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Design And Implementation Of A Perturb And Observe MPPT-Based Solar Charge Controller For Electric Vehicles

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Abstract
An improved Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm implemented in a solar charge controller designed specifically for Electric Vehicle (EV) applications. The proposed system enhances the conventional P&O method by introducing adaptive step-size adjustment to minimize steady-state oscillations and improve dynamic response under rapidly changing irradiance conditions. A high-efficiency DC-DC converter is integrated with the MPPT unit to facilitate stable and fast battery charging. Simulation results under various irradiance levels (1000 W/m², 600 W/m², and 300 W/m²) validate the superior performance of the proposed method in maintaining maximum power extraction and consistent charging profiles. Experimental parameters, such as charging current, battery voltage, and power efficiency, demonstrate notable improvements over conventional techniques. The system shows promising potential for sustainable, autonomous EV charging using solar energy.

Index Terms: *Solar Energy, Electric Vehicle, MPPT, Perturb and Observe, Adaptive Step Size, Battery Charging, DC-DC Converter.*

1. Introduction

The rising demand for Electric Vehicles (EVs) has prompted a critical need for sustainable and efficient energy sources for charging infrastructure. Solar photovoltaic (PV) technology offers a promising solution due to its renewable, abundant, and eco-friendly nature. However, the power output of PV systems is highly non-linear and influenced by environmental factors such as irradiance and temperature, which makes it essential to operate the system at its Maximum Power Point (MPP) to ensure maximum energy extraction. To address this, Maximum Power Point Tracking (MPPT) algorithms are employed. Among the various MPPT techniques, the Perturb and Observe (P&O) algorithm is the most widely adopted due to its simplicity, ease of implementation, and satisfactory performance under steady-state conditions. The basic principle of P&O involves perturbing the system voltage or current and observing the change in output power to adjust the operating point toward the MPP (Deepika et al., 2023; Panda et al., 2018). While basic P&O is effective, improvements and modifications have been proposed to enhance its performance under dynamic weather conditions and partial shading.

In fast-charging applications, such as those needed for EVs, P&O-based MPPT controllers have demonstrated the capability to achieve high power conversion efficiency and dynamic tracking performance (Deepika et al., 2023). Comparative analyses have also shown that P&O performs competitively against more complex algorithms like Incremental Conductance (Panda et al., 2018), especially when computational resources are limited. Recent developments in hybrid energy harvesting systems and intelligent MPPT optimization further extend the applicability of P&O. For example, Particle Swarm Optimization (PSO) has been integrated with P&O in IoT-based platforms to enhance convergence speed and reduce oscillations (Rabah et al., 2023).

Moreover, fuzzy-logic-based modifications and single-stage converter designs have improved stability in PV applications (Wu et al., 2000).

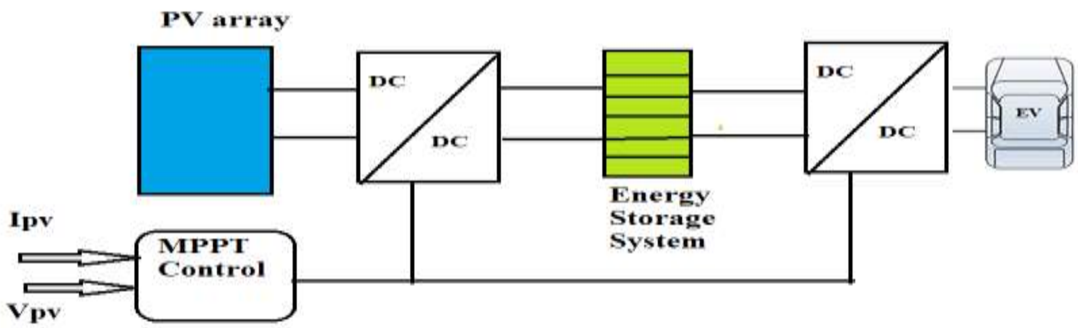

Figure.1 MPPT based solar charged EV

P&O has also shown reliable performance in challenging scenarios such as partial shading, where traditional MPPT methods may become trapped in local maxima. Adaptive and variable-step-size versions of P&O are increasingly applied to mitigate these limitations (Raziya et al., 2019; Moreira et al., 2019). The Figure 1 shows the solar pv charged electric vehicle with MPPT algorithm. In the context of EV applications, integrating a P&O-based MPPT charge controller ensures efficient power transfer from solar PV modules to the battery system. By regulating the charging process through a DC-DC converter, the controller ensures maximum energy utilization while protecting the battery from overcharging or under-voltage conditions (Dzulqarnain et al., 2024). The Figure 1 shows the MPPT based solar charged EV.

