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ORIGINAL STUDY

MPPT for PV Systems Under Partial Shading Using Cuckoo Search With Perturb and Observe Optimizations

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Abstract

This study offers a comparative assessment of Perturb and Observe (P&O) and Cuckoo Search (CS) maximum power point tracking (MPPT) methodologies, specifically within a photovoltaic (PV) system, under both standard test conditions (STC) and varying irradiance scenarios. The PV system was simulated and modeled using MATLAB/Simulink, and performance metrics were derived from the time-domain simulation outcomes. In the context of STC, the CS MPPT technique demonstrates an output power of 11.62 kW, coupled with an efficiency of 93.46 %. This result represents a substantial improvement over the P&O MPPT method, which yields 8.088 kW at an efficiency of 65.05 %. In a similar vein, the CS-based methodology exhibits robust performance across a spectrum of irradiance levels, generating 11.51 kW at an efficiency of 92.58 %. Conversely, the P&O method produces 8.05 kW with a 64.75 % efficiency. These findings indicate that the CS MPPT technique facilitates enhanced power extraction and superior efficiency relative to the traditional P&O algorithm, irrespective of whether the operating conditions are stable or fluctuating. Consequently, it presents a more advantageous solution for photovoltaic energy conversion systems.

Keywords: Cuckoo Search, Partial shading condition, Maximum power point tracking

1. Introduction

Growing concerns about environmental degradation and global energy shortages have significantly increased interest in clean and renewable energy sources. Among these, solar power stands out as one of the most promising technologies. In the last few decades, PV systems have become very popular in grid-connected settings, and they are an important part of modern electricity generation [1].

PV systems work by directly converting sunlight into electrical energy when solar photons collide with the PV panels. However, their performance is highly dependent on environmental factors such as the sun's position, ambient temperature, and solar irradiance. PV systems must run at their highest power output in order to maximize efficiency, which calls for the application of MPPT approaches [2].

To efficiently determine the MPP, various tracking algorithms have been developed due to the nonlinear power-voltage (P-V) and power-current (P-I) interactions in PV cells [3]. Even though these techniques are widely used, they may not work well in situations where temperature and sunshine intensity change quickly [4].

MPPT is used in conjunction with power converters, such as DC−DC converters and inverters,

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to reliably harvest the maximum power from PV arrays. Over the years, many MPPT strategies have been suggested and documented in research. These strategies can be broadly categorized into two groups: (1) traditional methods and (2) techniques based on soft computing. In-depth analyses of these methods [5,6].

The P&O approach [7] is one of the most widely used conventional procedures. Furthermore, more straightforward methods have been investigated, such as the fractional short-circuit current method [8], fractional open-circuit voltage method [9], ripple correlation control [10], sliding mode control [11], and mathematical-graphical techniques [12]. These techniques often track the MPP well under uniform sunshine, exhibiting quick convergence.

Despite their effectiveness, these methods frequently have a serious flaw: they continue to oscillate around the MPP when operating steadily, which results in power losses. Tracking performance has often decreased as a result of attempts to lessen this oscillatory effect. [13]. Furthermore, none of these conventional methods are well-suited for dealing with partial shading scenarios, where parts of the PV array experience uneven solar exposure [14]. This paper's primary contributions are summarized below:

This study focuses on how to improve the performance of a solar system using MPPT techniques, specifically by employing the CS algorithm and P&O algorithms. The two were tested under standard conditions and varying solar irradiance using a single model in MATLAB/Simulink. We present an innovative methodology for analyzing performance parameters based on time responses, demonstrating the superiority of CS MPPT over other methods in dynamic performance, power output, and efficiency.

2. Literature review

In 2024, Ayman Noah, Al-Hassan, conducted a study aimed at getting maximum power from a PV system using a hybrid technique (CSPSO) that combines the CS algorithm and the PSO algorithm. The performance of this hybrid technique (CSPSO) was evaluated by applying three different partial shading patterns, comparing its efficiency against standalone CS and PSO techniques.

The hybrid algorithm (CSPSO) approach was superior, as evidenced by the findings, which showed a 99.925 % tracking efficiency with a fast tracking time of only 0.13 s. This method was used on a PV system with three solar modules, and the boost converter-specific parameters (Cin = 10 F, Cout = 47 F, L = 1 m, and R = 60) were set for best results [15].

List of abbreviations

CS	Cuckoo Search
CSPSO	Hybrid Cuckoo Search - Particle Swarm Optimization
Epv	Energy of photovoltaic system
GMPP	global maximum power point
I_{PV}	PV array current
LMPP	Local Maximum Power Points
MPPT	Maximum Power Point Tracking
MPP	Maximum Power Point
P&O	Perturb and Observe
PSC	Partial shading Condition
PSO	Particle Swarm Optimization
PV	Photovoltaic
Rs	Series resistance
Rsh	Shunt resistance
SEPIC	Single-ended primary inductor converter
STC	Standard Test Conditions
V_{PV}	PV array voltage
V_{MP}	Maximum power voltage
V_{oc}	Open circuit Voltage

List of symbols

T	Temperature in Kelvin of p-n junction
q	electric charge ($1.60217646 \times 10^{-19}$) coulombs
I	Output current
K	Boltzman's, constant = 1.3807×10^{-23} J/kg
I_d	Diode current
I_{ph}	light generated current
I_{sh}	Current through shunt resistor R_{sh}
I_{MP}	Maximum power current

In 2020, Hussaian and Rani Chinnappa performed a study in which the SEPIC converter was utilized to simulate the MPPT technique to improve the performance of the solar system CS under partial shade situations using MATLAB/Simulink. This shadowing results in the appearance of one GMPP, which is crucial for obtaining the most power possible from the PV system, as well as two LMPPs. Under two distinct irradiation levels, the CS's MPPT was monitored. According to the simulation results, the CS tracking technique effectively used the entire search area of the current–voltage characteristics to exhibit accurate and quick MPP tracking. Furthermore, the evolution of the CS technique is distinguished by its efficacy and simplicity, with little to no complication in either design or implementation [16].

In 2019, Mohammed and Osama Abdulraou developed an MPPT system using the CS Algorithm, inspired by the natural behavior of cuckoo birds and simplified Levy flight distribution. The study demonstrated the superiority of this algorithm in tracking the maximum power point compared to incremental conductance and artificial neural network methods. The Cuckoo Search Algorithm achieved higher efficiency in extracting maximum power output while maintaining completely fluctuation-free performance, ensuring greater stability in the PV system's operation [17].

3. MPPT technology in PV systems

MPPT is a vital element of grid-tie PV systems, continuously adjusting the operating point to locate the MPP and thereby optimize the power output of PV arrays. To achieve this, various MPPT methods have been developed and implemented, each employing distinct algorithms and control strategies. MPPT algorithms are indispensable in PV applications because a solar panel's MPP is subject to variation due to temperature and irradiation levels. Consequently, the utilization of MPPT algorithms is essential for maximizing the power output of a solar array [18,19].

In Fig. 1, a diagram depicts a block diagram of a solar power system, commencing with a solar panel that generates electrical energy. Sensors are employed to measure voltage and current, and this data is subsequently transmitted to an MPPT controller, which is responsible for optimizing the extraction of maximum power. Following this, the power is directed into a DC–DC converter, which regulates the voltage prior to its delivery to the electrical load.

A multitude of MPPT techniques exist. The P&O and CS algorithms are among the most prevalent and frequently utilized, primarily due to their straightforward implementation [21,22].

The inherent variability of solar power, contingent upon fluctuating environmental factors, presents a significant challenge, leading to inconsistent power and voltage outputs. To optimize the operational efficiency of PV modules, various MPPT methods are implemented [23]. Consequently, these strategies are classified in Fig. 2, based on the specific tracking procedures employed.

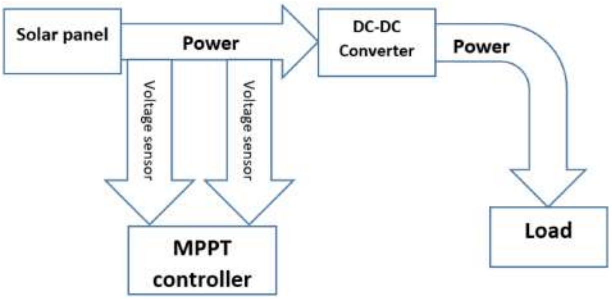

Fig. 1. MPPT block diagram [20].

4. PV cell modelling

The electrical behavior of a PV cell can be analyzed using either a one-diode or a two-diode model. This study used the single-diode model, which is the most common because it's simple to use and gives fairly accurate results [25]. Fig. 3 shows the circuit that represents the single-diode PV cell model. The mathematical equations that describe how the PV cell works are shown below [26].

$$P = V \quad I_{ph} - I_0 \quad exp \; \frac{q \; V_{pv} + I_{pv} * R_s}{nKT} \; -1 \; - \frac{V_{pv} + I_{pv} * R_s}{R_{sh}} \qquad (1)$$

I_{ph} represents the photocurrent, while q is the elementary charge of an electron, and I_0 denotes the diode's reverse saturation current. V_{PV} signifies the voltage across the PV panel. The series and shunt resistances of the solar cell, measured in ohms, are represented by R_s and R_{sh}, respectively. T denotes the absolute temperature, and K is Boltzmann's constant. Furthermore, the diode's ideality factor is indicated by n [27,28].

