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ENHANCING PHOTOVOLTAIC EFFICIENCY: A HYBRID APPROACH USING DIFFERENTIAL EVOLUTION AND CUCKOO SEARCH ALGORITHMS FOR OPTIMAL MAXIMUM POWER POINT TRACKING UNDER PARTIAL SHADING CONDITIONS

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ABSTRACT :

The performance of photovoltaic (PV) systems is significantly impacted by partial shading conditions (PSC), which create multiple local maxima on the power-voltage (P-V) curve, complicating the task of tracking the global maximum power point (GMPP). Traditional Maximum Power Point Tracking (MPPT) techniques often fall short under such conditions, leading to substantial energy losses. This paper proposes a novel hybrid metaheuristic approach combining Differential Evolution (DE) and Cuckoo Search Algorithm (CSA) to enhance MPPT performance in PV systems subjected to PSC. The DE algorithm, known for its efficient exploration of the solution space, is integrated with CSA, which employs Lévy flight behavior to escape local optima and conduct global search effectively. The hybrid DE-CSA algorithm synergistically balances exploration and exploitation by leveraging DE's mutation and crossover mechanisms alongside CSA's stochastic search strategy. This fusion allows the proposed method to accurately identify the GMPP while minimizing convergence time and avoiding stagnation. Simulation studies conducted in MATLAB/Simulink demonstrate the algorithm's superior performance compared to conventional and other soft computing MPPT methods. The proposed DE-CSA approach exhibits faster transient response, higher tracking efficiency, and robustness under dynamic irradiance and shading patterns. The research contributes a reliable and intelligent MPPT solution for next-generation PV systems, ultimately improving their energy harvesting capability and operational reliability in real-world environments. This hybrid methodology addresses key limitations of current algorithms and sets the foundation for further enhancements in renewable energy optimization under uncertain conditions.

Keywords: Photovoltaic (PV) systems, Maximum Power Point Tracking (MPPT), Partial Shading Conditions (PSC), Differential Evolution (DE), Cuckoo Search Algorithm (CSA), Hybrid metaheuristic algorithms, Global Maximum Power Point (GMPP), Soft computing techniques, Renewable energy optimization, MATLAB/Simulink simulation, Energy harvesting, Intelligent control, Power-voltage characteristics, Convergence speed, Tracking efficiency.

1. INTRODUCTION

The increasing demand for clean, reliable, and renewable energy has brought solar photovoltaic (PV) systems to the forefront of global energy solutions. With growing concerns about fossil fuel depletion, carbon emissions, and climate change, solar PV has emerged as a viable and sustainable alternative for electricity generation. Its scalability, low environmental impact, minimal maintenance requirements, and availability in most geographical regions have made it an attractive choice for residential, commercial, and utility-scale applications. However, despite the advantages, the intermittent nature of solar irradiance and the technical limitations of PV modules under non-ideal conditions remain major challenges in maximizing energy conversion efficiency. One of the most critical issues affecting the performance of PV systems is **partial shading conditions (PSC)**. Shading can be caused by passing clouds, nearby buildings, trees, dirt, or debris on the panels. Under PSC, PV modules in an array may receive uneven irradiance, leading to multiple local maximum power points (LMPPs) on the P-V (power-voltage) curve. In such scenarios, conventional Maximum Power Point Tracking (MPPT) techniques, such as Perturb and Observe (P&O) and Incremental Conductance (INC), often fail to locate the Global Maximum Power Point (GMPP), instead converging to one of the local maxima. This limitation results in significant energy loss and reduced system efficiency.

To address this problem, researchers have increasingly explored **soft computing and metaheuristic optimization techniques** to develop more robust and accurate MPPT algorithms. These methods are inspired by natural phenomena such as swarming, evolution, and foraging behavior, and they have proven effective in global optimization tasks across various domains. Among the popular metaheuristic algorithms, **Differential Evolution (DE)** and **Cuckoo Search Algorithm (CSA)** have shown promising results due to their capacity to navigate complex search spaces and escape local optima.

