillatory behaviour, indicating effective closed-loop stabilization. After the transient interval, the output power settles near 3.5 kW and remains almost constant throughout the operating period.

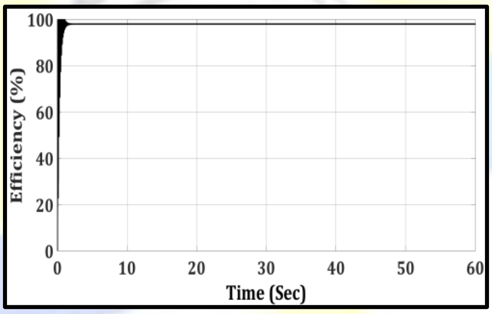

Figure 8 Efficiency response of the photovoltaic-fed fed Closed-Loop PSO-MPPT Controlled Fast EV Charging System

The converter efficiency characteristics are illustrated in Figure 8, The efficiency initially rises rapidly during the start-up interval and subsequently stabilizes near 98% under steady-state operating conditions. The high efficiency achieved by the proposed system confirms that the PSO-MPPT-controlled converter effectively minimizes switching and conduction losses during power conversion. The stable efficiency response further demonstrates proper synchronization between the MPPT controller, PWM switching mechanism, and converter power stage. The obtained results therefore verify that the proposed closed-loop charging architecture provides highly efficient and stable charging performance suitable for renewable-energy-based electric vehicle charging applications. Overall, the simulation results confirm that the proposed closed-loop PSO-MPPT-controlled photovoltaic charging system achieves stable voltage regulation, controlled charging current, smooth SOC progression, and high converter efficiency throughout the charging interval. The coordinated operation of the photovoltaic array, MPPT controller, PWM switching mechanism, and converter enables efficient maximum power extraction and reliable energy transfer to the storage system. The absence of major oscillations, instability, or performance degradation validates the robustness of the proposed charging framework for advanced EV charging applications requiring efficient, fast, and sustainable energy management

4. CONCLUSIONS & FUTURE WORKS

This chapter presented the design and performance evaluation of a closed-loop photovoltaic-assisted fast charging system employing a Particle Swarm Optimization (PSO)-based Maximum Power Point Tracking (MPPT) controller integrated with a DC-DC converter and supercapacitor energy storage unit. The proposed charging architecture was developed to improve photovoltaic power utilization, enhance charging stability, and achieve efficient energy transfer suitable for advanced electric vehicle applications.

The PSO-based MPPT controller effectively tracked the maximum power point of the photovoltaic array under varying operating conditions by continuously optimizing the converter duty cycle. The closed-loop control mechanism enabled stable regulation of converter output voltage and charging current, thereby ensuring efficient charging operation with improved dynamic response characteristics. The pulse-generator-driven switching control further contributed to smooth converter operation and reduced steady-state oscillations during the charging process. Simulation analysis performed in MATLAB/Simulink demonstrated that the proposed system achieved stable photovoltaic voltage, regulated charging current, and efficient power transfer throughout the charging interval. The supercapacitor charging characteristics confirmed rapid energy absorption capability with stable voltage and State of Charge (SOC) variation. The charging process remained smooth and controlled without significant fluctuations, indicating improved converter stability and reliable system operation.

The obtained results also verified that the PSO algorithm provided faster convergence toward the maximum power point with enhanced tracking accuracy compared with conventional MPPT approaches. The adaptive optimization capability of the controller improved the overall efficiency of the charging system while minimizing energy loss during power conversion. Overall, the proposed closed-loop PSO-MPPT-controlled charging architecture demonstrated reliable operation, efficient photovoltaic power extraction, improved converter performance, and stable supercapacitor charging behavior. The system offers a suitable solution for high performance renewable energy-based EV charging applications requiring rapid charging capability, efficient energy management, and improved operational stability.

Extensions of this work in the future could consider dynamic environmental conditions to study the robustness of the controller under varying irradiance and temperature. More advanced techniques for maximum power point tracking (MPPT) can be employed in future studies such as adaptive, hybrid or AI-based algorithms to allow for quicker power tracking and lower steady state error. Hardware-in-the-loop (HIL) testing or implementation at prototype level would allow for better practical verification of the proposed system. Future work could also include battery thermal modelling, state of charge (SOC) estimation and health-aware charging to allow improved safety while charging at more rapid rates. Additionally, expansion of the system to include bidirectional converters may allow for vehicle-to-grid (V2G) and vehicle-to-home (V2H). Moreover, hybrid PV–grid connected systems, energy storage integration and designs for higher power converters could also be explored to further facilitate commercial deployment in EV charging stations.

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