4.1. P&O algorithm

The P&O algorithm is one of the most widely used traditional methods for controlling the duty cycle in MPPT for PV systems. It is favored for its simplicity, ease of implementation, minimal parameter requirements, rapid convergence, cost-effectiveness, and reliable performance under steady irradiance conditions [29]. However, the algorithm exhibits oscillatory behavior around the MPP, which becomes a drawback, particularly during PSC, leading to significant power losses. The operation of the P&O algorithm relies on monitoring the relationship between the PV module's output power and voltage [30].

As illustrated in Fig. 4, the algorithm assesses the slope of the power-voltage (P-V) curve to determine the system's operating point. If the change in power with respect to voltage (P/ V) is positive, the operating point is on the left side of the MPP. This means that the PV module's voltage needs to be raised to get closer to the MPP and increase power output [31]. Conversely, a negative (P/ V) indicates that the operating point is on the right side of the MPP, requiring a decrease in voltage to approach the optimal point and improve efficiency [32].

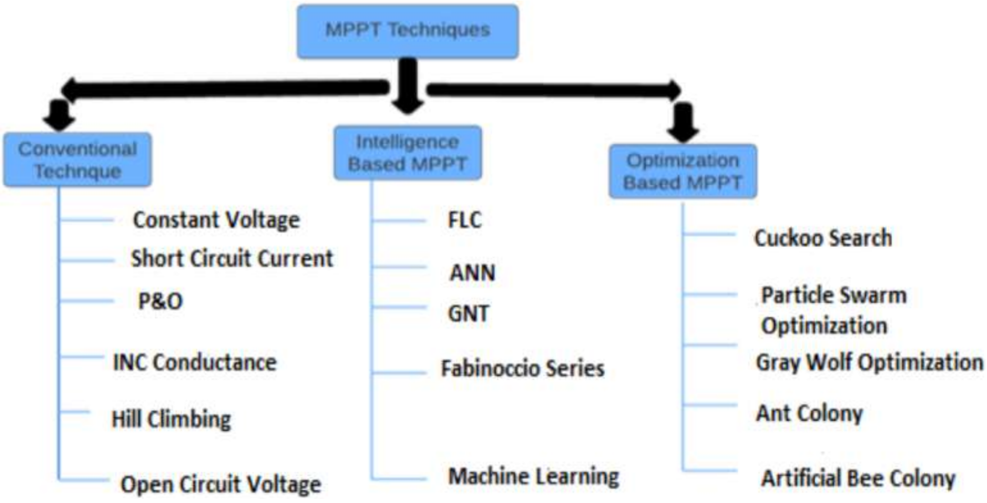

Fig. 2. Categorization of MPPT techniques [24].

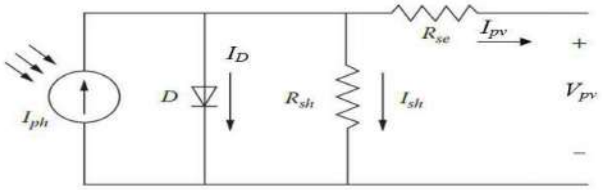

Fig. 3. Equivalent circuit of a PV cell with (Rs, Rsh).

4.2. Cuckoo algorithm

Cuckoo birds are known for their fascinating calls and unusual reproductive behaviors. Among the many types, species like the ani and the guira exhibit unique nesting habits by laying their eggs in communal nests and sometimes incorporating eggs from other nests to boost their offspring's chances. A several of cuckoo species, such as the Tapera, practice brood parasitism. These birds cleverly mimic the appearance and coloration of their host species, increasing the success rate of their parasitic strategy. Watching how Tapera times their egg-laying to match their host's cycle is both remarkable and visually striking [33].

Cuckoo females often choose hosts with similar nesting environments and egg characteristics to ensure that their eggs are accepted. Despite this mimicry, some hosts detect and remove the foreign eggs or abandon and destroy the entire nest before starting fresh elsewhere. Brood parasitism can be categorized into three primary types: intraspecific (within the same species), cooperative (with some level of mutual benefit or tolerance), and nest takeover, where the parasitic bird overtakes the nest entirely [34]. Fig. 5 illustrates the CS algorithm.

4.3. Levy flight

Cuckoo birds begin their reproductive process by searching for the most suitable nest, a critical step in their life cycle. Their approach to finding nests mirrors how they search for food. A commonly used

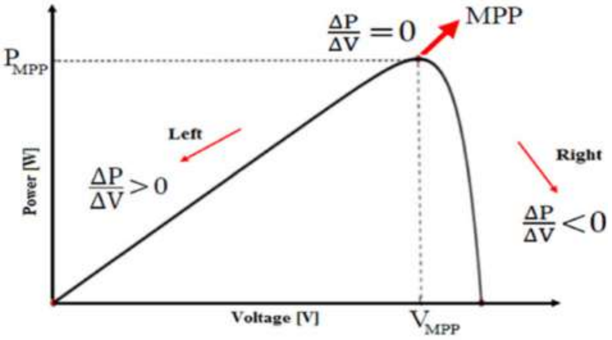

Fig. 4. There is a divergence from the MPP-based P&O algorithm.

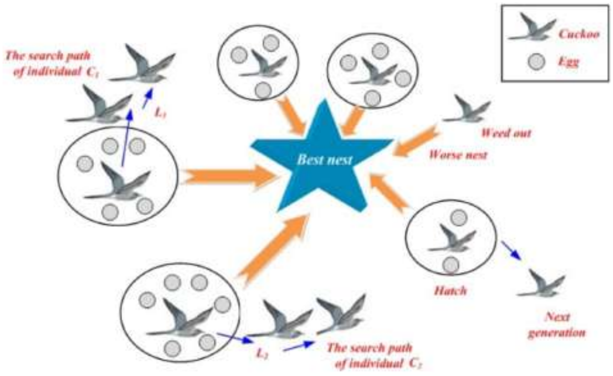

Fig. 5. CS algorithm.

model to simulate such search behaviors is the Levy flight, which helps in modelling movement paths and decision-making processes [35]. Reynolds and Frey's research has demonstrated that fruit flies (*Drosophila melanogaster*) navigate their environment via a sequence of linear flights interspersed with sudden 90-degree turns. This exploration strategy has inspired optimization techniques in problem-solving.

Levy flight defines a type of random walk where the lengths of the steps follow a probability distribution, generally modeled using a power law. In the context of Cuckoo Search (CS), the step lengths in Equation (2) are obtained from this Levy distribution, which is represented as

$$\text{Levy} \sim u = t - \qquad (2)$$

where the parameter lies between 1 and 3. This results in a random walk with a heavy-tailed distribution, effectively capturing the essence of long exploratory steps interspersed with shorter ones [36].

4.4. CS-MPPT algorithm

The Cuckoo Search (CS) algorithm operates based on three fundamental principles:

- Every cuckoo lays just one egg per iteration, placing it in a randomly selected nest.
- Only the nests containing the most promising eggs are retained for the next generation.
- The number of surrogate nests is fixed, and a cuckoo lays an egg in them based on a certain probability if the surrogate bird is already present.

If the host bird detects the presence of cuckoo eggs in its nest, it may respond by consuming the eggs or destroying the entire nest. Additionally, there's a probability (Pa) that a new nest will be formed. This probability can be simply expressed using the (Pa) ratio. In the next phase, the newly generated nests replace a portion (n) of the existing ones with randomly generated solutions. Each egg symbolizes a potential solution, with a cuckoo egg representing a novel idea. When a foreign egg is discovered, it leads to the elimination of certain poor nests containing less effective results. As a result, only the promising solutions are retained for further consideration and analysis [37]. To generate a new solution *Xi(t+1)* for cuckoo *i*, a Levy flight is performed. The update equation is given by:

$$Xi(t+1) = Xi(t) + \alpha \oplus \text{Levy flight}(\ ) \qquad (3)$$

Here, > 0 represents the step size, which depends on the scale of the optimization problem. Typically, is set to 1. The first term in Equation (3) denotes the current position, while the second term accounts for the transition probability. The symbol $\oplus$ signifies entry-wise multiplication.

The flow of the CS controller's search mechanism is shown in Fig. 7. Initially, a random duty cycle value is selected and applied to the PV panels. The system then measures voltage and current to estimate the PV power, which serves as the fitness value. The duty cycle corresponding to the highest fitness is identified as the current best solution (d_{best}). New candidate solutions, or nests, are generated using Levy flight as defined in Equation (2). These new solutions are assessed using the PV system to determine their fitness values. With a probability of Pa, the least effective nest is eliminated, mimicking the behavior of a host bird removing a cuckoo's egg. This nest is replaced by a new one created via Levy flight, after which the PV power is re-evaluated and the best-performing nest is updated. The CS controller concludes its operation when the stopping condition is met, indicating that the algorithm has effectively found the optimal global solution by identifying the best duty cycle [38]. Fig. 6 illustrates the flowchart of CS MPPT.