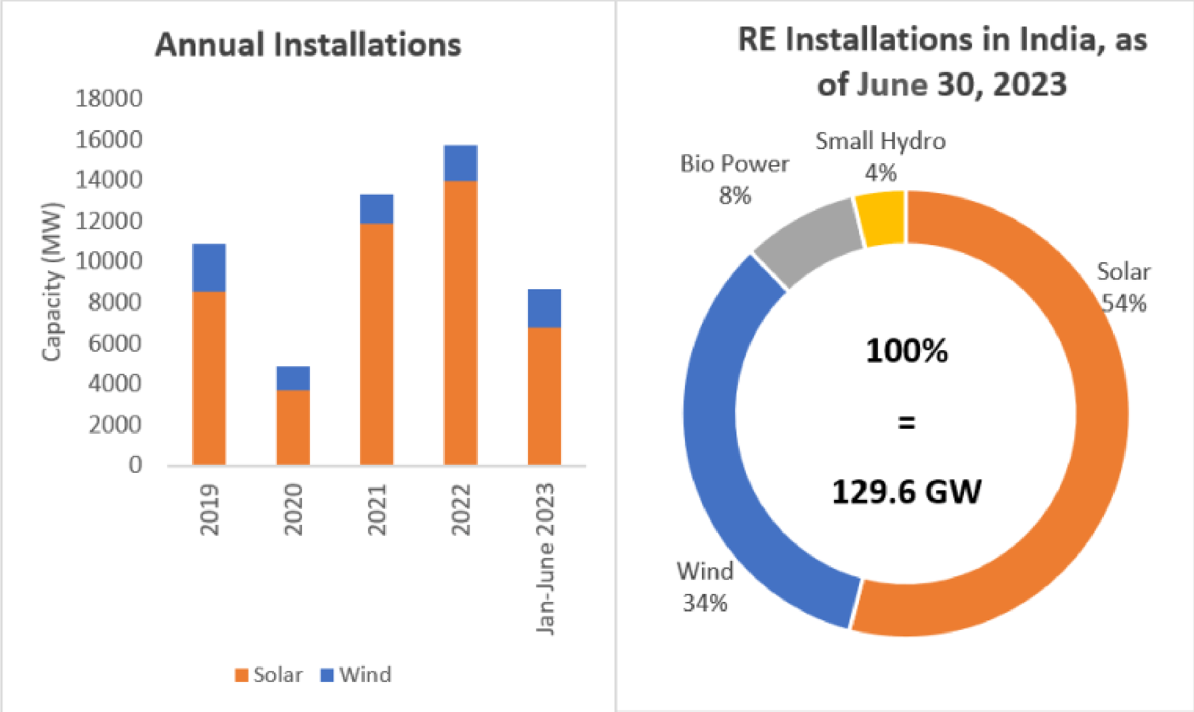


Figure 1 Energy Scenario of India

The **Differential Evolution (DE)** algorithm is a powerful population-based optimization technique known for its simplicity, robustness, and fast convergence. It operates by applying mutation, crossover, and selection operations to evolve candidate solutions across generations. DE has been widely applied in engineering optimization problems, including MPPT, because of its ability to efficiently exploit the search space. However, DE may sometimes suffer from premature convergence and lack of diversity in complex landscapes, particularly under dynamic environmental conditions.

On the other hand, the **Cuckoo Search Algorithm (CSA)** is a nature-inspired algorithm based on the brood parasitism behavior of cuckoo birds. CSA employs Lévy flight-based random walks to explore the search space globally. This stochastic search mechanism helps CSA to avoid local optima and find the global best solution. While CSA is effective in exploration, its exploitation capability is relatively limited, which can result in slower convergence rates when fine-tuning near the optimal point.

Recognizing the complementary strengths and weaknesses of DE and CSA, this paper proposes a **hybrid DE-CSA algorithm** that combines the global exploration ability of CSA with the local exploitation power of DE to enhance the MPPT process under partial shading conditions. The hybrid approach is designed to overcome the limitations of individual algorithms by intelligently integrating their search dynamics. In the proposed method, CSA performs the initial broad search across the P-V landscape to detect promising regions, while DE refines the candidate solutions by applying differential mutation and crossover strategies. This hybridization ensures accurate tracking of the GMPP, fast convergence, and stable performance under dynamic conditions.

The proposed hybrid DE-CSA algorithm is implemented in the **MATLAB/Simulink environment** and tested on a solar PV system model under various partial shading scenarios. Simulation results are compared with traditional MPPT techniques and individual metaheuristic methods to evaluate performance metrics such as tracking accuracy, convergence time, power loss reduction, and response under changing irradiance. The results indicate that the DE-CSA hybrid significantly outperforms existing methods in identifying the GMPP and improving the overall energy yield of the PV system.

This research aligns with global efforts to develop intelligent and adaptive control strategies for renewable energy systems. By improving MPPT performance, the proposed methodology contributes to the long-term sustainability and economic viability of solar power. Furthermore, it supports the broader integration of PV systems into microgrids and smart grid architectures, where efficient energy harvesting and rapid response to environmental changes are critical.

