Enhanced incremental conductance MPPT method for maximizing photovoltaic power generation

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ABSTRACT

This research proposes an enhanced maximum power point tracking (MPPT) algorithm that integrates the variable step size (VSS) method to significantly improve power extraction from photovoltaic (PV) systems. The primary objective is to optimize performance under dynamic environmental conditions. Through comprehensive experimental studies, the proposed algorithm's performance was evaluated and directly compared against conventional incremental conductance (INC) and perturb and observe (P&O) algorithms. The results demonstrate a substantial increase in power generation, with the proposed algorithm delivering 18.79% more power compared to INC and 39.67% more power than P&O. These findings underscore the efficacy of the developed algorithm at improving the efficiency and robustness of PV power generation, particularly in variable operating environments.

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1. INTRODUCTION

Solar energy is an abundant and sustainable renewable resource, making it a vital alternative to depleting fossil fuels [1]. Its utilization through photovoltaic (PV) systems produces no carbon emissions, thus contributing to the mitigation of climate change and air pollution [2], [3]. Unstable environmental conditions, including fluctuation in solar irradiance and temperature, can seriously impede the efficiency of PV systems [4]. Therefore, it is crucial to develop methods that can maximize power output from PV even under unpredictable operating environments.

To overcome this challenge, the maximum power point tracking (MPPT) algorithm is essential for ensuring that PV system always operate at their maximum power point (MPP) [5]-[7]. Three main classes of MPPT algorithms exist: conventional [8], [9], intelligent [10]-[12], and optimization [13], [14]. The perturb and observe (P&O) and incremental conductance (INC) algorithms are popular choices due to their direct nature, ease of use, and minimal computational requirements [15], [16]. Nevertheless, these methods exhibit notable weaknesses, including slow convergence and considerable power fluctuations near the MPP, which may compromise the system's efficiency in dynamic weather conditions [7], [17]. On the other hand, the use of intelligent techniques in MPPT increases complexity, which leads to higher costs [18], data scarcity, and the challenge of algorithm fine-tuning [19]. Optimization techniques also present numerous challenges such as parameter initialization, parameter tuning, and the number of iterations [20].

Therefore, this paper examines enhancing the performance of conventional methods to maximize electrical power generation, which is tested under various real-world environmental conditions. An innovative hybrid MPPT algorithm is proposed in this study, which integrates an enhanced INC with variable step size (VSS) and conventional INC. The proposed method is distinguished from other adaptive MPPT algorithms by its unique irradiance-based switching mechanism. This mechanism allows the algorithm to intelligently switch its operating mode, resulting in rapid convergence and minimal power oscillation. This is the first study to combine these specific elements into a single, highly efficient MPPT algorithm. The efficacy of the approach was validated through experimental testing in real conditions, comparing its power output with P&O and INC algorithms.

2. QUANTITATIVE FORMULATION OF PHOTOVOLTAIC

Figure 1 displays the configuration of the PV cell equivalent circuit employing a single diode commonly used to perform characteristic analysis. Mathematically, the PV module in Figure 1 can be modelled using (1)-(4) [21], [22].

$$I_{ph} = \left[I_{SCR} + k_i(T - 298) * \frac{G}{G_n}\right] \quad (1)$$

I_{ph} is the photocurrent, I_{SCR} is the short-circuit current of the PV module at a temperature of 25 °C and solar radiation has intensity of approximately 1000 W/m^2, k_i is the temperature coefficient of current, T is the temperature of the PV module when operating (K), G solar radiation value when operating (W/m^2), and G_n is solar radiation value of the standard PV module (W/m^2).

$$I_{rs} = \frac{I_{SCR}}{\left[exp\left(\frac{qV_{OC}}{N_S AKT}\right)-1\right]} \quad (2)$$

The variable I_{rs} define the module's reverse leakage parameter, q is the electron charge (1.6×10^{-19} K), V_{OC} is the module open circuit voltage, N_s is the total number of series cells, A s the ideality factor, and K is Boltzmann's constant (1.38×10^{-23} J/K).