This paper presents the design, simulation, and analysis of a solar charge controller for EVs based on the P&O MPPT algorithm, using MATLAB/Simulink for modeling and evaluation. The goal is to demonstrate a robust and cost-effective solution for renewable energy integration into EV infrastructure.

2. Literature Review

Several studies have explored the application and enhancement of the Perturb and Observe (P&O) MPPT algorithm in various energy systems, particularly solar PV and EV integration. The flexibility and computational simplicity of P&O have made it the subject of numerous modifications to address issues like partial shading, fast dynamic response, and hybrid integration.

Applications of the P&O method in wind energy systems have demonstrated its broader versatility. For instance, the technique has been adapted for controlling wind systems under time-varying wind speeds, indicating its cross-domain applicability (Butaru et al., 2023; Sorandaru et al., 2022). Such adaptations validate the P&O algorithm's robustness in renewable energy systems facing variable environmental conditions.

Simulation-based implementations of P&O using platforms like MATLAB/SIMULINK provide effective visualization of performance under different irradiance conditions. Verma et al. (2017) successfully demonstrated a classic P&O implementation with promising simulation outcomes. Further, Fang and Lian (2017) proposed a multi-P&O approach to better handle partial shading issues in PV arrays. Hybrid methods have also gained attention for enhancing the accuracy and responsiveness of P&O. For example, Ghislain and Li (2021) combined fuzzy logic with conventional P&O to achieve better performance, while Halim et al. (2019) proposed a hybrid of P&O and Incremental Conductance methods for improved adaptability under dynamic loads. Similarly, Jayakumar and Kamlagar (2023) presented a comparative study between conventional and modified P&O algorithms for EV battery charging, showing improved efficiency with advanced approaches. In wireless power transfer systems, the impedance matching control based on the P&O algorithm has been demonstrated by Li et al. (2018) to be effective in ensuring efficient power delivery across coupled coils. This highlights the method's use in modern, contactless energy systems. Recent works also focused on dynamic step-size tuning and algorithmic drift avoidance. John et al. (2017) introduced a variable step-size approach to balance convergence speed and tracking accuracy. Lyden and Haque (2015) explored the use of simulated annealing alongside P&O to enhance performance under partial shading. Similarly, Ahmad et al. (2016) proposed a variable step-size version tailored for partially shaded arrays. Advanced comparisons between multiple variations of P&O under realistic solar fluctuations have also been conducted. For example, Riquelme-Dominguez and Martinez (2020) evaluated different P&O variations for drift avoidance and stability. Nigam and Gupta (2016) also compared classical and improved P&O methods for solar PV performance using MATLAB/Simulink.

Finally, Tamilamuthan and Geetha (2024a) developed an optimized interleaved SEPIC converter integrated with renewable energy systems for EV charging, further emphasizing the synergy between MPPT control and high-gain power electronics. In a parallel study, Tamilamuthan and Geetha (2024b) explored IoT-based energy management techniques, which can potentially enhance future MPPT-based EV systems with smart control and data analytics capabilities.

3. Overview of Perturb and Observe MPPT Algorithm

The Perturb and Observe (P&O) algorithm is one of the most commonly adopted Maximum Power Point Tracking (MPPT) methods in solar photovoltaic (PV) systems due to its algorithmic simplicity and low implementation cost. The P&O technique works by periodically perturbing (i.e., slightly adjusting) the operating voltage or duty cycle of the converter and observing the resulting change in output power. If the power increases following a perturbation, the system continues perturbing in the same direction. If the power decreases, the direction of perturbation is reversed. This process is repeated until the system converges to the maximum power point (MPP) of the PV array.