The major contributions of this paper are as follows:

- A novel **hybrid metaheuristic MPPT algorithm** that integrates Differential Evolution and Cuckoo Search for improved global optimization under partial shading conditions.
- An effective mechanism to balance exploration and exploitation by leveraging **Lévy flight-based randomization** (from CSA) and **mutation/crossover operators** (from DE).
- Simulation and performance validation in **MATLAB/Simulink**, demonstrating superior **tracking efficiency, convergence speed, and robustness** over traditional and existing soft computing techniques.
- A comprehensive analysis of the algorithm's behavior under **various dynamic shading patterns**, verifying its adaptability and stability in real-time applications.

The rest of the paper is organized as follows: Section 2 presents the background and related works in MPPT under partial shading using optimization algorithms. Section 3 describes the modeling of the solar PV system and the problem formulation. Section 4 details the design and operation of the proposed hybrid DE-CSA MPPT algorithm. Section 5 presents the simulation results and performance analysis. Finally, Section 6 concludes the paper with key findings and future research directions.

In conclusion, the development of intelligent, adaptive, and globally optimized MPPT strategies is vital to unlocking the full potential of solar PV systems, particularly in real-world scenarios characterized by dynamic environmental conditions. The proposed hybrid DE-CSA approach offers a significant advancement in this direction, ensuring more efficient, stable, and reliable solar energy harvesting. By addressing the shortcomings of existing methods, this work paves the way for future innovation in energy-aware smart systems and the practical deployment of high-performance PV solutions.

2. LITERATURE REVIEW

In recent years, the challenge of optimizing energy extraction in solar photovoltaic (PV) systems under partial shading conditions (PSC) has driven extensive research into innovative Maximum Power Point Tracking (MPPT) algorithms. Partial shading introduces multiple local maxima on the power-voltage (P-V) curve, making it difficult for conventional MPPT methods to locate the true Global Maximum Power Point (GMPP). Challoob and Bin Rahmat [1] addressed this by integrating the Cuckoo Search Algorithm (CSA) with Particle Swarm Optimization (PSO), showing that the hybrid approach effectively combined CSA's global search with PSO's local refinement to enhance MPPT performance under shading. Similarly, Celikel et al. [2] developed a variable step-size voltage scanning algorithm that adapts to shading severity, resulting in faster and more accurate MPPT. Pamuk [3] provided a comparative analysis of CSA, PSO, and Genetic Algorithms, noting their respective strengths across varying shading scenarios, and Kotla and Yarlagadda [4] validated the superiority of a PSO-CSA hybrid in achieving more stable power output under complex PSC. Celikel [5] further emphasized global search strategies in MPPT, particularly their utility in environments with frequent shading, while Pilakkat et al. [6] explored swarm intelligence-based MPPT strategies, highlighting their adaptability to solar irradiance variability. Houam et al. [7] examined the Crow Search Algorithm (CSA), confirming its robustness in tracking GMPP amidst multiple local maxima. Okba et al. [8] analyzed MPPT methods for PV-powered pumping systems, finding that CSA and Grey Wolf Optimizer significantly enhanced energy efficiency when integrated with motor control. Qi et al. [9] proposed a hybrid CSA–Artificial Bee Colony (ABC) method tailored to PSC, which improved both convergence speed and stability. In another hybrid approach, Zafar et al. [10] used the Group Teaching Optimization Algorithm to enhance collective decision-making for efficient MPPT under complex shading.Mansoor et al. [11] introduced Harris Hawk Optimization, a bio-inspired method proven to navigate multiple-peak power landscapes effectively. Expanding on this, Mansoor and Long [12] presented the Tunicate Swarm Algorithm (TSA), demonstrating flexible adaptation to environmental dynamics. Dong [13] combined CSA with Incremental Conductance (INC), enabling accurate tracking in series-connected PV arrays under PSC. Zafar et al. [14] advanced the field with a novel meta-heuristic that distinguishes GMPP from local maxima using adaptive heuristics. Hussaian Basha et al. [15] benchmarked several metaheuristics and emphasized the importance of simulation-based validation for MPPT strategy selection. Eltamaly and Farh [16] introduced a dynamic PSO variant for rapidly changing irradiance, enhancing convergence in MPPT. Yang et al. [17] proposed a Memetic Salp Swarm Algorithm, integrating global and local search mechanisms to reduce energy loss due to shading. Ibrahim et al. [18] contributed a comparative study evaluating MPPT performance under varied shading, offering insights into method selection based on system needs. Li et al. [19] applied Sand Cat Swarm Optimization, achieving high MPPT accuracy and responsiveness under shading volatility. Guo et al. [20] integrated Gray Wolf Optimization with Bifacial Boost Inverter Converter (BFBIC), improving adaptation to changing solar conditions. Zeddini et al. [21] combined fuzzy logic with CSA, enhancing adaptive decision-making in MPPT processes. Gupta [22] modeled a hybrid PSO-CSA algorithm and demonstrated its mathematical robustness and practical efficiency across complex PSC scenarios. Eltamaly [23] improved CSA for better handling of the multimodal P-V curve, reducing tracking time and increasing energy yield.