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{qEg}{Ak}\left\{\frac{1}{T_r} - \frac{1}{T}\right\}\right] \quad (3)$$

I_0 represents the saturation current value of the PV module, T_r is the temperature reference (298 K), and Eg is the band gap value of silicon (1.1 eV).

$$I_{PV} = N_p * I_{ph} - N_p * I_o\left[exp\left\{\frac{q*(V_{PV}+I_{PV}*R_S)}{N_S AkT}\right\} - 1\right] \quad (4)$$

Meanwhile, I_{PV} and V_{PV} are the voltage and current of PV module output, N_p represents the number of parallel-connected cells, and R_s is the series resistance value.

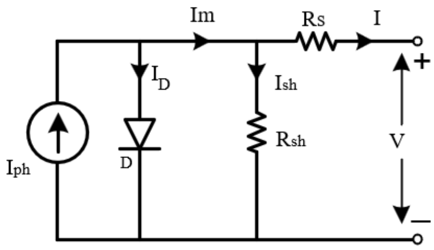

Figure 1. Single diode equivalent circuit used for modeling the PV cell

Many factors influence the production of electricity through solar panels such as solar radiation, temperature, wind speed, air humidity, shadow effects, and panel cleanliness (dust and other debris on the solar panel's surface) [23], [24]. The (5) can be used as a theoretical basis in calculating the electricity generated by solar panels [25].

$$P_{PV} = P_{STC}\frac{G_S}{G_{STC}}\left[1 + \gamma(T_C - T_{STC})\right] \quad (5)$$

P_{PV} is PV output (kW), P_{STC} is the solar panel's electrical power at STC (kW), G_S is the amount of solar radiation received by solar panels (W/m$^{2)}$, G_{STC} is the standard solar radiation intensity (W/m^2), γ is the power coefficient with respect to temperature, T_C is the temperature of the solar panel when operating (°C), dan T_{STC} is the normal temperature (25 °C). T_C can also be calculated using (6).

$$T_C = T_{air} + KG_S \quad (6)$$

T_{air} is air temperature and K is a solar constant. Furthermore, (6) may be expressed as (7).

$$P_{PV} = \frac{P_{STC}}{G_{STC}} (KG_S + \gamma G_S T_{air} - G_S T_{STC} + G_S) \quad (7)$$

3. DC-DC BOOST CONVERTER

A DC-DC boost converter serves as a vital component within a PV system, primarily to elevate the output voltage. Its circuit is illustrated in Figure 2. The (8)–(11) [26], [27] is employed to ascertain the parameter values of the boost converter, as illustrated in Figure 2.

$$\frac{V_O}{V_{PV}} = \frac{1}{1-D} \quad (8)$$

$$C_1 \geq \frac{D}{8\, x\, f^2\, x\, L\, x\, 0.01} \quad (9)$$

$$C_2 \geq \frac{D}{f\, x\, R\, x\, 0.02} \quad (10)$$

$$L = \frac{D\, x\, (1-D^2)\, x\, R}{r\, x\, f} \quad (11)$$

By employing (8) to (11), the parameters of the boost converter used in the designed PV system can be acquired as illustrated in Table 1.

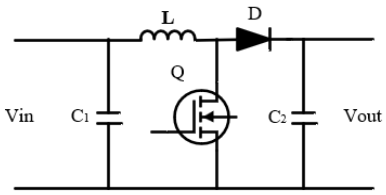

Figure 2. Boost converter circuit

Table 1. Calculated parameters for boost converter

No	Component	Value
1	L	2.2 mH
2	C_1	100 uF
3	C_2	100 uF
4	F	7,812 Hz
5	R	135 Ohm
6	D	0.7

4. METHOD

A proposed hybrid MPPT system, which is designed to maximize power generation in changing environments, is thoroughly described in terms of its design and implementation in this section.