4.5. MPPT model based on algorithms

Using MATLAB/SIMULINK, the P&O and CS algorithms are implemented on a standalone PV system, employing a 70 resistive load as illustrated in Fig. 7.

4.6. First case

Both P&O and CS algorithms were applied to an MPPT for PV system under solar radiation 1000 W/m^2 and a temperature of 25 °C (STC). Comparison between the two algorithms applied to the MPPT in terms of power, current, voltage, energy, duty cycle and efficiency was observed from the results that the CS algorithm gives better results than the P&O algorithm. Fig. 8 shows the output power curve over time when applying the CS and P&O algorithms.

Fig. 9 presents the input power profile over time for both the CS and P&O algorithms under STC. It is both logical and anticipated that the input power would exceed the output power within practical electrical systems. The input power reaches 12.09 kW, whereas the output power is 11.62 kW; this disparity is attributable to inherent system losses. These losses encompass power consumption by the 70- resistive

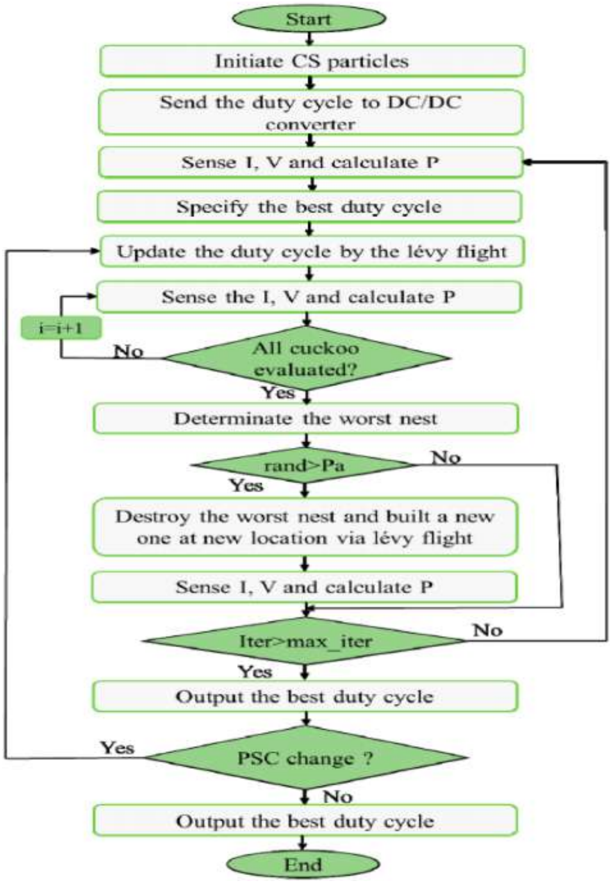

Fig. 6. CS-MPPT algorithm.

load, alongside thermal losses within power electronic components and interconnecting cables. The existence of these losses aligns with the principle of energy conservation, thereby validating the system's realistic functionality.

Fig. 10 shows the duty cycle curve over time when applying the CS algorithm under STC. Duty cycle is constantly modified to optimize power extraction from solar panels under fluctuating irradiation conditions. If sunlight diminishes, the system may modify duty cycle to sustain ideal voltage.

Fig. 11 shows the duty cycle curve over time when applying the P&O algorithm under STC.

Fig. 12 shows the output voltage curve over time when applying the CS and P&O algorithms under STC. The boost converter must be engineered to provide a stable and load-compatible output voltage, using automatic duty cycle modulation to accommodate fluctuations in solar panel voltage.

Fig. 13 shows the output current curve over time when applying the CS and P&O algorithms under STC. In order to maximize power, MPPT algorithms optimize both voltage and current.

Fig. 14 shows the energy curve over time when applying the CS and P&O algorithms under STC. A well-adjusted boost converter maintains ideal V_{out} and I_{out} to optimize daily energy yield.

4.7. Second case

The second case involves analyzing the system's behavior using P&O MPPT and CS MPPT techniques under changing irradiance conditions. This variation simulates the effect of cloud movement, causing the irradiance levels to shift across the values (1000, 610, 720, 1000, 645, and back to 1000) W/m^2 within a 5-s timeframe. The irradiance variation over time is illustrated in Fig. 15.

Fig. 16 shows the output power curve over time when applying the CS and P&O algorithms techniques under changing irradiance conditions.

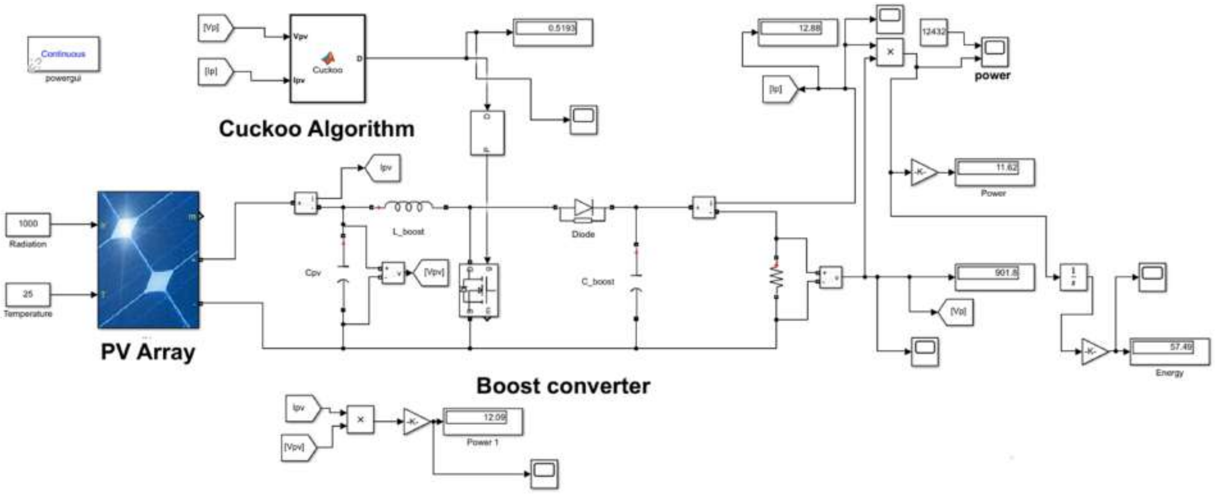

Fig. 7. PV array with MPPT.

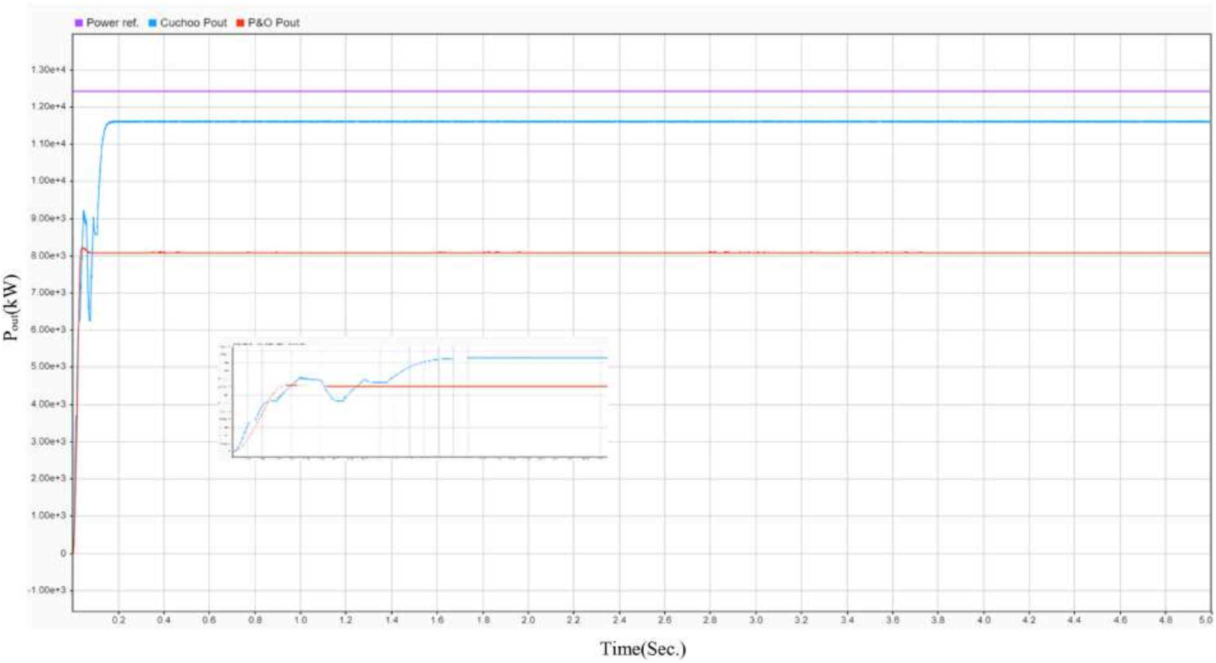

Fig. 8. Output power vs time.