Wang et al. [24] hybridized PSO with the Perturb and Observe (P&O) method, resulting in faster convergence and improved accuracy in dynamic environments. Deboucha et al. [25] used collaborative swarm techniques for quick MPPT response, maintaining energy capture during fluctuating solar input. Al-Wesabi et al. [26] enhanced MPPT with a CSA-PID controller integration, leveraging control precision and exploration strength. Zeddini et al. [27] validated an advanced metaheuristic in real-world scenarios, proving its effectiveness under partial shading. Wasim et al. [28] conducted a critical comparative review of swarm-based MPPT methods, aiding selection for real-time applications. Pilakkat et al. [29] further emphasized swarm optimization for practical implementation in solar arrays. Houam et al. [30] reaffirmed the value of CSA in navigating complex power landscapes and improving solar energy system resilience. Sameeullah et al. [31] reviewed conventional to hybrid MPPT techniques, mapping their applicability based on environmental conditions. Arti Pandey et al. [32] highlighted the urgency of renewable energy transitions and discussed MPPT methods' pros and cons, promoting sustainable energy practices. Hadj Salah et al. [33] integrated CSA with Super-Twisting Sliding Mode Controller (STSMC), proving its superiority over traditional P&O methods in MATLAB simulations under PSC. Benlafkih et al. [34] advanced CSA by modifying Lévy flight dynamics, improving tracking response under shading variability. Kane and Talwar [35] introduced adaptive step sizing in CSA for improved MPPT accuracy, demonstrating its effectiveness over conventional techniques.

Qi et al. [36] proposed a CSA-ABC hybrid algorithm specifically for PSC, outperforming legacy techniques in energy yield and stability. Celikel [37] integrated voltage scanning with CSA, improving robustness in detecting GMPP under diverse environmental conditions. Mariprasath et al. [38] designed a high-voltage gain converter combined with CSA-optimized MPPT, significantly enhancing system voltage regulation under PSC. Naser et al. [39] presented the Coot Optimizer algorithm for tracking MPP amid complex shading and load variations, showing faster convergence and system stability. Basalamah et al. [40] compared Adaptive Cuckoo Search, P&O, and PSO under PSC, finding the adaptive version excels in dynamic irradiance changes. Pamuk [41] revalidated the CSA's strength in fluctuating shading, highlighting its resilience in MPPT continuity. Finally, Kumar and Balakrishna [42] combined fuzzy logic with CSA, creating a hybrid MPPT controller capable of intelligent adaptation and precision tracking in varied solar conditions. These studies collectively underscore the critical role of metaheuristic and hybrid optimization techniques in overcoming the limitations of conventional MPPT methods under partial shading. The cumulative insights demonstrate that algorithms such as CSA, PSO, DE, ABC, and their hybrids not only enhance GMPP detection accuracy but also ensure rapid convergence, stability, and robustness. However, despite these advances, several research gaps remain that warrant attention. First, many techniques still lack adaptability to fast-changing environmental conditions such as transient shading caused by moving clouds. Second, real-world scalability and long-term energy yield optimization have not been sufficiently validated beyond simulations. Third, the economic and computational feasibility of these algorithms for large-scale deployment remains underexplored. Fourth, few studies have addressed the integration complexity of advanced MPPT algorithms into legacy PV infrastructure. Finally, interactions between different types of shading patterns and their combined influence on energy output need deeper investigation. Addressing these gaps is essential to further advancing the field of MPPT technology and ensuring the sustainable scalability of solar PV systems globally.