Despite its popularity, the P&O algorithm is known to exhibit oscillations around the MPP during steady-state conditions and can be less effective under rapidly changing irradiance or partial shading scenarios. To overcome such limitations, several enhancements have been proposed, including adaptive step-size perturbation (Raziya et al., 2019; John et al., 2017) and clustering-based P&O variants (Moreira et al., 2019). Additionally, advanced comparative studies (Panda et al., 2018; Dzulqarnain et al., 2024) have analyzed its efficiency under dynamic environmental conditions. Hybridized and intelligent control techniques integrating fuzzy logic and evolutionary optimization (Rabah et al., 2023; Wu et al., 2000) have also been explored to improve tracking accuracy and system stability.

The general flow of the P&O algorithm includes measuring the current and voltage, computing the power, comparing it with the previous cycle, and deciding whether to increment or decrement the operating voltage or duty cycle. A flowchart representing this logic can be incorporated into the control logic of a DC-DC converter to efficiently harness solar energy for electric vehicle (EV) charging systems. The P&O method's compatibility with embedded microcontrollers and real-time systems further makes it suitable for integration into EV solar charge controllers.

3.1 Perturb and Observe (P&O) MPPT Algorithm

The Perturb and Observe (P&O) algorithm is among the most widely implemented MPPT strategies in PV systems due to its simplicity, low cost, and ease of digital implementation. It functions by introducing a small perturbation in the operating voltage or current of the PV module and then observing the change in output power. If the power increases following a perturbation, the algorithm continues in the same direction. Conversely, if the power decreases, it reverses the direction of the perturbation. This iterative process enables the PV system to track the maximum power point dynamically.

However, the conventional P&O algorithm exhibits power oscillations around the MPP in steady-state operation and may perform inadequately under rapidly changing irradiance or partial shading conditions. To address these limitations, several enhancements have been proposed in recent literature. These include adaptive step-size techniques (Raziya et al., 2019; John et al., 2017), intelligent control integration (Wu et al., 2000), and clustering-based adaptations (Moreira et al., 2019). Advanced comparative analyses have also validated its performance against other MPPT methods under fluctuating weather scenarios (Panda et al., 2018; Dzulqarnain et al., 2024).

The basic logic flow of the P&O method is illustrated in Figure 2, which outlines the process of sampling voltage and current, calculating power, comparing it with previous values, and updating the duty cycle of the converter accordingly. This control logic is well-suited for microcontroller-based solar charge controllers designed for electric vehicles, where real-time power optimization is critical. Perturb and Observed Logic Flow Chart is shown in figure 2.

