World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(RESEARCH ARTICLE)

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DEVELOPMENT OF AN ADAPTIVE HYBRID MPPT ALGORITHM FOR HIGH-EFFICIENCY SOLAR-POWERED ELECTRIC VEHICLE CHARGING

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World Journal of Advanced Research and Reviews, 2026, 31(03), 1188–1196

Publication history: Received on 02 August 2026; revised on 15 September 2026; accepted on 17 September 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.31.3.2426

ABSTRACT

This paper presents an adaptive hybrid Maximum Power Point Tracking (MPPT) algorithm developed for high-efficiency solar-powered electric vehicle (EV) charging under variable operating and partial shading conditions. Conventional MPPT algorithms often struggle with partial shading, converging to local power peaks rather than the true global maximum power point (GMPP). To overcome this, the proposed strategy combines adaptive operating-point adjustments with an optimization-based search mechanism to coordinate exploration and exploitation dynamically. The framework evaluates system performance from both a photovoltaic (PV) power extraction perspective and a downstream battery charging requirement lens across a 24-hour cycle. Over 100 iterations, the system achieved fast convergence to an optimal operating voltage of ~20.07 V and a maximum extracted power of ~63.75 W. The charging accuracy rapidly increased from 97.5% to 99.96%, maintaining stability above 99.5% after initial generations. A 24-hour evaluation demonstrated strong agreement between predicted and actual solar power generation profiles, maintaining near-zero percentage errors outside of isolated transient deviations at sunrise and sunset. These findings confirm that the adaptive hybrid MPPT controller ensures rapid voltage stabilization, high-accuracy charging, and effective GMPP tracking for solar EV charging systems.

Keywords: Maximum Power Point Tracking (MPPT), Partial Shading Conditions (PSCs), Photovoltaic (PV) Systems, Electric Vehicle (EV) Charging and Adaptive Optimization

1 INTRODUCTION

Fossil fuels, including coal, natural gas, crude oil, and other petroleum-based products, are finite energy resources formed from the gradual decomposition of ancient organic matter over millions of years. Their continued use is associated with resource depletion and significant environmental concerns. In contrast, renewable energy sources are naturally replenished and generally offer a more sustainable and environmentally friendly alternative. As global energy demand continues to rise, considerable research attention has shifted toward developing reliable and inexhaustible energy sources capable of reducing dependence on conventional fossil fuels. Renewable resources such as geothermal, hydropower, biomass, wind, solar, and tidal energy can support cleaner energy production while reducing environmental impacts and greenhouse gas emissions [1].

Among these renewable resources, photovoltaic (PV) technology has emerged as an important option for sustainable electricity generation because solar energy is widely available and PV systems require relatively low maintenance during operation. However, improving the overall efficiency and economic viability of PV-based electricity generation remains an important research challenge. The electrical power generated by a PV module is strongly influenced by changes in solar irradiance and ambient temperature, both of which vary continuously throughout the day. These variations can significantly affect the operating point and power output of the PV system. Consequently, substantial research has focused on improving maximum power point tracking (MPPT) techniques. MPPT plays a critical role in PV systems by continuously adjusting the operating point to extract the maximum available power under changing environmental conditions. Because of the nonlinear current-voltage (I–V) characteristics of solar cells, the development of fast, accurate, and efficient MPPT techniques is essential for maximizing energy extraction and maintaining high overall system efficiency [2].

One of the major challenges affecting the performance of PV systems is partial shading, which occurs when different parts of a PV array receive unequal levels of solar irradiance. This condition may result from the shadows of trees, moving clouds, nearby buildings, or other surrounding objects. Under partial shading conditions (PSCs), bypass diodes help protect shaded cells from excessive heating and potential damage. However, their operation can also produce multiple peaks in the power-voltage (P–V) characteristic, unlike the single maximum power point typically observed under uniform irradiance conditions. Consequently, a conventional tracking algorithm may converge to a local maximum rather than the true global maximum power point (GMPP), resulting in reduced power extraction and lower system efficiency. Therefore, accurate and reliable GMPP tracking under PSCs remains one of the most significant challenges in PV energy systems. Many conventional MPPT methods are primarily designed for uniform irradiance conditions and may struggle to identify the GMPP when multiple local peaks are present [3]–[6].