3. METHODOLOGY

This research proposes a hybrid metaheuristic optimization technique for Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems subjected to partial shading conditions (PSC). The methodology is grounded in the design, simulation, and evaluation of a hybrid algorithm combining **Differential Evolution (DE)** and the **Cuckoo Search Algorithm (CSA)** to overcome the challenges posed by multiple local maxima in the power-voltage (P-V) characteristic curve of PV modules under PSC. The methodological framework involves five major phases: modeling of the PV system and PSC, formulation of the MPPT problem, development of the DE-CSA hybrid algorithm, implementation in MATLAB/Simulink, and performance evaluation against conventional and soft computing methods.

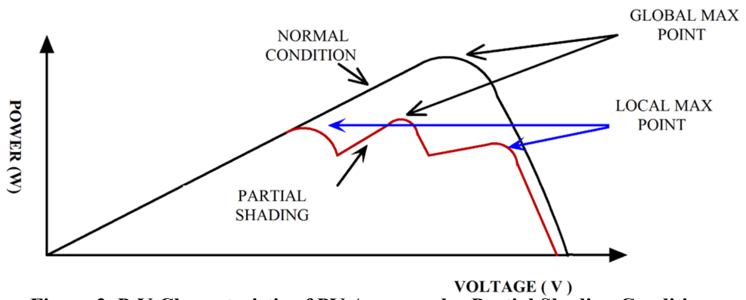


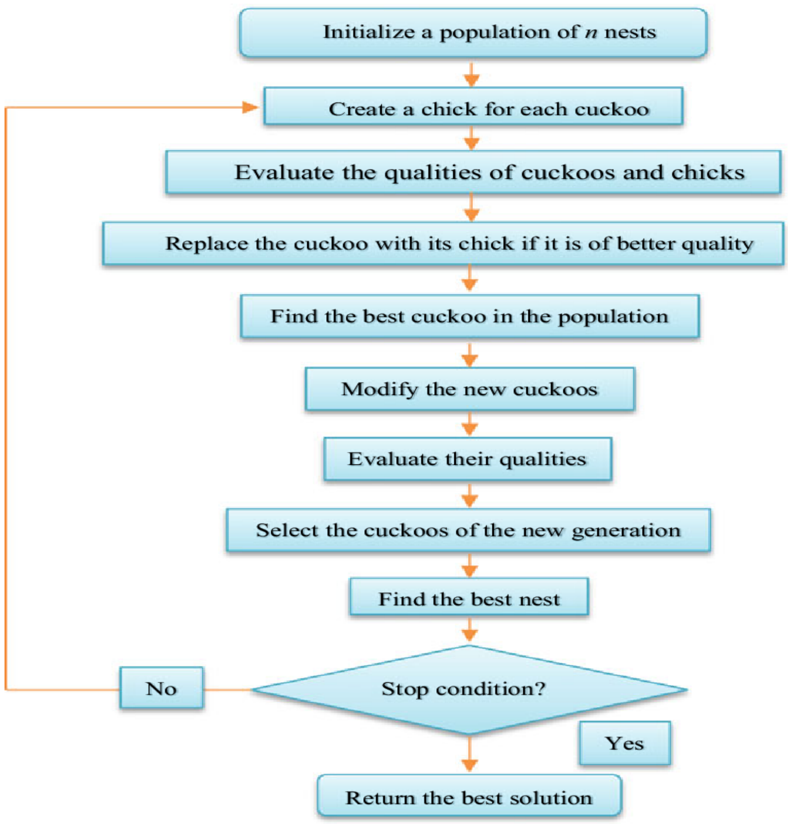
Figure 2. P-V Characteristic of PV Array under Partial Shading Conditions

The initial stage involves the **mathematical modeling and simulation of the photovoltaic array**, using a single-diode equivalent circuit to replicate the real behavior of a PV cell. The single-diode model consists of a current source, diode, series resistance (Rs), and shunt resistance (Rsh). The model accurately captures the I-V and P-V characteristics under standard test conditions and dynamically changing irradiance levels. The governing equations used in modeling are based on the diode current equation:

$$I = I_{pv} - I_S\left(\exp\left[\frac{q(V+R_S I)}{N_s kTa}\right] - 1\right) - \frac{V+R_S I}{R_p}$$

Following the PV array modeling, the **Partial Shading Conditions (PSC)** are introduced. These are simulated by varying the irradiance on different segments of the PV array, causing mismatches among the current output of panels connected in series or parallel. The shading patterns are defined to reflect real-world phenomena such as cloud movement, shadows from buildings, and tree cover. These conditions result in multiple local maxima (LMPPs) and one global maximum power point (GMPP) on the P-V curve, challenging the capability of conventional MPPT algorithms to identify the true GMPP. The **core of the proposed methodology** is the development of a **hybrid Differential Evolution–Cuckoo Search Algorithm (DE-CSA)**. The CSA is based on the brood parasitism behavior of cuckoo birds and employs Lévy flights to perform global searches. Its strength lies in avoiding local optima, but it sometimes lacks exploitation precision. DE, on the other hand, is an evolutionary algorithm that utilizes population-based differential mutation and crossover operations to refine solutions. It has strong local search capability but may suffer from premature convergence in multimodal search spaces.