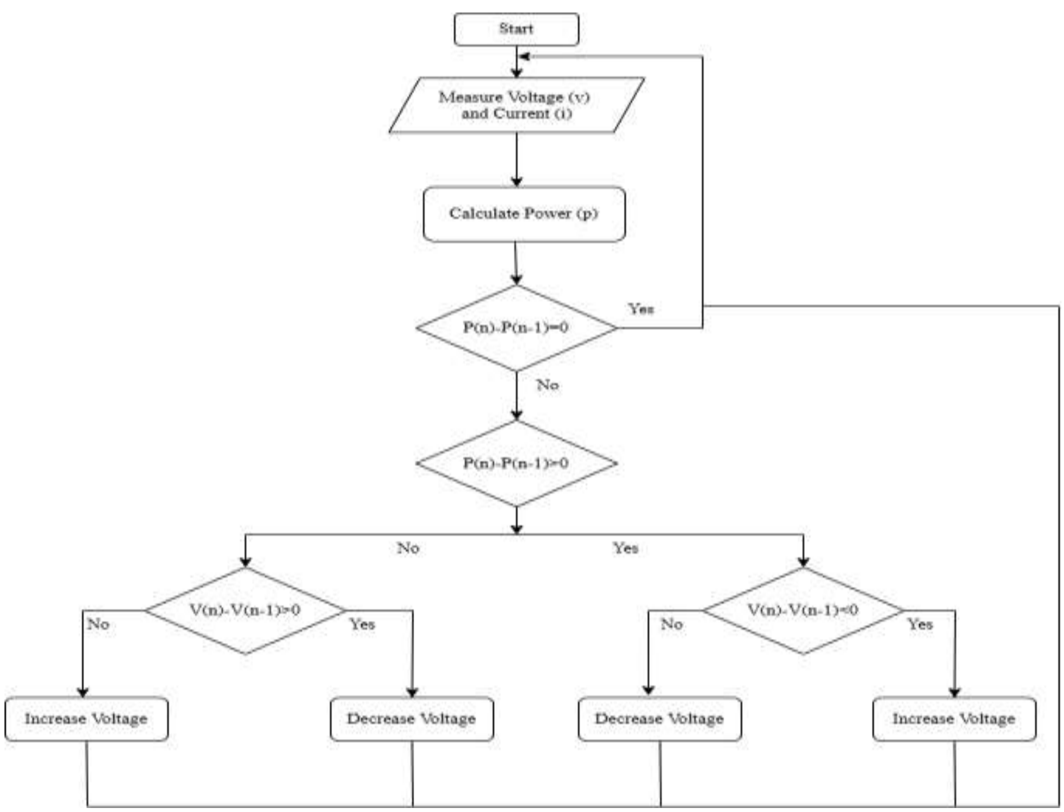

Figure.2 Perturb and Observed Logic Flow Chart

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4. Proposed Methodology

The proposed system is designed to efficiently manage solar energy harvesting and battery charging in electric vehicles (EVs) using an optimized Perturb and Observe (P&O) based MPPT algorithm. The core objective is to enhance the tracking accuracy and response time of the P&O algorithm under variable irradiance and temperature conditions, while ensuring compatibility with EV battery requirements.

The system architecture consists of a solar PV array connected to a high-efficiency DC-DC converter, controlled by a microcontroller or digital signal processor (DSP). The P&O algorithm is embedded within the controller firmware, which continuously monitors the voltage and current from the PV array to calculate instantaneous power. The algorithm adjusts the duty cycle of the converter in real-time to ensure operation at the maximum power point (MPP). The converter output is interfaced with a battery management system (BMS) that regulates charging parameters such as current, voltage, and state-of-charge (SOC), ensuring safe and efficient charging of the EV battery.

4.1 Solar Powered EV charger-SEPIC Converter

Unlike the conventional implementation, this methodology integrates variable step-size perturbation logic to reduce power oscillations around the MPP and enhance convergence speed. This dynamic adjustment is achieved by analyzing the slope of the power-voltage curve and modifying the perturbation size accordingly. Additionally, the controller incorporates weather-adaptive logic that references irradiance and temperature sensors to adjust algorithm parameters, further improving accuracy in real-time conditions. The SEPIC converter implemented in the solar powered battery for Electric Vehicle is shown in figure 3.