Fig. 17 shows the input power curve over time when applying the CS and P&O algorithms under changing irradiance conditions.

Fig. 18 shows the duty cycle curve over time when applying the CS algorithm under changing irradiance conditions.

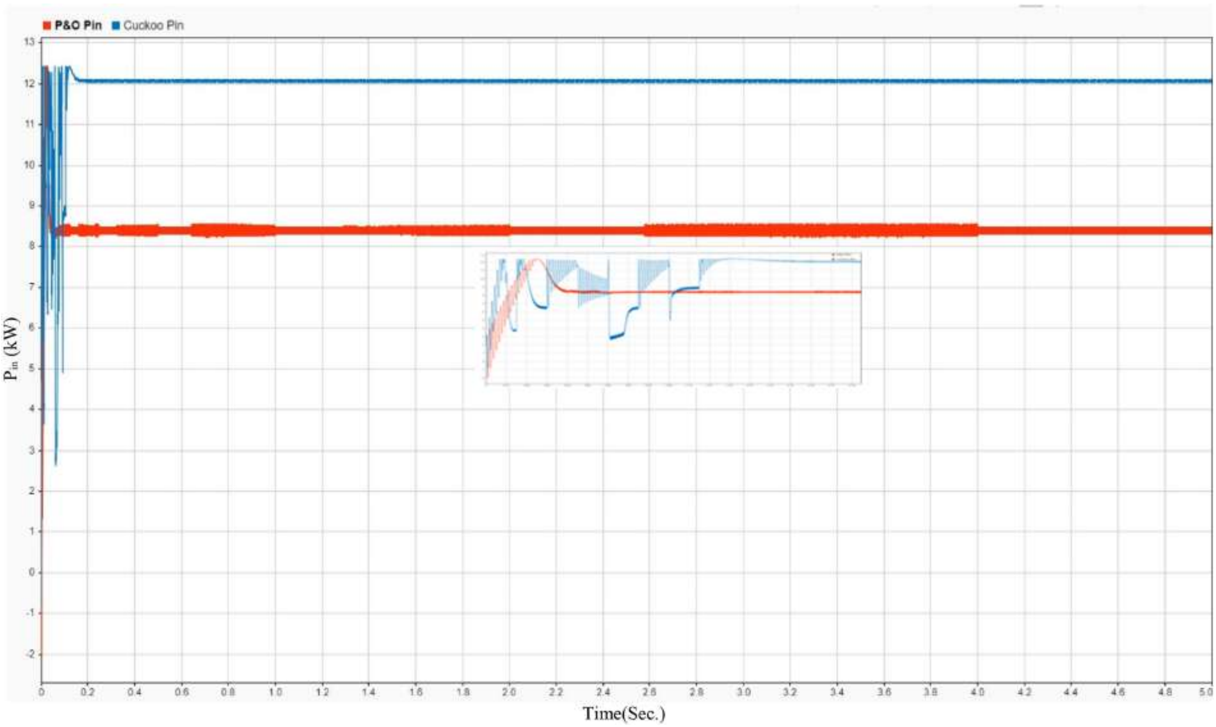

Fig. 9. Input power vs time.

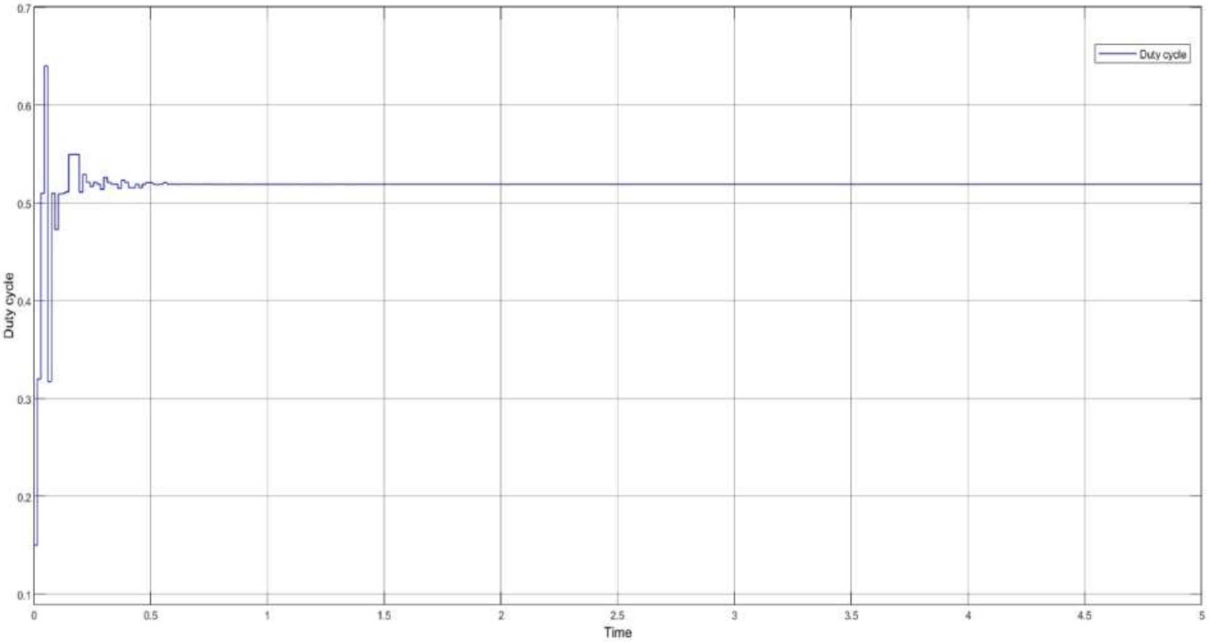

Fig. 10. Duty cycle vs time.

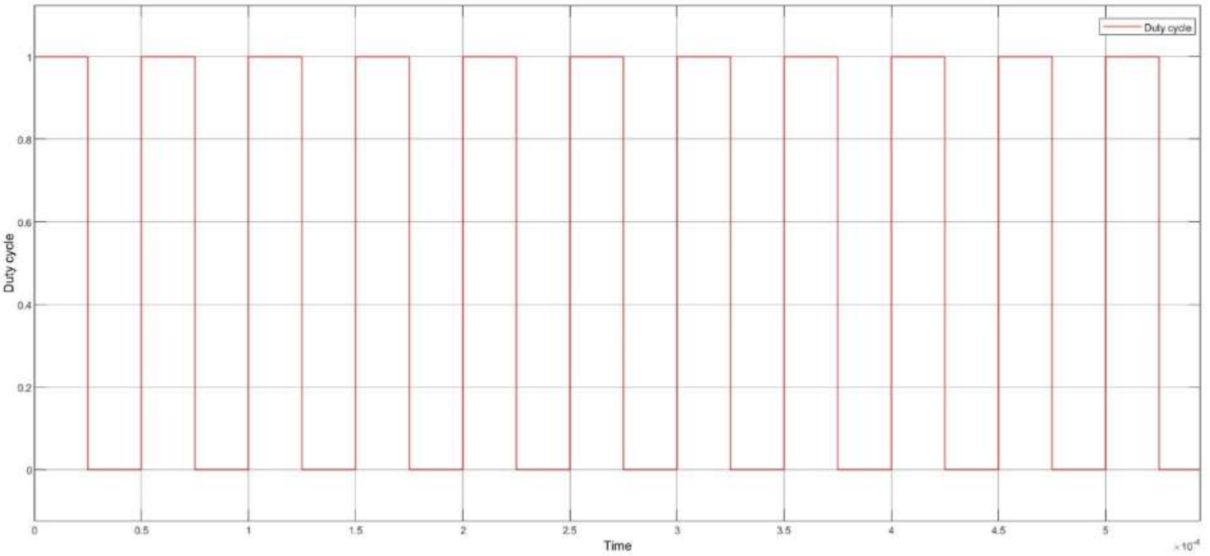

Fig. 11. Duty cycle vs time.

Fig. 19 shows the duty cycle curve over time when applying the P&O algorithm under changing irradiance conditions.

Fig. 20 shows the output voltage curve over time when applying the CS and P&O algorithms algorithm under changing irradiance conditions.

Fig. 21 shows the output current curve over time when applying the CS and P&O algorithms under changing irradiance conditions.

Fig. 22 shows the energy curve over time when applying the CS and P&O algorithms under changing irradiance conditions.