4.1. Maximum power point tracking algorithm

This research proposed a novel hybrid MPPT algorithm that intelligently combines the conventional INC method with an enhanced INC developed using VSS concept. The selection of the operating algorithm is determined by the solar irradiance value. Should the insolation be greater than 500 W/m^2, the MPPT algorithm operates using the VSS concept, as outlined in (12) [28], [29]. This approach allows for an adaptive adjustment of the step size to achieve fast convergence to the MPP under high irradiance conditions.

$$Step = N * |dP| \quad (12)$$

Where *Step* is the adjustment step size, *N* is the scaling factor and *dP* is the change in the PV system's power output. The use of (12) ensures that the step size becomes larger when the system is far from the MPP and shrinks as it approaches the MPP, thereby reducing power oscillation and accelerating convergence. Conversely, if the solar irradiance value is less than 500 W/m^2, the conventional INC algorithm will operate. This choice is based on the robustness and correctness of the conventional INC method under low irradiance conditions.

This switching mechanism based on the 500 W/m^2 threshold is a key advantage that distinguishes this approach from other adaptive methods. This combination aims to achieve a balance between fast convergence during high power conditions and minimal power oscillation during low power conditions. For a clear understanding of the algorithm's implementation, refer to the flowchart in Figure 3.

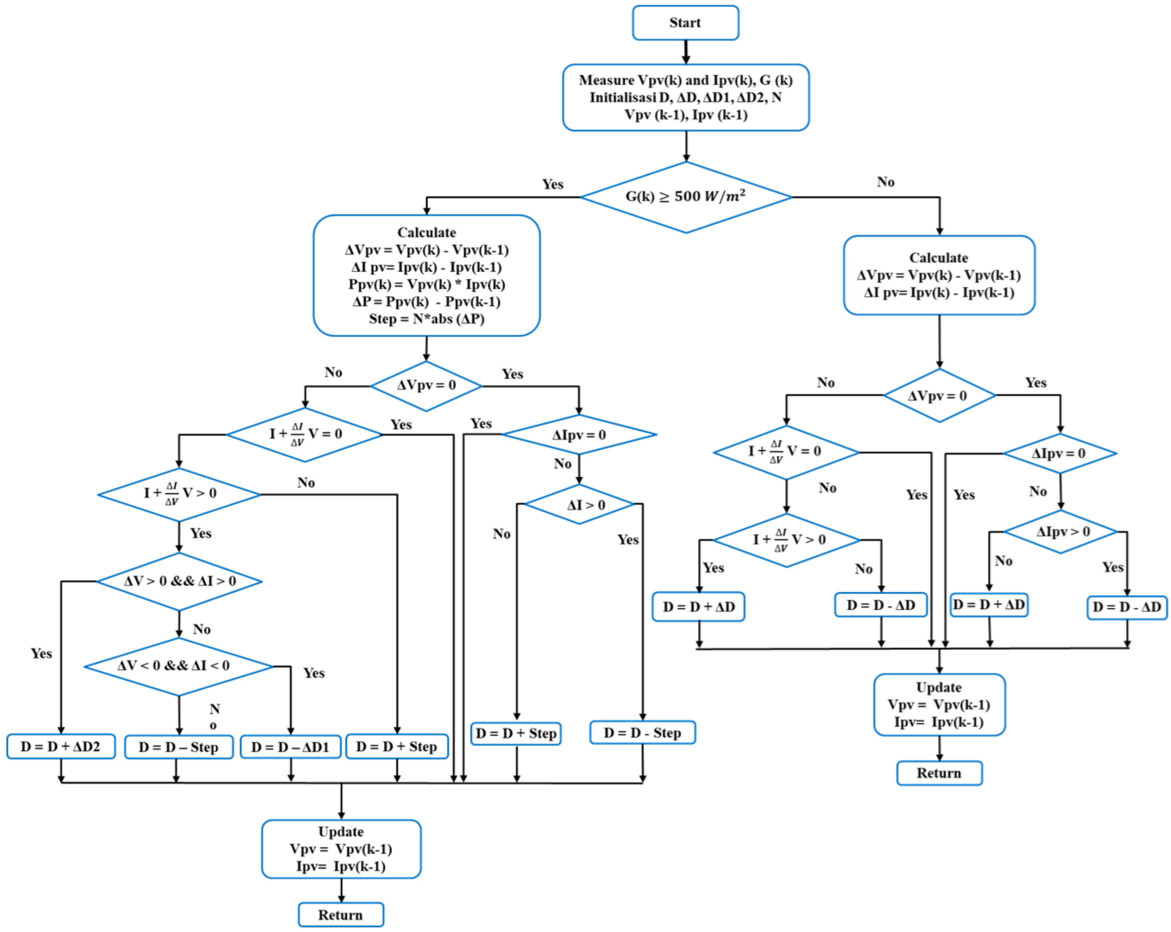

Figure 3. The proposed MPPT algorithm

4.2. System and experimental parameters description

The experimental methodology employed to evaluate the MPPT system's performance is detailed in Figure 4, which illustrates its main components. The system is powered by three Greentek MSP-100W PV modules, each with a capacity of 100 Wp, which convert solar energy into electrical power. A power converter, specifically DC-DC boost converter, is a critical part of this energy conversion system, used to increase the voltage from the PV modules. The converter is controlled by a microcontroller that generates an 8-bit pulse width modulation (PWM) signal. This provides 256 distinct duty cycle levels, enabling precise voltage adjustments to track the MPP.