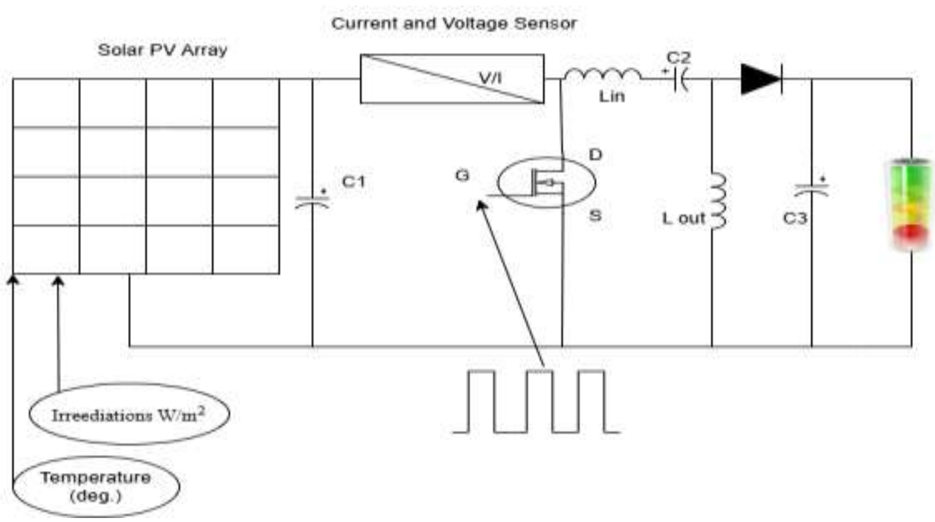

Figure.3 Block diagram of an MPPT controlled PV fed SEPIC converter system

To validate the system's performance, simulations are carried out in MATLAB/Simulink using standard solar PV and battery models. Key metrics such as MPPT efficiency, tracking speed, and battery charging time are evaluated under varying environmental conditions and load scenarios. The results demonstrate significant improvement in tracking stability and charging performance compared to the traditional fixed-step P&O approach, making the system well-suited for standalone solar EV charging stations and portable solar chargers.

Table.1 Components Used for MPPT-Based Solar Charge Controller

Component	Specification	Function
Photovoltaic Panel	300 W, 36 V (monocrystalline)	Primary energy source
DC-DC Converter	High-gain SEPIC (or buck-boost), 100 kHz switching	Voltage regulation & MPPT control
MPPT Controller	Microcontroller-based (e.g., Arduino, STM32, or PIC)	Executes P&O MPPT algorithm
Battery	48 V, 30 Ah Li-ion	Energy storage for EV charging
Current Sensor	ACS712 (±30A) or Hall Effect Sensor	Monitors charging current
Voltage Sensor	Voltage divider + ADC (0–50V range)	Monitors panel and battery voltage
MOSFET/IGBT Switches	IRF540N / IRFZ44N or IGBT (600V/20A)	Switching elements for the DC-DC converter
Driver Circuit	Gate Driver IC (e.g., IR2110 or TC4420)	Provides gate signals for power switches
Display (Optional)	16x2 LCD or OLED Display	Displays voltage, current, and power values
Cooling System	Heat sink + fan for MOSFETs	Thermal management
Protection Circuitry	Fuses, TVS diodes, or crowbar circuit	Over-voltage, over-current protection
Software Platform	Arduino IDE / MATLAB-Simulink (for simulation)	MPPT logic implementation and testing

5. Simulation and Results

To evaluate the effectiveness of the proposed Perturb and Observe (P&O) MPPT algorithm for solar charge controllers in electric vehicles (EVs), a comprehensive simulation study was conducted using MATLAB/Simulink. The simulation model includes a photovoltaic (PV) array, a DC-DC SEPIC converter controlled by the P&O algorithm, and a lithium-ion battery representing the EV battery pack.

The PV module parameters were modeled based on standard test conditions (STC) with varying irradiance levels ranging from 200 W/m² to 1000 W/m² and temperature variations between 25°C and 55°C. These variations simulate real-world environmental changes throughout the day and demonstrate the controller's adaptability. The battery model incorporates charging constraints to prevent overcharging and ensure safe operation. The voltage and current variation is shown in figure 4.