5. Results and discussions

In contrast to prior research on MPPT, including the study by Ahmed and Salam (2014), which assessed conventional P&O-based methods under

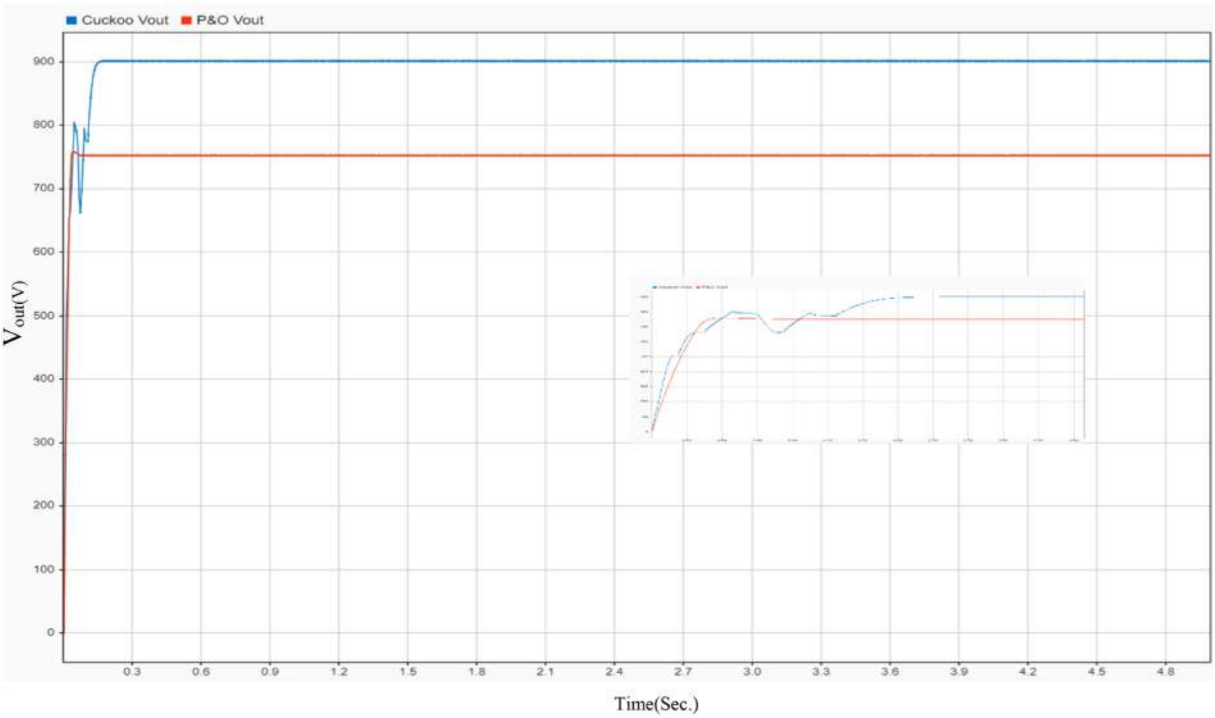

Fig. 12. Output voltage vs time.

fluctuating irradiance, the findings of this investigation reveal a significant enhancement in both dynamic behavior and energy yield. Whereas the cited research primarily concentrated on mitigating steady-state oscillations and optimizing tracking efficiency, this study broadens the scope of analysis

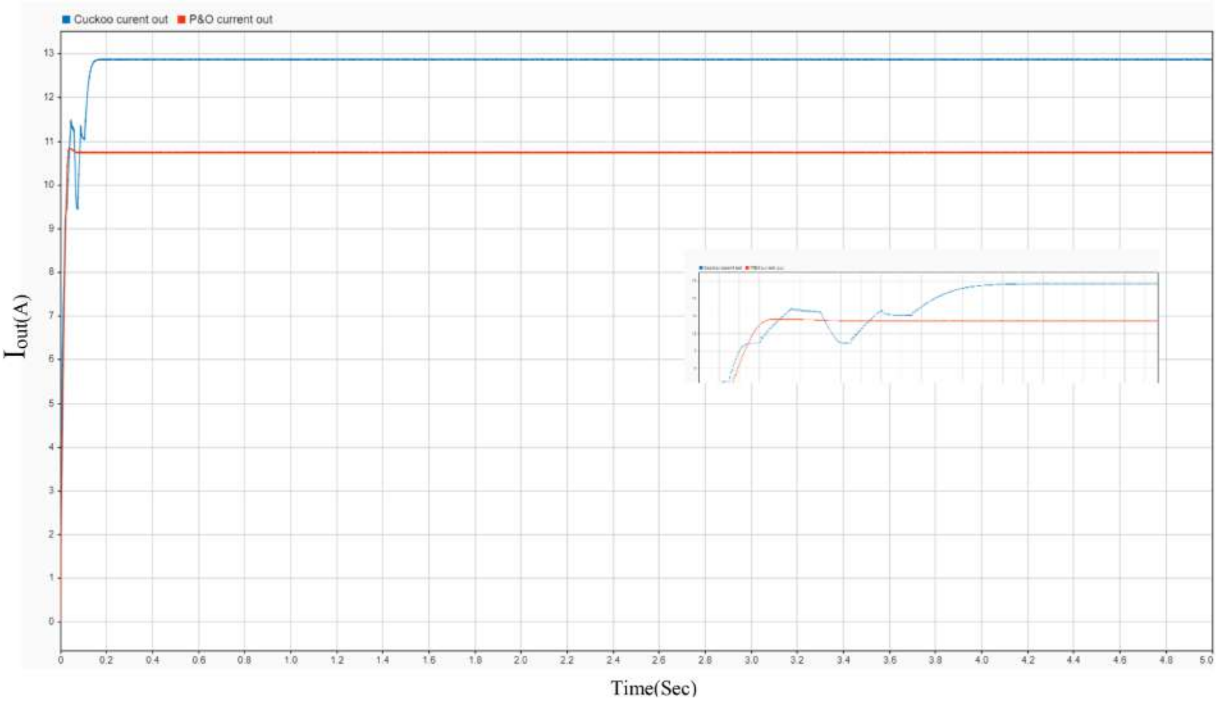

Fig. 13. Output current vs time.

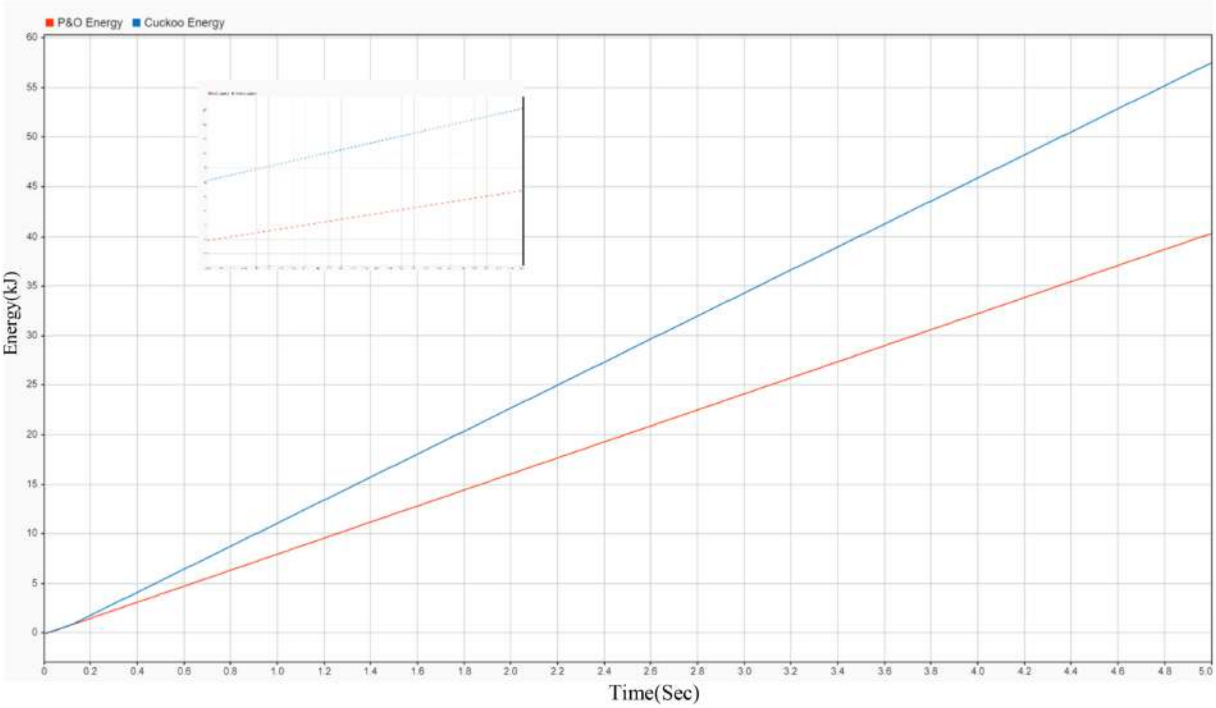

Fig. 14. Output energy vs time.

by utilizing a CS MPPT algorithm and deriving all performance metrics directly from time-domain responses [39].

In contrast to the conventional P&O method described in existing research, which experiences diminished efficiency under fluctuating irradiance, the suggested CS MPPT consistently achieves efficiencies exceeding 92 % across both standard testing conditions and dynamic irradiance environments. Furthermore, the incorporation of energy-based performance metrics (kJ), a factor often overlooked in prior studies, underscores the CS MPPT's enhanced capacity to optimize the total energy harvested, rather than merely focusing on instantaneous power output. Table 1 shows the results of PV system under three weather cases.