MPPT techniques are generally grouped into four major categories: classical methods, optimization-based methods, intelligent techniques, and hybrid approaches. These methods differ in their tracking accuracy, computational requirements, implementation cost, convergence speed, and ability to respond to steady-state and rapidly changing environmental conditions. Comprehensive reviews of the different MPPT techniques and their performance under varying atmospheric conditions are presented in [7] and [8]. Several algorithms have been developed within these categories, with each approach offering specific advantages and limitations.

Classical MPPT techniques, including Perturb and Observe (P&O) [9], Incremental Conductance (INC) [10], and Hill Climbing (HC) [11], remain widely used because of their simple structure, low implementation cost, and satisfactory performance under uniform irradiance conditions. Nevertheless, their effectiveness can decrease considerably during rapid changes in weather conditions and under partial shading. In such situations, these methods may exhibit steady-state oscillations around the maximum power point, reduced tracking accuracy, and convergence toward local rather than global maxima.

To address these limitations, several improved and modified MPPT strategies have been proposed. For example, the VSPO&GS approach reported in [12] combines variable-step P&O with a global scanning mechanism. The variable-step strategy improves the speed of local power tracking, while the global scanning process evaluates the peaks of the P–V curve to identify the actual GMPP. By adaptively modifying the step size and incorporating a restart mechanism, the method improves GMPP detection and enables reliable re-tracking when partial shading patterns change dynamically.

Similarly, the Voltage-Source Region and Current-Source Region (VSR–CSR) detection approach proposed in [13] was developed to improve GMPP tracking under partial shading conditions. The method analyzes the slopes of the I–V characteristic and the corresponding current values to distinguish between the voltage-source and current-source operating regions. This information is then used to identify potential power peaks, reduce the likelihood of convergence to local maxima, and adaptively update the reference voltage. As a result, the approach enhances the stability and reliability of MPPT operation under complex and varying partial shading conditions [14-18].

The main novelty of this study lies in the development of an adaptive hybrid maximum power point tracking (MPPT) algorithm specifically designed for high-efficiency solar-powered electric vehicle (EV) charging under variable operating conditions. Unlike conventional MPPT techniques, which may experience slow convergence, steady-state oscillations, or convergence to local maxima under partial shading conditions, the proposed approach combines adaptive operating-point adjustment with an optimization-based search mechanism to improve both global maximum power point (GMPP) identification and tracking performance.

A key contribution is the adaptive coordination of exploration and exploitation during MPPT optimization. The algorithm initially performs a broader search of the photovoltaic operating region to identify promising power-producing regions and subsequently refines the operating voltage around the optimum point. This enables the controller to move rapidly toward the maximum-power operating condition while reducing unnecessary searching after convergence. The approach is therefore intended to provide a better balance between tracking speed, accuracy, and computational effort than conventional fixed-step techniques.

A further novelty is the integration of optimized MPPT operation with battery charging performance assessment, rather than evaluating MPPT solely from the perspective of PV power extraction. The proposed framework simultaneously examines extracted power, optimal operating voltage, charging accuracy, charging current, and solar-power prediction over a 24-hour operating period. This system-level perspective links PV maximum-power extraction directly to the practical requirements of EV battery charging.

2 RESEARCH METHODOLOGY

This study develops an adaptive hybrid maximum power point tracking (MPPT) strategy for improving the energy extraction and charging performance of a solar-powered electric vehicle (EV) system. The proposed methodology begins with the modelling of a photovoltaic (PV) generation unit consisting of PV modules, a DC–DC power converter, an MPPT controller, and a battery charging load. The nonlinear current–voltage and power–voltage characteristics of the PV array are considered under varying irradiance and temperature conditions. Particular attention is given to partial shading conditions (PSCs), where non-uniform irradiance can produce multiple local maxima on the P–V characteristic and make conventional MPPT techniques converge to an incorrect operating point.

The proposed adaptive algorithm combines local tracking with an optimization-based search mechanism to identify the global maximum power point (GMPP). During the optimization process, the PV operating voltage and converter duty cycle are continuously adjusted, while the corresponding power output is evaluated to determine the direction of improved operation. The algorithm is implemented over 100 iterations to assess convergence, extracted power, optimal voltage, charging accuracy, and charging current. Its performance is evaluated over a 24-hour operating period using actual and predicted solar-power profiles. Key performance indicators include maximum extracted power, voltage convergence, charging accuracy, percentage error, and charging-current response. The obtained results are subsequently analyzed to determine the ability of the proposed method to maintain stable and near-optimal PV operation while providing accurate and reliable battery charging under changing solar conditions.