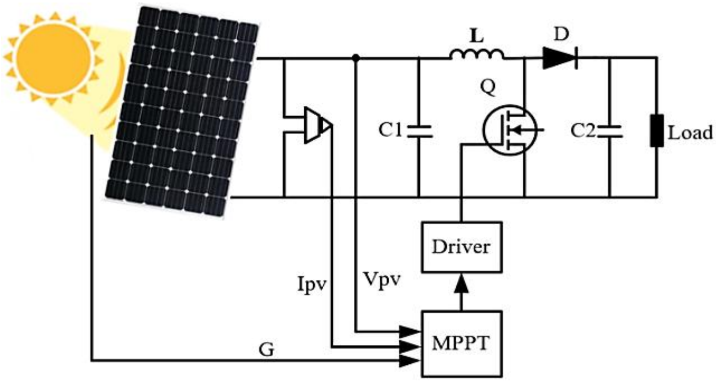

Figure 4. The designed PV system

Functioning as the system's core intelligence, the MPP algorithm constantly observes the PV module's output voltage (V_{pv}), current (I_{pv}), and irradiance (G). Using this data, the algorithm calculates the optimal duty cycle. It is important to note that the control frequency and sampling time are implemented with delay () commands in the microcontroller's code, resulting in a variable sampling interval. Despite this, the implementation remains effective for evaluating the algorithm's performance under real-word conditions. A separate driving circuit is also employed to convert the algorithm's control signal into a robust signal for the main switch of the converter. To sustain system's efficiency, the fundamental role of the MPPT algorithm is to maintain the PV module's operation at its MPP, thereby sustaining the system's efficiency. The signal generated by the algorithm directly controls the power converter's duty cycle to achieve this objective. The converter's parameters were calculated by applying (8) to (11) and are presented in Table 1.

5. RESULTS AND DISCUSSION

The PV system constructed for this research, as illustrated in Figures 5 and 6, is a physical implementation of the methodology described in the previous section. Figure 5 shows the overall layout of the experimental system, including the PV modules used and their physical configuration. Meanwhile, Figure 6 displays the MPPT control system utilizing a DC-DC boost converter based on an Arduino Uno microcontroller. To collect experimental data from all sensors and monitor the electrical parameters, this research utilized parallax data acquisition (PLX-DAQ), which enabled real-time data observation in Microsoft Excel format on a personal computer (PC). The system underwent a three-day testing period to evaluate its effectiveness under various environmental conditions, with Figures 7-9 presenting the test result.