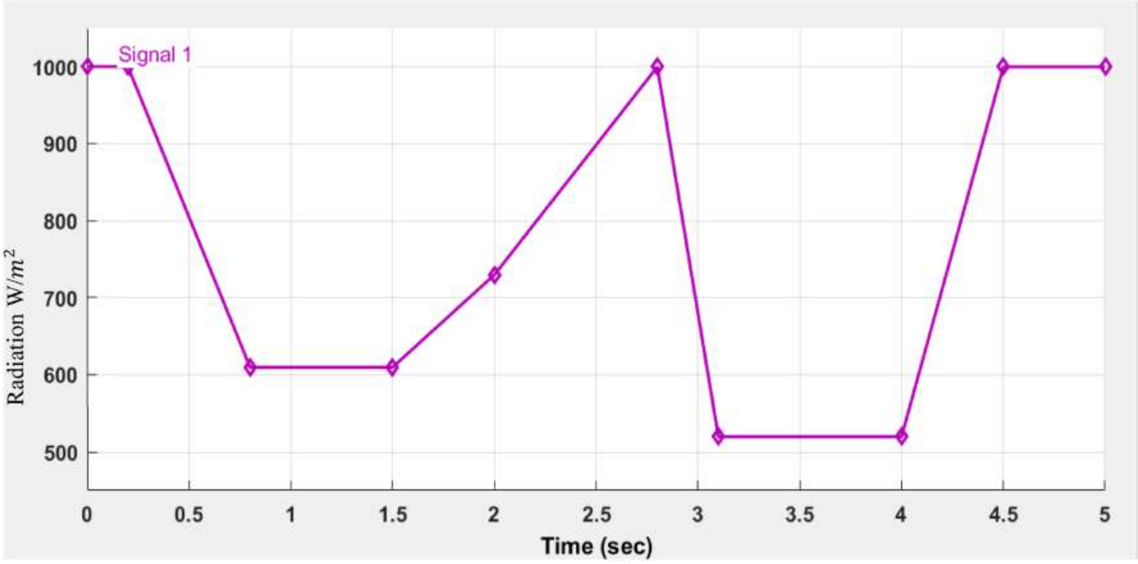

Fig. 15. Variation of solar irradiance with respect to time.

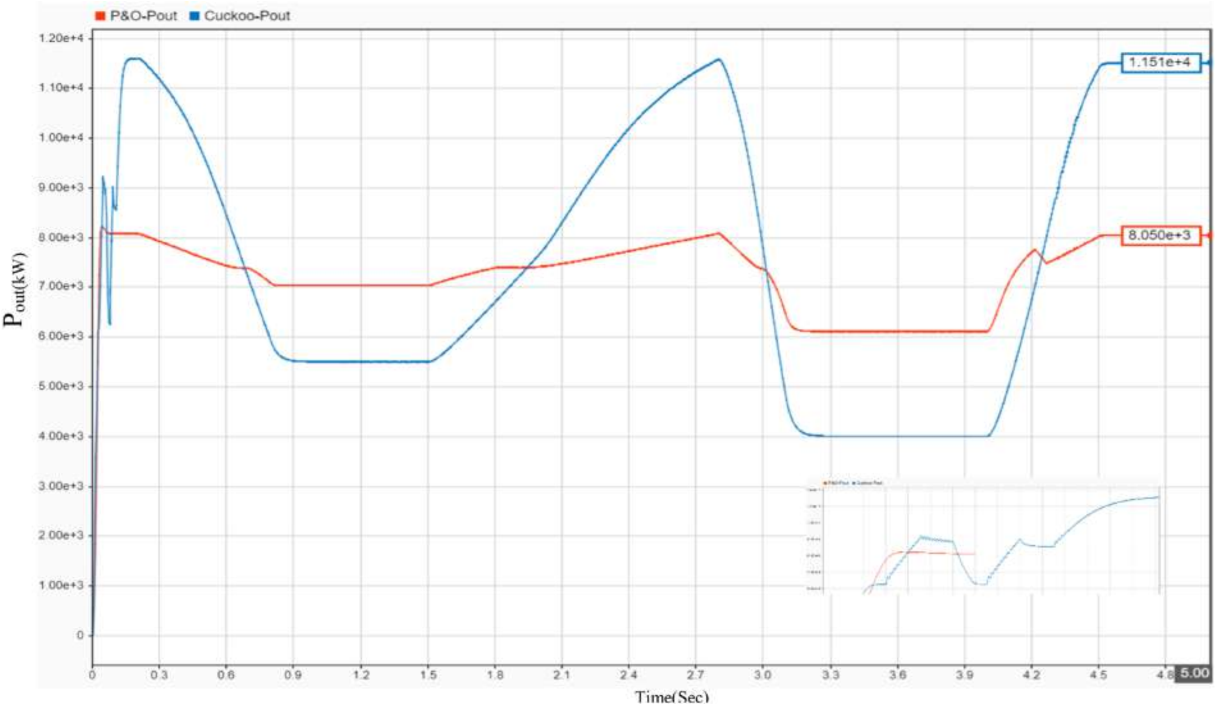

Fig. 16. Output energy vs time.

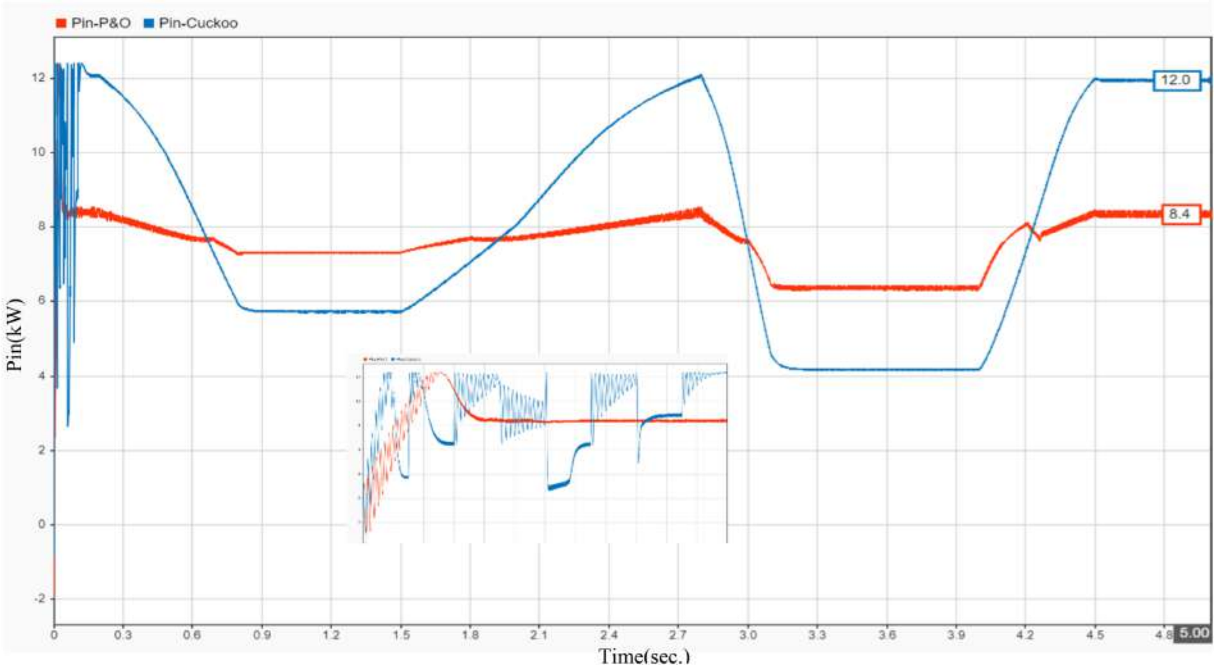

Fig. 17. Input power vs time.

The study is limited to global search methods, and the P&O algorithm doesn't refine a CS-based solution locally. Each MPPT method works independently. The CS-based MPPT naturally combines exploration and exploitation in its optimization process to find the maximum power point.