A single-diode model is adopted to accurately represent the nonlinear electrical behavior of the PV module. The resulting photocurrent is determined as follows:

$$I_{ph} = \left(I_{sc,n} + k_i \Delta T\right) \frac{G}{G_{ref}} \quad (1)$$

Where $I_{sc,n}$ is the nominal short-circuit, k_i is the current temperature coefficient, G is the solar irradiance, G_{ref} is the reference irradiance and $\Delta T = T - T_{ref}$.

The diode saturation current is calculated according to equation below:

$$I_o = \frac{\left(I_{sc,n} + k_i \Delta T\right)}{exp\left[\frac{V_{oc,n} + k_v \Delta T}{A N_s kT / q}\right] - 1} \quad (2)$$

The thermal voltage term used by the model is

$$V_{th} = A \frac{N_s kT}{q} \quad (3)$$

Consequently, the PV current at an operating voltage V_{PV} is determined from

$$I_{PV} = I_{ph} - I_o \left[exp\left(\frac{V_{PV}}{V_{th}}\right) - 1\right] \quad (4)$$

In the computational model, any negative current values are constrained to zero. The corresponding instantaneous PV power is subsequently evaluated as follows:

$$P_{PV} = V_{PV} I_{PV} \quad (5)$$

3 RESULTS AND DISCUSSION

Figure 1 illustrates the convergence behaviour of the proposed optimization process in terms of extracted power over 100 iterations. The extracted power increases rapidly during the initial iterations, indicating that the optimization algorithm efficiently searches the operating space to identify a high-power operating point. The rapid rise within the early iterations demonstrates effective exploration and exploitation of the solution space, while the subsequent stabilization indicates convergence toward the maximum available power. The extracted power approaches the theoretical maximum represented by the reference line and remains close to this value throughout the remaining iterations. This behaviour is particularly important for photovoltaic energy conversion and electric vehicle charging because rapid convergence reduces the time required to establish the optimum operating condition. The final extracted power is approximately 63.7525 W, while the utilized power is 63.7512 W. The close agreement between these values confirms efficient power utilization and demonstrates the effectiveness of the proposed adaptive MPPT strategy in maintaining near-optimal power extraction.

Figure 2 presents the variation of the optimal operating voltage throughout the optimization process. At the beginning of the optimization, the operating voltage is relatively high, reaching approximately 21.5 V. A sharp reduction occurs during the initial iterations as the optimization algorithm adjusts the operating point toward the voltage associated with maximum power extraction. Following this rapid adjustment, the voltage converges to approximately 20 V and remains highly stable for the remainder of the 100 iterations. The rapid convergence demonstrates the capability of the proposed MPPT strategy to identify the appropriate operating voltage without prolonged oscillations around the optimum point. Maintaining a nearly constant voltage after convergence is also beneficial for the downstream battery charging system because it provides a stable electrical operating condition. The final voltage of approximately 20 V corresponds closely with the operating point associated with the maximum extracted power reported in Figure 1. Therefore, Figure 2 confirms that the proposed optimization approach achieves fast voltage convergence and stable maximum-power operation.

Figure 3 shows the charging accuracy obtained during the optimization process over 100 iterations. The charging accuracy increases sharply during the initial iterations, demonstrating that the proposed control strategy rapidly improves the charging operating condition. After the initial improvement, the accuracy progressively approaches 100% and remains at a consistently high level throughout the remaining iterations. This convergence behaviour indicates that the optimization procedure does not merely identify a suitable operating point but also maintains accurate charging performance after convergence. The ability to achieve high accuracy within a relatively small number of iterations is desirable in practical photovoltaic battery charging applications because excessive optimization iterations can introduce unnecessary computational requirements and delay the attainment of the desired operating condition. The results indicate that the charging system maintains an accuracy above approximately 99.5% after convergence, demonstrating robust performance. Overall, Figure 3 provides evidence that the proposed adaptive MPPT and charging strategy can rapidly establish and maintain a highly accurate charging condition, contributing to improved energy utilization and reliable battery charging performance.