Figure 5. The built PV system used in this research

(a) (b)

Figure 6. The hardware system: (a) a boost converter and (b) hardware connected to a computer for measurement monitoring

5.1. Daily performance analysis

Over a three-day period, the three MPPT algorithms were subjected to testing to determine their performance, with each day having different solar radiation conditions. The output data from each algorithm was directly compared to assess its effectiveness. Figure 7 presents the complete profile of the test conducted on the first day, which includes solar radiation, voltage, current and electrical power. As depicted in Figure 7(a), the solar radiation pattern showed a gradual increase throughout the day, reaching its peak at midday and then decreasing. In these situations, the algorithm developed produced a very stable output voltage, while the INC and P&O algorithms showed more significant fluctuations as demonstrated in Figure 7(b). Similarly, as shown in Figure 7(c), the output current was more dominant using the proposed algorithm even though fluctuations occurred, followed by the INC and P&O algorithms. Therefore, the electrical power generated, shown in Figure 7(d), was most significant in the system using the proposed algorithm, followed by INC and P&O.

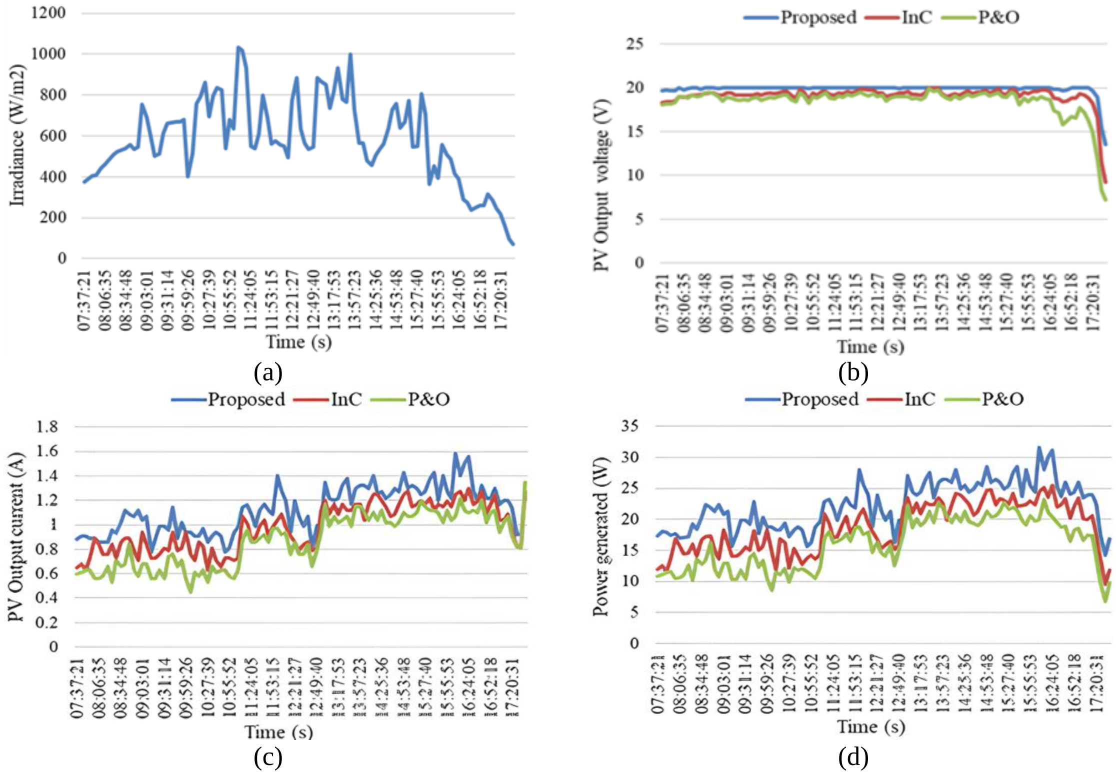

Figure 7. The system test results on the first day: (a) irradiance, (b) PV output voltage, (c) PV output current, and (d) power generated

The test results profile for the second day can be seen in Figure 8, The environmental conditions, particularly the solar radiation intensity as depicted in Figure 8(a), slightly increased compared to the first day. This phenomenon was caused by higher temperatures and the presence of clouds that blocked sunlight from reaching the surface of the solar panels. Under these conditions, the proposed algorithm demonstrates a superior ability to track the MPP, yielding higher voltage and current values compared to the INC and P&O algorithms, as shown in Figures 8(b) and 8(c). This proves the effectiveness of the VSS mode in optimizing power under high radiation conditions. The conditions on the second day resulted in lower electrical power generation compared to the first day; however, the proposed algorithm still produced greater power than the INC and P&O algorithms, as displayed in Figure 8(d).