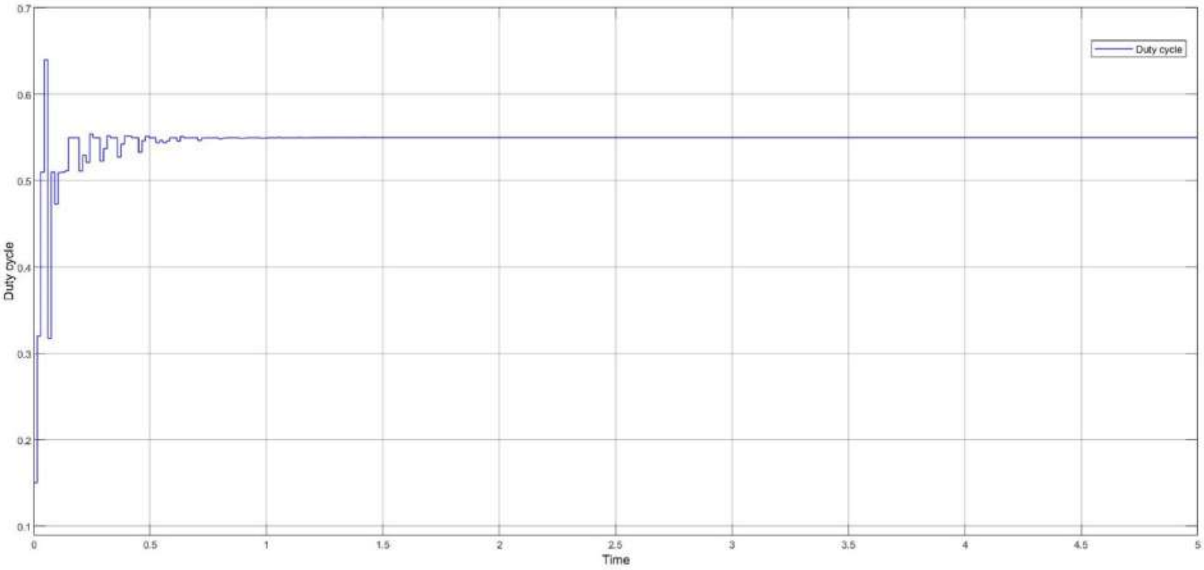

Fig. 18. Duty cycle vs time.

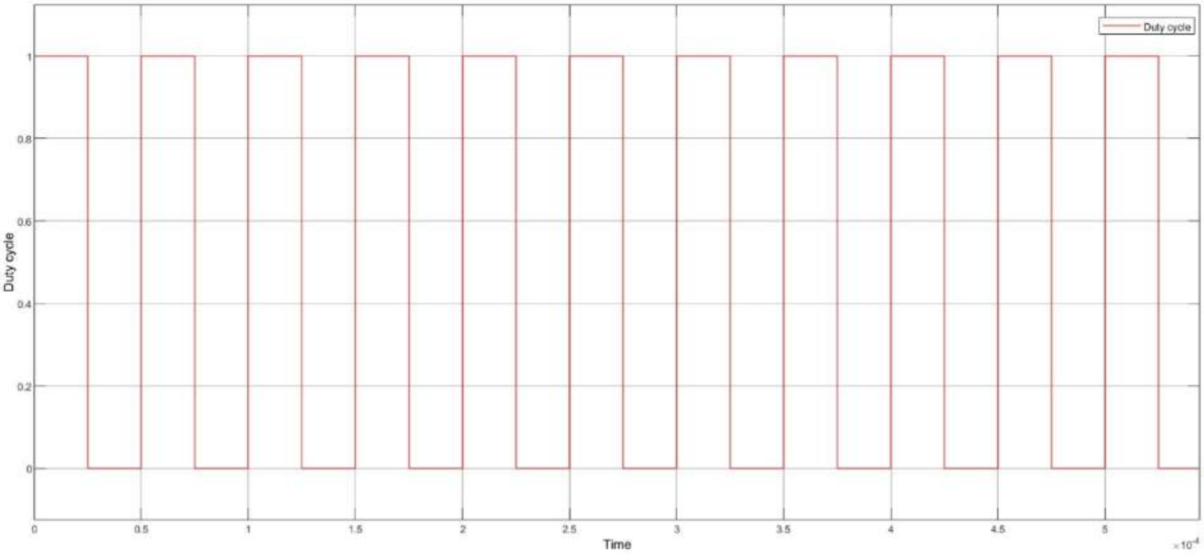

Fig. 19. Duty cycle vs time.

Similarly, the P&O MPPT works as a separate local search algorithm, using perturbation and observation of the operating point.

Therefore, this research doesn't use a hierarchical or combined global-local search approach. The results presented are solely based on a comparison of the two MPPT methods.

Table 1 compares the performance of CS MPPT and P&O MPPT under standard test conditions (25 °C and 1000 W/m^2). The results clearly indicate that CS MPPT outperforms P&O MPPT in terms of power extraction and overall system efficiency. This superior performance reflects the ability of CS MPPT to more accurately track the maximum power point and maintain stable operation.

The improved voltage and current regulation observed with CS MPPT highlights its effectiveness in delivering consistent electrical output under ideal conditions. In contrast, the fixed duty cycle observed in the P&O MPPT suggests limited control flexibility, which may lead to converter stress and reduced operational stability. Furthermore, the higher energy yield achieved by CS MPPT

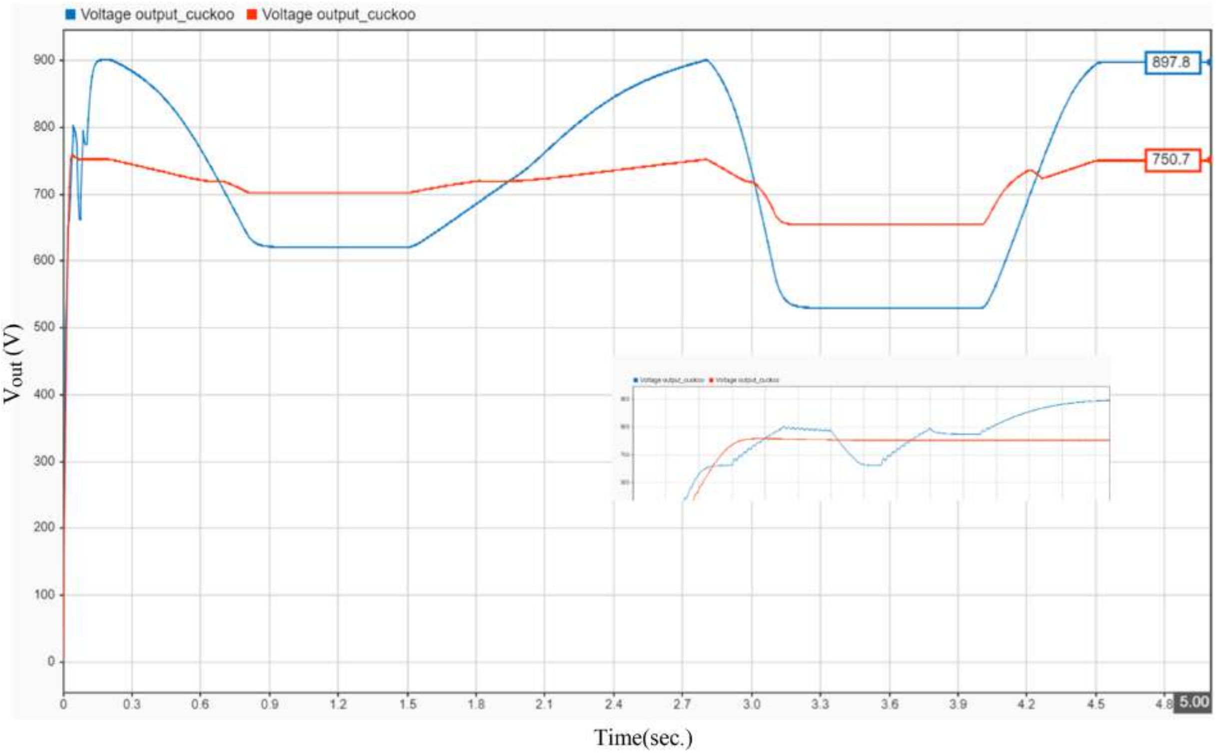

Fig. 20. Output voltage vs time.

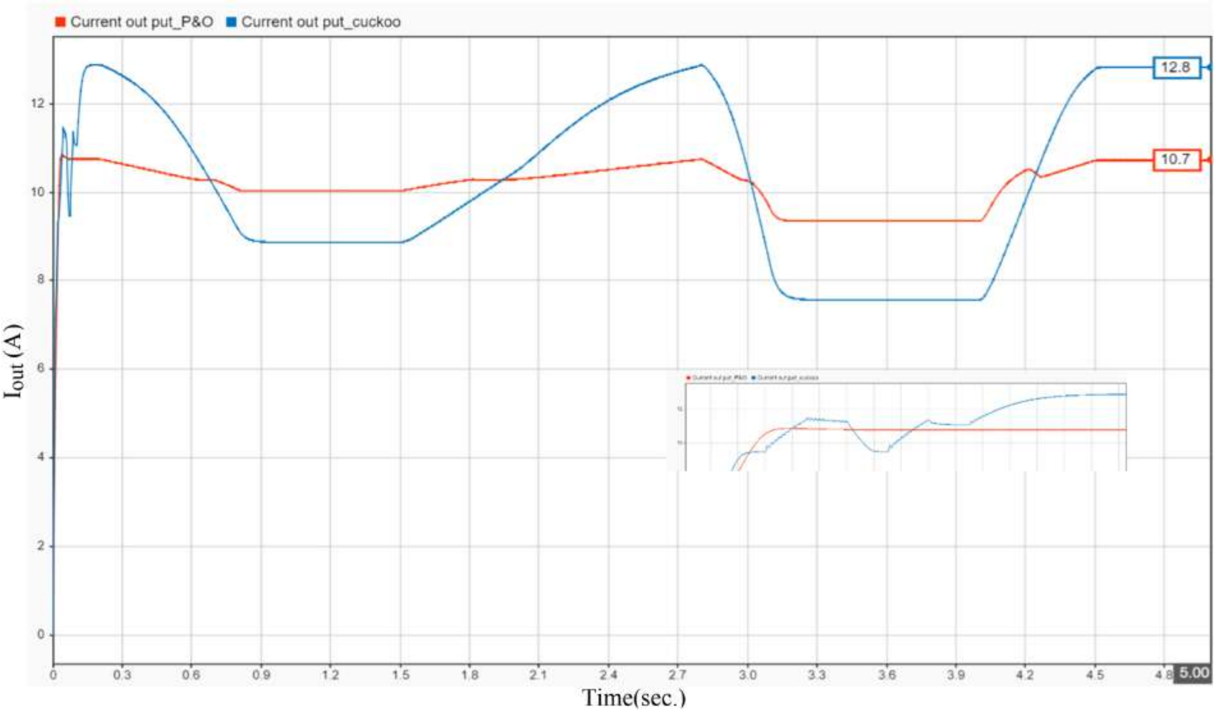

Fig. 21. Output current vs time.