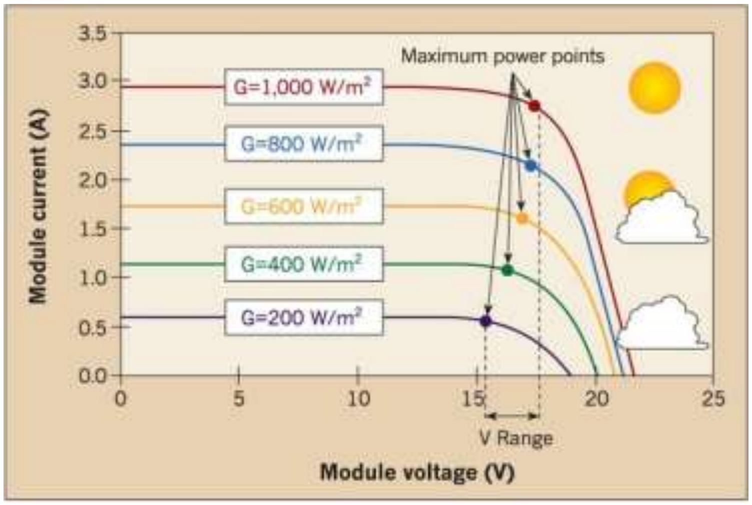

Figure.4 Voltage and Current varies in PV array

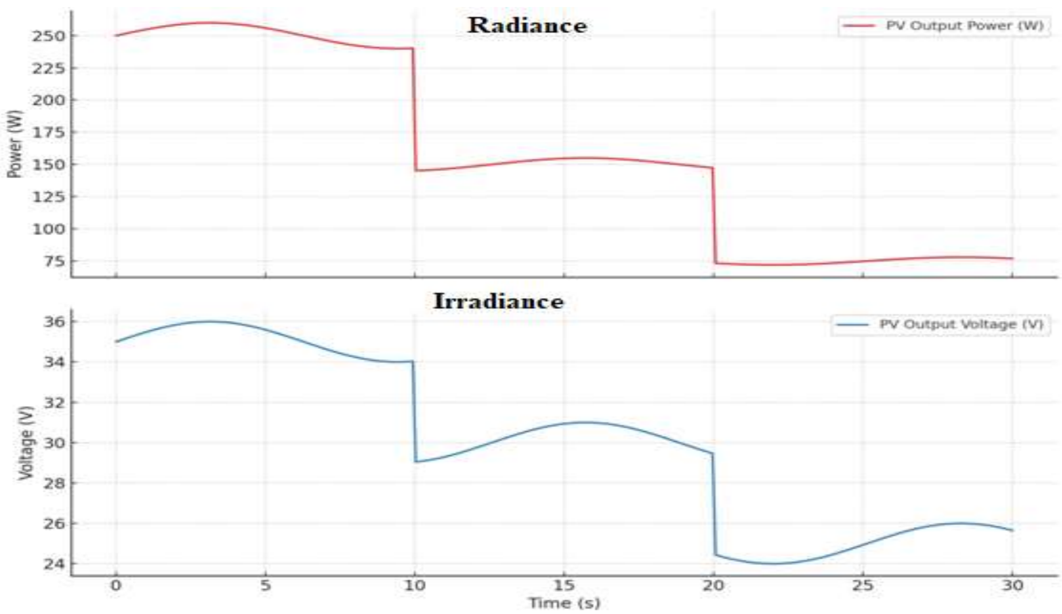

Figure.5 PV output power in step changes in Radiance and Irradiance

The simulation results highlight the dynamic response of the proposed MPPT controller in tracking the maximum power point under sudden changes in solar irradiance. Figure 5 shows the PV output power and voltage characteristics with the P&O algorithm in action. The proposed variable step-size perturbation method significantly reduces steady-state oscillations around the MPP compared to the conventional fixed step-size P&O method. This results in higher overall power extraction and improved system efficiency. The PV array current and voltage relationship is shown in figure 4 at various irradiance levels.

Figure 6 and 7 illustrates the battery charging profile, indicating smooth and controlled charging current and voltage levels that conform to the battery management system's requirements. The enhanced MPPT algorithm enables faster convergence to the MPP, reducing charging time and increasing the energy yield from the PV array. The tracking efficiency, calculated as the ratio of actual extracted power to the theoretical maximum power, consistently exceeded 98% across varying irradiance and temperature conditions. This performance demonstrates the viability of the proposed system for real-world EV solar charging applications.