The most significant test was conducted on the third day, where Figure 9(a) shows drastic and rapid fluctuations in solar radiation due to thick clouds and light rain in the afternoon. Although there was a consistent increase in radiation at the beginning, the radiation level started to decline in the afternoon due to cloud formation. This change was also accompanied by an increase in wind speed, which caused a drop in temperature, indirectly affecting the power output. These conditions also directly impacted on the resulting voltage. As shown in Figure 9(b), the proposed algorithm maintained a stable voltage from the beginning of the test, while the INC and P&O algorithms exhibited fluctuations. However, after the radiation dropped, the output voltage experienced significant fluctuations until the end of the test. In contrast, the output current displayed in Figure 9(c) remained quite stable, hovering between 1 and 1.2 A. These dynamic conditions effectively tested the convergence speed and robustness of each algorithm. As seen in Figure 9(d), the P&O and INC algorithms experienced significant difficulty in tracking the MPP during rapid fluctuations, which was evident from severe power oscillations and a sharp decrease in efficiency. Conversely, the proposed algorithm was consistently able to track the MPP changes quickly, demonstrating its adaptive capability and effectiveness in the most challenging environmental conditions.

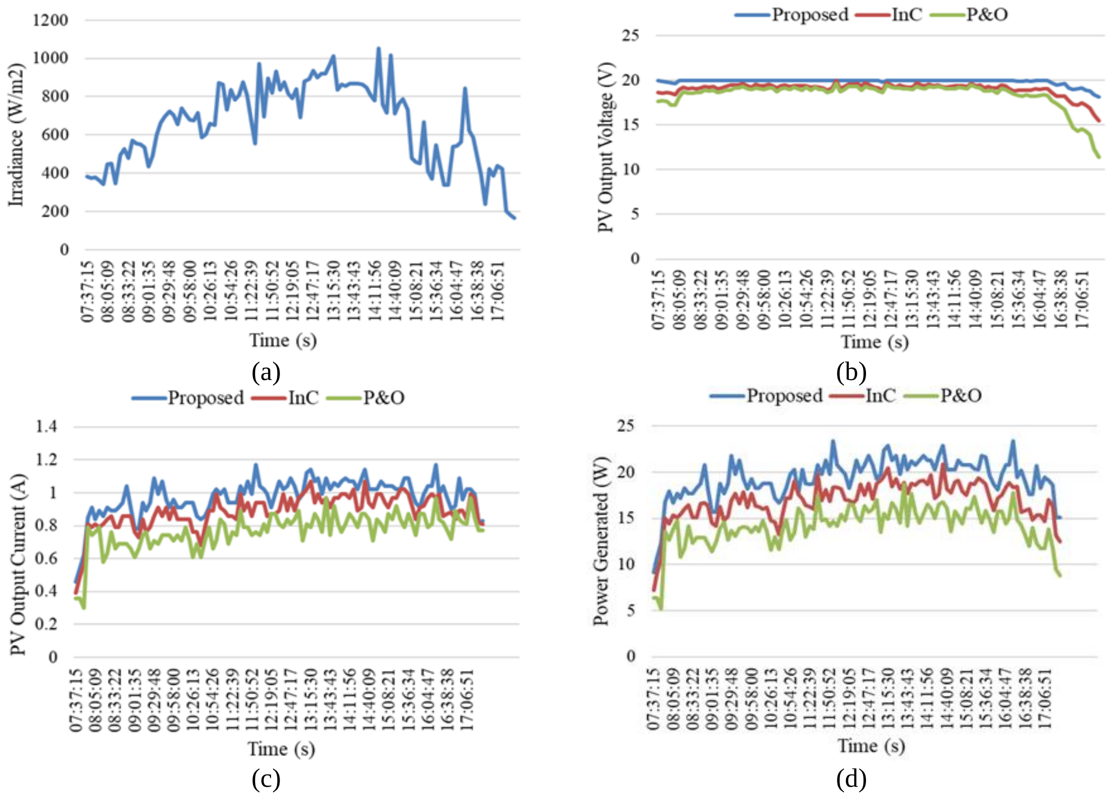

Figure 8. The system test results on the second day: (a) irradiance, (b) PV output voltage, (c) PV output current, and (d) power generated