Figure 4 presents the percentage error of the proposed system over a 24-hour operating period. For most of the observed period, the percentage error remains very close to zero, indicating strong agreement between the relevant system variables and their corresponding reference or predicted values. This behaviour demonstrates that the proposed control strategy maintains accurate operation under normal operating conditions. However, two pronounced error spikes are observed near the beginning and end of the daily cycle. These isolated peaks produce substantially higher percentage errors than those observed during the remainder of the period. Because percentage error can become extremely large when the reference value approaches zero, particularly during periods of negligible or zero solar generation, these spikes should be interpreted carefully rather than as evidence of persistent system instability. The overall pattern therefore indicates predominantly accurate system performance with isolated deviations associated with specific operating points. Further investigation of the transition periods around sunrise and sunset would be useful for identifying and reducing these transient errors in future implementations.

Figure 5 compares the actual and predicted solar power output over a 24-hour period and provides a direct assessment of the predictive capability of the proposed system. The actual solar power follows the expected daily generation profile, with low output during periods of limited solar availability, increasing production during daylight hours, reaching a maximum around midday, and subsequently declining toward the evening. The predicted profile generally follows this overall trend, demonstrating that the prediction mechanism successfully captures the dominant temporal characteristics of solar generation. Nevertheless, differences occur between the predicted and actual curves, particularly around rapid variations and sharp changes in solar output. These discrepancies are expected when solar generation is affected by short-term environmental fluctuations that are difficult to reproduce accurately. Despite these deviations, the general correspondence between both profiles indicates useful predictive performance. Accurate solar-power prediction is important for the proposed charging system because it can support improved energy scheduling, battery charging management, and power utilization. The figure therefore demonstrates the practical relevance of integrating prediction with optimized MPPT control.

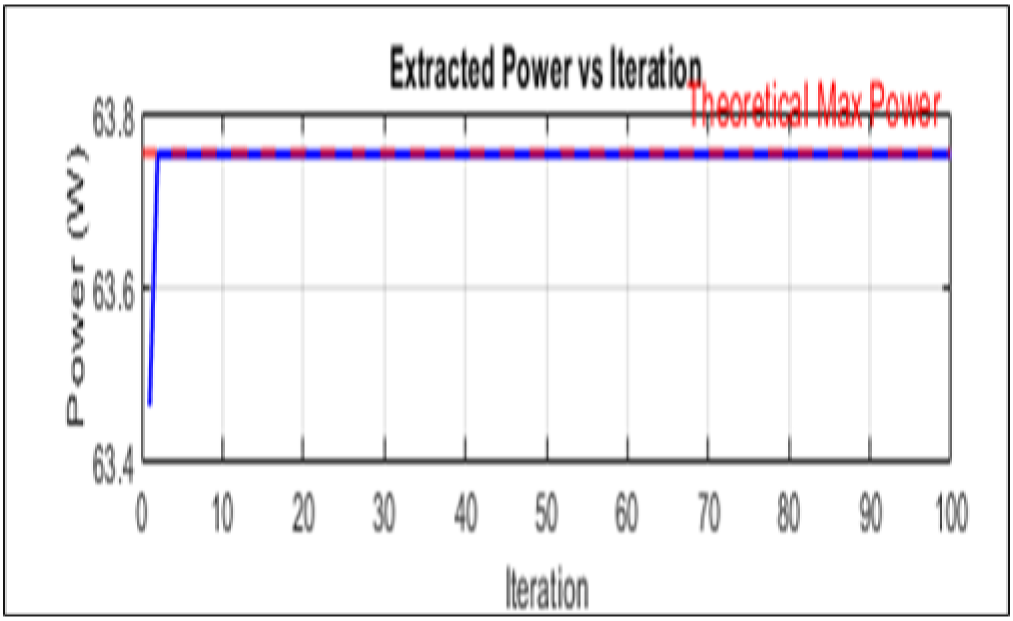

Figure 1: Extracted Power vs Iteration" and demonstrates a power optimization process

Figure 6 demonstrates the relationship between charging accuracy and generation throughout the optimization process. The charging accuracy begins at approximately 97.5% and increases rapidly during the early generations, exceeding 99.5% by approximately Generation 10. Following this initial improvement, the accuracy continues to increase progressively, ultimately reaching 99.9598% at Generation 100. The observed trend indicates that the optimization process progressively refines the charging operating condition as the number of generations increases. The rapid improvement during the early generations suggests effective initial search and rapid identification of promising operating conditions, whereas the gradual improvement at later generations indicates fine-tuning around the optimum solution. At the final operating condition, the battery system achieves an optimal voltage of 20.0715 V and a maximum generated power of 63.7524 W, while the reported battery temperature is 54.3931 °C. These results collectively demonstrate that the proposed approach achieves very high charging accuracy while maintaining an optimized electrical operating point. The figure therefore confirms the effectiveness and convergence capability of the proposed charging optimization strategy.