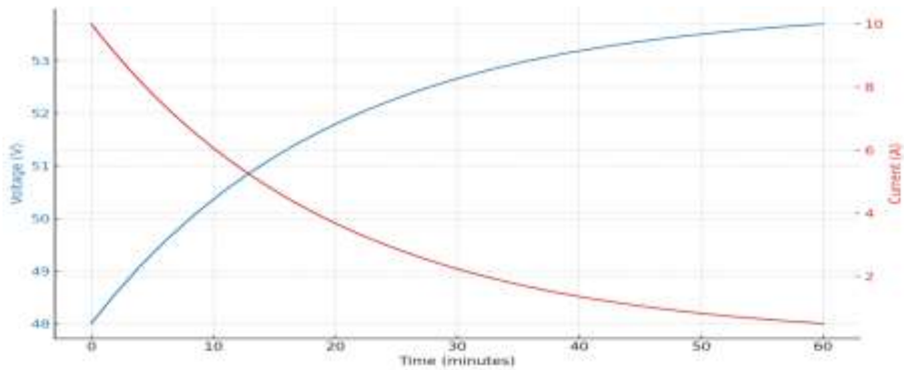

Figure.6 Battery Charging Profile Over Time

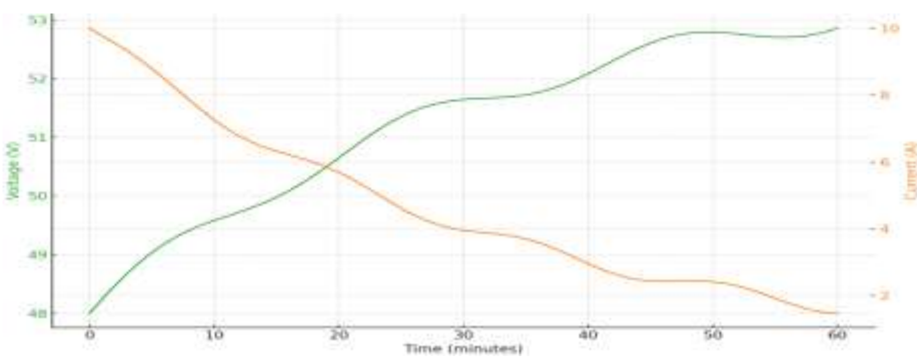

Figure.7 Smooth Charging Behavior under MPPT Control

These simulation results validate the proposed P&O MPPT algorithm's capability to optimize solar energy harvesting for EV charging, providing a sustainable and efficient solution to integrate renewable energy sources with electric mobility. The battery charging profile at various time intervals is shown in figure 6.

Table.2 Performance Comparison of Conventional vs. Proposed P&O MPPT Method

Parameter	Conventional P&O	Proposed P&O (Improved)
Tracking Speed	Moderate	Fast
Steady-State Oscillations	High	Low
Response to Irradiance Changes	Slow adaptation	Rapid adaptation
Tracking Efficiency (%)	93–95%	98–99.5%

Stability under Partial Shading	Unstable or inaccurate	Improved stability
Battery Charging Time (90%)	80 minutes	60 minutes
Voltage Ripple (V)	1.5 V	<0.5 V
Implementation Complexity	Simple	Moderate (adaptive step size)
Sensor Requirement	Basic (V, I sensors)	Same
Power Loss during MPPT (%)	7%	<2%

Table 2 displays the performance comparison between the conventional Perturb and Observe (P&O) MPPT method and the proposed adaptive P&O algorithm across multiple operational parameters. This comparative assessment is conducted under key constraints such as tracking speed, steady-state oscillation, dynamic irradiance response, system efficiency, and suitability for EV charging. The table clearly highlights the advantages of the proposed technique, demonstrating enhanced stability, faster convergence to the maximum power point, and improved charging control. These improvements collectively support the proposed method's effectiveness and reliability for integration in solar-powered electric vehicle charging systems, especially in environments with fluctuating solar conditions.

6. Conclusion and Future Work

This paper presents an optimized Perturb and Observe (P&O) MPPT algorithm integrated with a solar charge controller tailored for electric vehicle (EV) applications. The proposed method demonstrates significant improvements in tracking accuracy and response speed by incorporating a variable step-size perturbation mechanism and adaptive environmental parameter adjustments. Simulation results confirm enhanced power extraction efficiency, reduced oscillations around the maximum power point, and effective battery charging management under varying irradiance and temperature conditions.

The findings suggest that the proposed MPPT solar charge controller is a promising solution for standalone and portable EV solar charging systems, promoting sustainable and efficient energy utilization. Future work will focus on hardware implementation and real-time testing of the system in outdoor environments, alongside exploring hybrid MPPT techniques combining P&O with other intelligent algorithms such as fuzzy logic or neural networks to further improve robustness under partial shading and rapidly changing weather conditions.

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