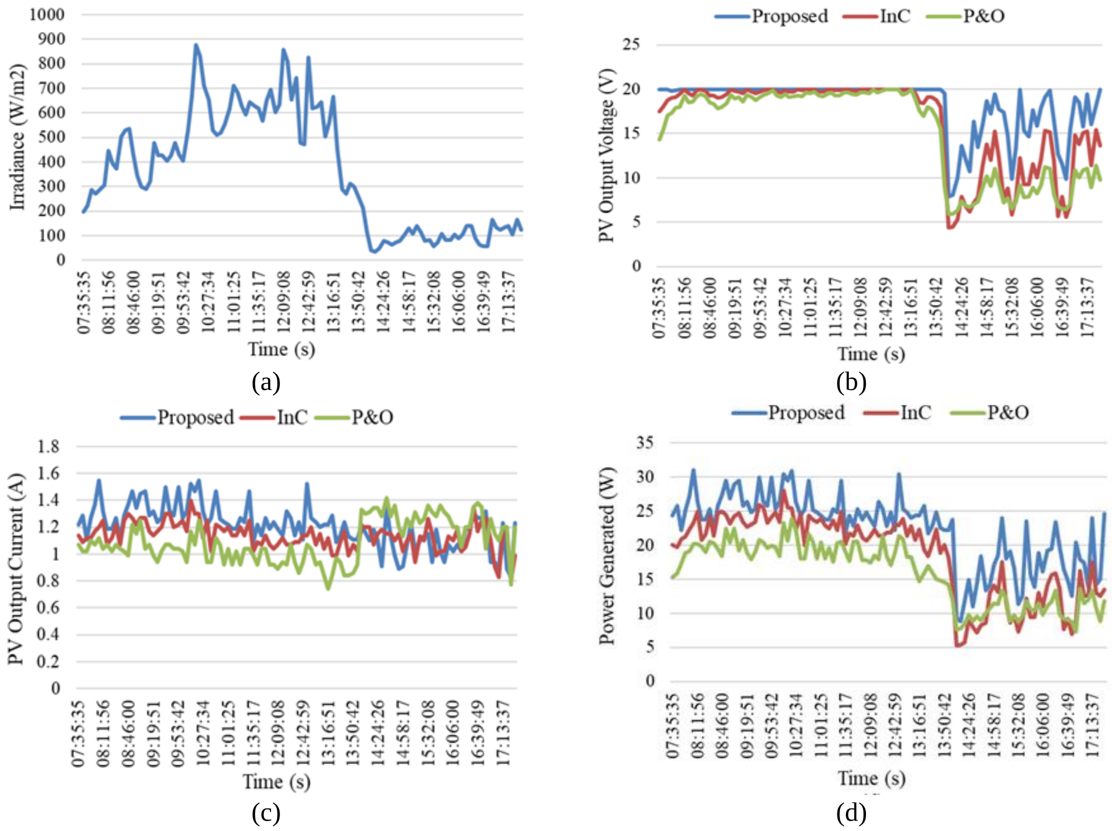

Figure 9. The system test results on the third day: (a) irradiance, (b) PV output voltage, (c) PV output current, and (d) power generated

5.2. Statistical analysis and key findings

After analyzing the qualitative performance from the figures, a quantitative evaluation was conducted to provide strong statistical evidence. This analysis includes a comparison of the average and statistical dispersion of the power output from each algorithm during the testing period. Figure 10 illustrates the comparison of the average daily electrical generated.