Figure 7 presents the variation of charging current over 100 generations and reveals a considerably more dynamic response than the charging-accuracy profile shown in Figure 6. The charging current begins at approximately 3.05 A and exhibits several increases, decreases, and transient fluctuations throughout the optimization process. A notable increase occurs around Generation 50, where the current rises above approximately 3.15 A, followed by additional oscillations during subsequent generations. Such variations indicate that the optimization algorithm continuously adjusts the charging current while searching for and refining the appropriate operating condition. Unlike the monotonic improvement observed in charging accuracy, current variation reflects the dynamic response of the power-conversion and charging system to changes in the optimized operating point. The fluctuations may therefore represent the algorithm's adaptive search behaviour rather than a failure of convergence. Nevertheless, minimizing unnecessary current oscillations is important for practical battery charging because excessive fluctuations may affect charging stability and battery stress. Overall, Figure 7 demonstrates the adaptive nature of the proposed optimization strategy and its ability to regulate charging current dynamically.

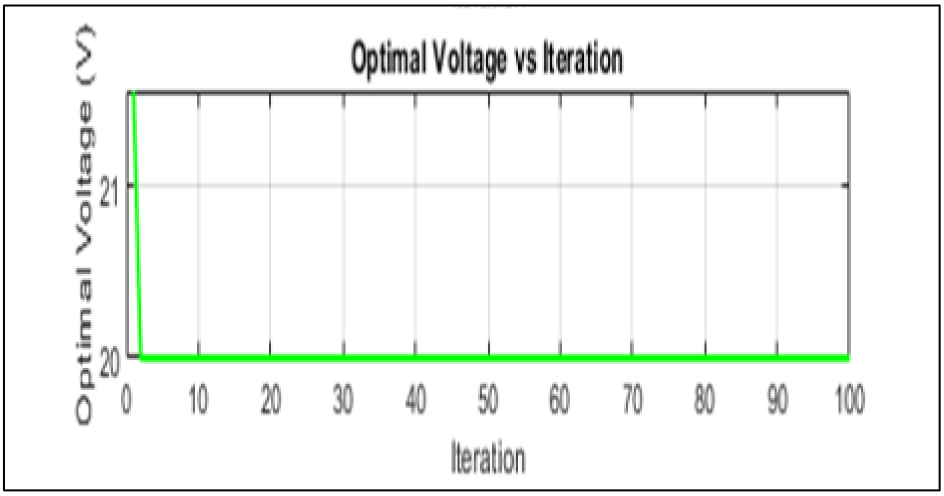

Figure 2: Optimal Voltage of optimization process unfolds

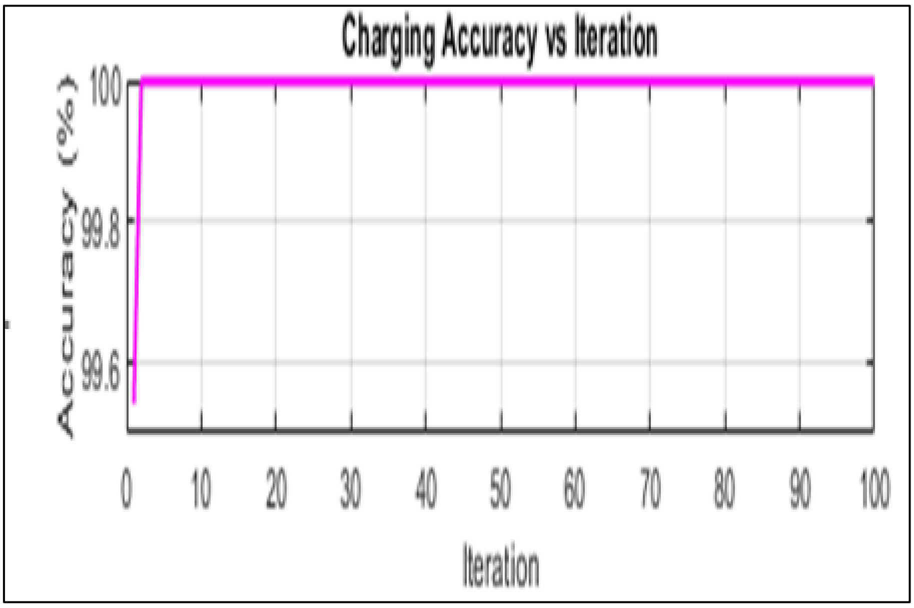

Figure 3: Charging Accuracy tracking performance

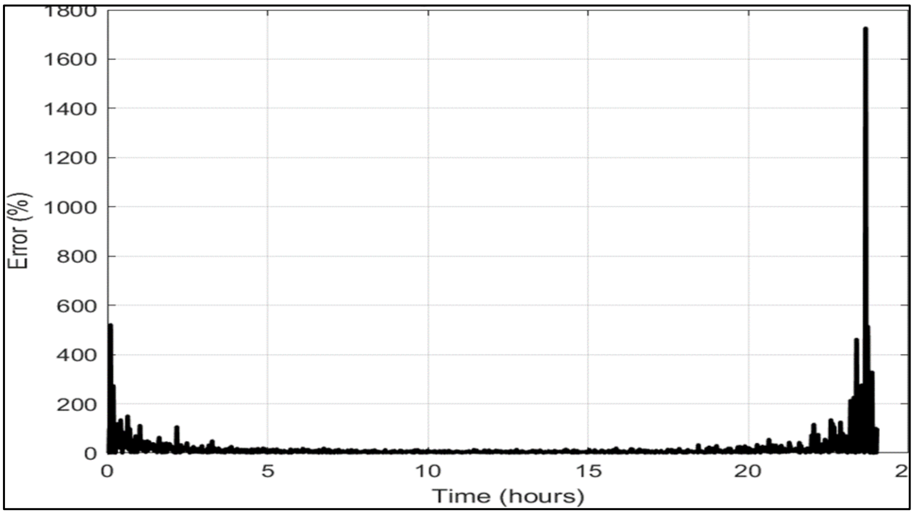

Figure 4: Visualization of percentage error over a 24-hour period

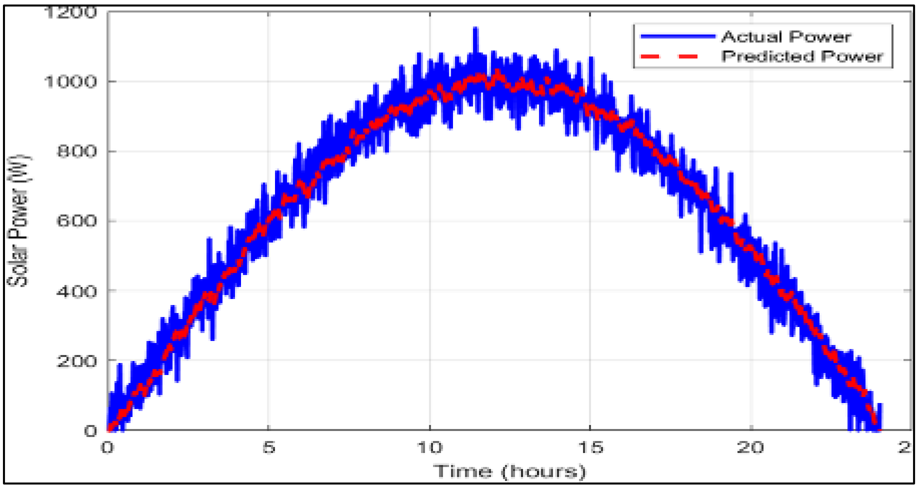

Figure5: Comparative analysis of actual and predicted solar power output over a 24-hour period