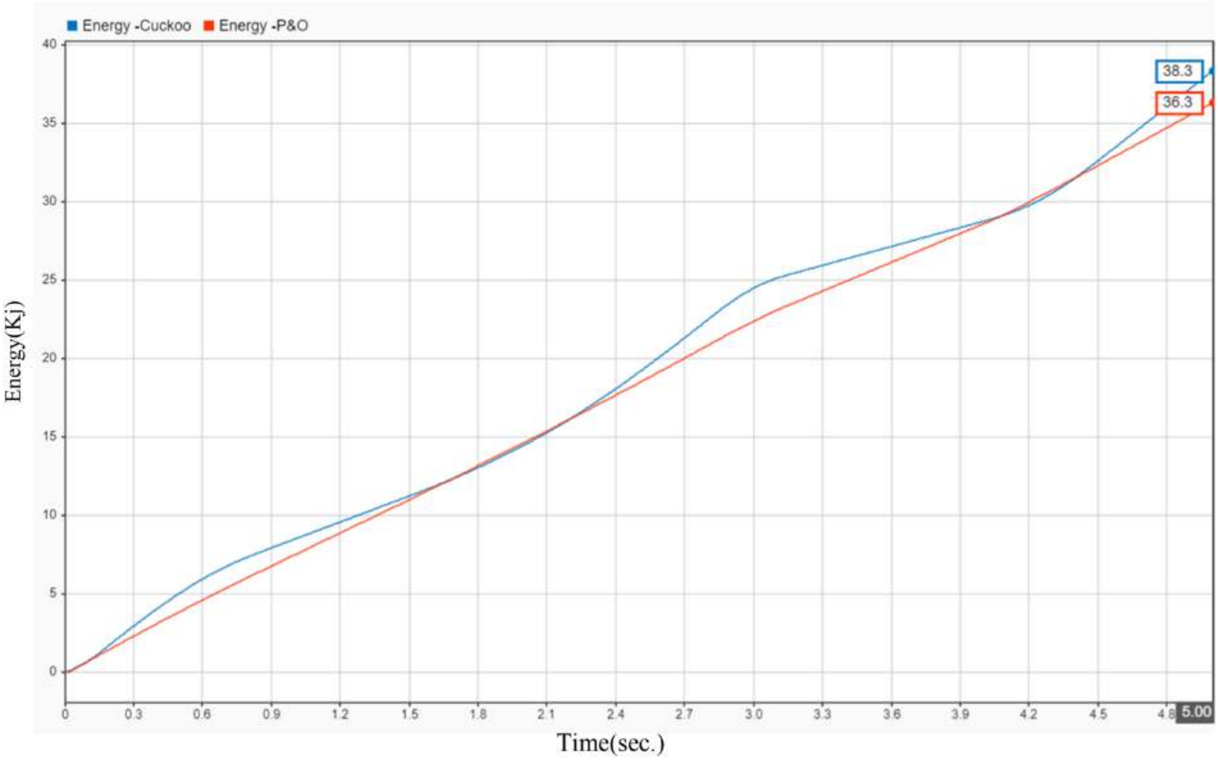

Fig. 22. Output energy vs time.

Table 1. Summary of variables results under STC case one.

Values of parameters under STC case one							
MPPT Technique	P_{in}(kW)	P_{out} (kW)	V_{out} (V)	I_{out} (A)	Duty cycle	Epv (kJ)	Efficiency (%)
CS MPPT	12.09	11.62	901.8	12.88	0.5193	57.49	93.46
P&O MPPT	8.402	8.088	752.4	10.75	1	40.28	65.05

demonstrates its enhanced capability in maximizing harvested solar energy.

Overall, the significantly higher efficiency obtained with CS MPPT confirms its advantage in minimizing conversion losses and improving energy utilization compared to the conventional P&O approach.

Table 2 illustrates the system's performance across a range of irradiance scenarios, thereby mirroring the conditions encountered in actual photovoltaic (PV) operations. Within these fluctuating circumstances, the CS MPPT algorithm continues to exhibit enhanced adaptability and resilience when contrasted with the P&O MPPT approach.

The findings indicate that CS MPPT ensures consistent power output, notwithstanding variations in solar irradiance, which suggests a more rapid and precise tracking of the maximum power point. Its capacity to maintain dependable voltage and current levels underscores its robust dynamic control capabilities. Conversely, the restricted duty cycle adjustments inherent in P&O MPPT limit its responsiveness, consequently diminishing its tracking efficiency.

Table 2. Summary of variables results under changing irradiance conditions second case.

Values of parameters under changing irradiance conditions second case.							
MPPT Technique	P_{in} (kW)	P_{out} (kW)	V_{out} (V)	I_{out} (A)	Duty cycle	E_{out} (kJ)	Efficiency (%)
CS MPPT	11.98	11.51	897.8	12.83	0.5499	38.33	92.58
P&O MPPT	8.362	8.05	750.7	10.72	1	36.31	64.75

Regarding energy yield and overall efficiency, CS MPPT consistently surpasses P&O MPPT, even when subjected to non-uniform irradiance. This observation underscores the practical applicability of CS MPPT in real-world PV applications, where environmental conditions are subject to inherent variability.

In contrast to prior research on CS-based MPPT, which primarily emphasizes the development or hybridization of the CS algorithm, this study offers a comprehensive comparative performance assessment of CS MPPT and traditional P&O MPPT. This evaluation is conducted under identical operational and irradiance parameters, thereby elucidating their practical distinctions in terms of efficiency, energy output, and dynamic responsiveness [40].

6. Conclusions

From Table 1, it has been concluded that the under stander condition that in every performance metric, CS MPPT performs noticeably better than P&O MPPT. It produces more steady voltage and current output, is more energy-efficient, and extracts more energy. Even in the best of circumstances, this makes CS MPPT a better option for high-efficiency solar systems.

The findings demonstrate that the CS MPPT method surpasses the P&O MPPT approach. Specifically, CS MPPT yields a greater output power, approximately 3.53 kW, which translates to an enhancement of roughly 44 %. Furthermore, it delivers a higher output voltage, approximately 149.4 V, and a greater output current, 2.13 A, both of which represent nearly a 20 % improvement. Moreover, CS MPPT facilitates the extraction of more energy, roughly 17.21 kJ, equivalent to an improvement of around 43 %, and exhibits a considerably higher efficiency, with an absolute increase of 28.41 % relative to P&O MPPT.

From Table 2, it has been concluded that the Under situations of fluctuating irradiance:

When it comes to power tracking, output consistency, and efficiency, CS MPPT performs noticeably better than P&O MPPT.

For real-world applications where solar irradiation fluctuates, CS MPPT works better. Despite its simplicity, the P&O approach loses energy because it lacks the dynamic adaptability required in changing conditions.

The results indicate that the CS MPPT approach yields a significant enhancement relative to the P&O MPPT method. Specifically, the output power exhibited a 3.46 kW increase, which translates to an approximate 43 % improvement; concurrently, the output voltage rose by 147.1 V, and the output current saw a 2.11 A increase. Furthermore, the output energy improved by 2.02 kJ, and the efficiency experienced a 27.83 % increase, thereby validating the CS MPPT method's superior efficacy in optimizing PV system performance.

7. Recommendations

For better performance of the solar system, it is preferable to use CSMPPT technology.

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Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Ethical Approval

This study does not involve human participants, animals, or clinical trials. Therefore, ethical approval was not required.

Data Availability

All data supporting the findings of this study are fully available within the article.

Author Contributions

Abdullah A. Alwani: Conceptualization, methodology, simulation, writing – original draft preparation.

Sura H. Faraj: Algorithm development, validation, data analysis.

Salih Y. Darweesh: Theoretical framework, supervision, scientific review, editing.

Ahmed J. Ali: Software implementation, performance evaluation.

Muhammad Hamza Zafar: Manuscript review, technical verification, final approval.

All authors have read and approved the final manuscript.

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