To provide a more accurate depiction of the reliability and consistency of each algorithm, the standard deviation (σ) of the power output data was calculated. The main objective of this calculation is to measure the magnitude of data fluctuation of dispersion around its mean value. A lower standard deviation indicates that the power output is more stable and consistent, which is a key indicator of effective MPPT performance, especially under fluctuating environmental conditions. This calculation uses the sample standard deviation formula, which is more appropriate for limited data, with (13) [30].

$$\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \quad (13)$$

Where $\bar{x}$ is the meaning of the data, x_i is, each individual data value, n is the total count of data points. Table 2 provides a summary of the key statistical data of the power output for each algorithm during the testing period.

As shown in Table 2, the proposed algorithm generated the highest average power (21.37 W), outperforming both INC (17.99 W) and P&O (15.30 W). The standard deviation of the INC algorithm is slightly lower than that of the P&O algorithm and the proposed algorithm. This reflects the characteristics of trade-off between stability and t0racking speed. The INC algorithm uses a fixed and relatively small step size, minimizes power fluctuations when near the MPP, thus yielding high consistency. Conversely, the proposed algorithm, with its VSS mode, aggressively adjusts its step size to track rapid changes in radiation. While this results in a significantly higher average power and better overall efficiency, this aggressive tracking process causes minor fluctuations, which are reflected in the slightly higher standard deviation value. In summary, the test results confirm that the developed algorithm successfully improves the electrical power generation.

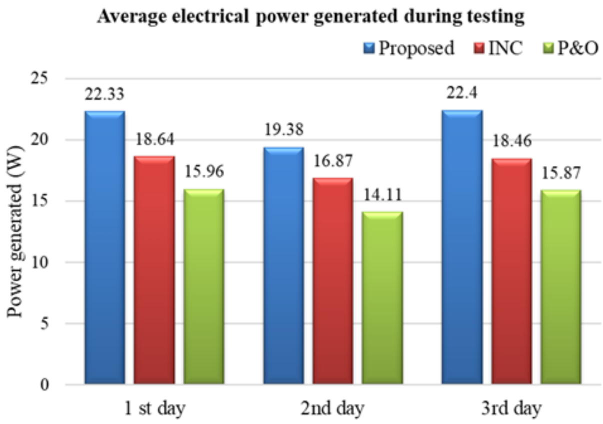

Figure 10. The average electrical power generated during the test

Table 2. Statistical analysis of algorithm performance

No	Algorithm	Average power (W)	Standard deviation (W)
1	P&O	15.30	1.03
2	INC	17.99	0.97
3	Proposed	21.37	1.72

6. CONCLUSION

This research discusses the development of an MPPT algorithm aimed at enhancing electrical power from a PV system. To evaluate its effectiveness, the proposed hybrid algorithm was experimentally tested and compared against two conventional algorithms, namely INC and P&O. The tests were conducted over a three-day period under varying climatic conditions in a filed setting. Based on the experimental results, the proposed algorithm was found to significantly increase the power generation capacity. The hybrid algorithm produced the highest average power of 21.37 W, representing a significant increase of 18.79% compared to the INC algorithm and 39.67% compared to the P&O algorithm. This improvement is crucial, especially in dynamic environmental conditions, as tested on the third day, where rapid radiation fluctuations can cause conventional algorithms to fail to track the MPP optimally. Specifically, the contributions of this research are highly relevant to the fields of power electronics and energy system. The efficient MPPT algorithms embedded directly into the control of the boost converter, which is a key element in optimizing power for various solar-powered electrical drive systems and hybrid systems. The proven increase in power output will also enhance energy availability for battery charging and support more reliable integration into smart grids. Despite its excellent performance, the proposed method still has limitations, such as its reliance on solar radiation levels to determine the algorithm's selection process. Therefore, this research can be extended in the future. Further development may include integrating this algorithm with Artificial Intelligence (AI)-based methods, such as neural network, to improve its accuracy and adaptability. Additionally, its application can be expanded to grid-tied PV system or hybrid energy systems. To assess the algorithm's performance in more intricate environmental scenarios, Hardware-in-the-loop (HIL) validation can also be utilized.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [RN], upon reasonable request.

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