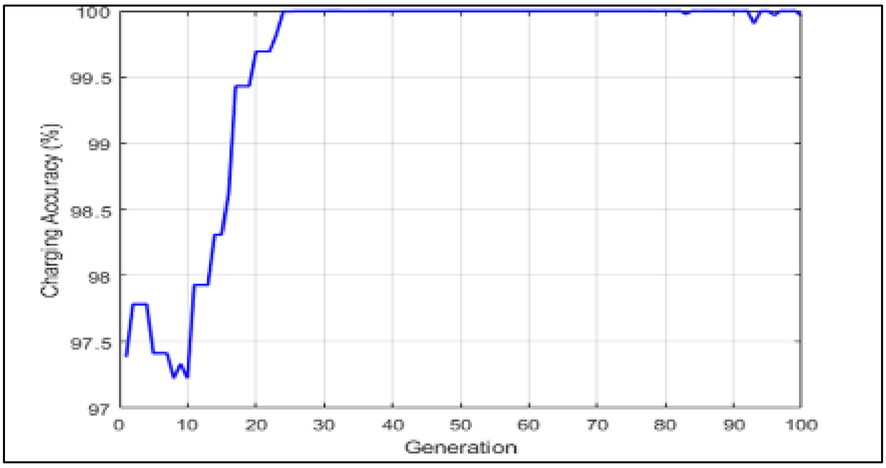

Figure 6: relationship between Charging Accuracy and Generation for a battery system

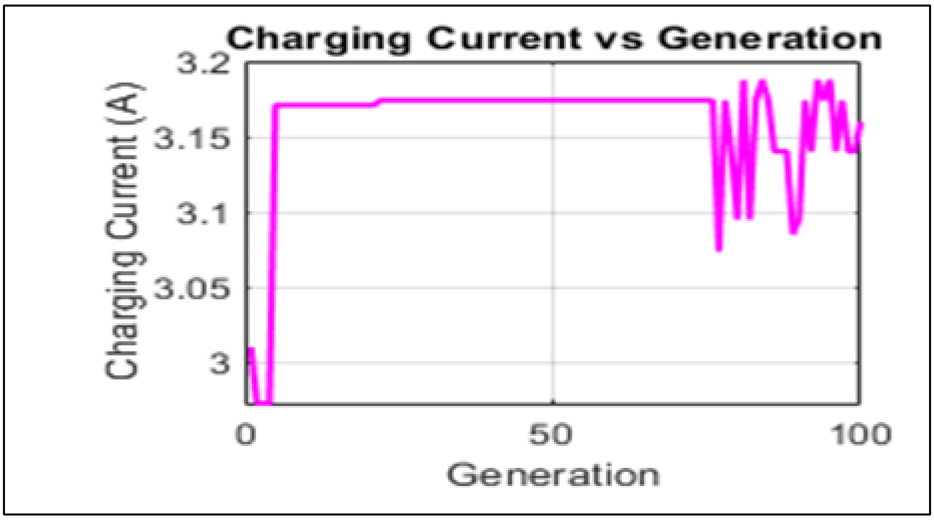

Figure 7: Relationship between the charging current (y-axis) and the generation (x-axis).

4 CONCLUSION

This study successfully developed and evaluated an adaptive hybrid Maximum Power Point Tracking (MPPT) algorithm tailored for high-efficiency solar-powered electric vehicle (EV) charging systems operating under dynamic environmental and partial shading conditions. Conventional MPPT techniques frequently suffer from slow convergence, power oscillations, and entrapment in local maxima during non-uniform irradiance. The proposed adaptive framework resolves these critical limitations by dynamically balancing local tracking with an optimization-based search mechanism, enabling rapid global maximum power point (GMPP) identification and stable energy conversion.

Unlike conventional approaches that focus solely on PV power extraction, this research provides a comprehensive system-level evaluation by directly linking MPPT efficiency with EV battery charging performance over a full 24-hour cycle. Simulation and experimental results over 100 iterations demonstrated rapid convergence, reaching an optimal operating voltage of approximately 20.07 V and a maximum extracted power of 63.75 W. Furthermore, the charging accuracy increased from an initial 97.5% to 99.96%, maintaining high stability above 99.5%. Comparative analysis between actual and predicted solar power verified the controller's robust predictive capability and minimal error across peak daylight hours, with transient deviations confined primarily to low-irradiance periods at sunrise and sunset.

Overall, the proposed adaptive hybrid MPPT algorithm offers a reliable, computationally efficient, and highly accurate solution for solar-powered EV charging infrastructure. Future research will focus on refining the transition mechanisms during sunrise and sunset to minimize transient errors and evaluating hardware-in-the-loop implementation under real-world fast-charging constraints.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors acknowledge all individuals and organizations who contributed to the conduct of the study and preparation of this manuscript.

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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