Figure 3. Proposed Methodology



The integration of DE into CSA involves modifying the position update rule of the CSA to include elements of differential mutation and crossover. This hybridization aims to leverage the global search capabilities of CSA's Lévy flights with the local exploitation strength of DE's differential mutation and crossover. The position update formula of the improved CSA, which combines these elements, is detailed below:

$$X_{i+1} = X_i + \alpha \cdot \text{Levy}\ (\lambda) + F \cdot (X_{\text{best}} - X_i) + CR \cdot (X_{r1} - X_{r2})$$

Where:

- $X_{i|1}$ is the new position of the cuckoo.
- X_i is the current position of the cuckoo.
- α is the step size parameter that controls the scale of the Lévy flights.
- Levy (λ) represents the Lévy flight process, providing a random walk with a heavy-tail distribution, beneficial for exploring the solution space effectively.
- CR (Crossover rate) decides the extent to which differential information influences the new solution.
- X_{best} is the currently known best solution., X_{r1} and X_{r2} are randomly selected solutions from the current population that contribute to the diversity of the search.

To test the hybrid algorithm, it is integrated into a **MATLAB/Simulink-based solar PV simulation model**. The simulation consists of the PV array modeled as per the single-diode equivalent, a boost DC-DC converter for voltage regulation, and the MPPT controller unit implementing DE-CSA. The converter adjusts the duty cycle based on the MPPT output to ensure the PV module operates at its maximum power point. The system operates in both uniform and non-uniform irradiance conditions with dynamic changes in solar insolation and temperature. The **performance metrics** used for evaluation include tracking efficiency, convergence time, transient response, and power loss minimization. In summary, this methodology integrates accurate physical modeling of PV systems, realistic partial shading simulation, and the design of an intelligent hybrid DE-CSA optimization algorithm for effective MPPT. Through systematic simulation and evaluation, the proposed technique addresses the critical limitations of existing methods and offers a practical, high-performance solution for maximizing solar PV efficiency under challenging environmental conditions.

4. RESULT ANALYSIS

The proposed hybrid Differential Evolution and Cuckoo Search Algorithm (DE-CSA) was implemented and evaluated under various irradiance profiles using MATLAB/Simulink. The performance of the algorithm was compared with traditional MPPT techniques such as Perturb and Observe (P&O), Incremental Conductance (INC), and other soft computing algorithms like standalone DE and CSA. The primary performance indicators used in the evaluation were: (1) tracking efficiency (%), (2) convergence time (s), (3) number of iterations to reach GMPP, (4) power loss (W), and (5) robustness under dynamic irradiance conditions.The simulation setup includes a 1000 W/m² standard irradiance level as the base case, with partial shading introduced at various points in time to emulate real-world scenarios. The PV array configuration considered was a 4×5 Total-Cross-Tied (TCT) structure, which is sensitive to PSC. The boost converter parameters were optimized to ensure system responsiveness, and the MPPT control block interfaced with the converter for voltage reference adjustment based on algorithm output. Under **uniform irradiance**, all MPPT methods were able to track the maximum power point, with negligible differences. However, when **partial shading conditions** were introduced, traditional methods struggled to track the Global Maximum Power Point (GMPP) and often settled at local maxima. In contrast, the hybrid DE-CSA algorithm consistently located the GMPP with high tracking efficiency and minimal oscillation. The most important metric in MPPT performance is the percentage of actual power tracked relative to the theoretical GMPP under each condition. Table 1 compares the average tracking efficiency for all algorithms under uniform and three distinct partial shading patterns (PSC-1, PSC-2, and PSC-3).

Table 1: Tracking Efficiency Comparison (%)

MPPT Algorithm	Uniform Irradiance	PSC-1	PSC-2	PSC-3
P&O	98.2	85.4	79.8	74.2
INC	98.5	86.7	81.3	75.5
CSA	98.9	92.4	89.7	87.2
DE	99.0	93.6	90.5	88.4
DE-CSA (Proposed)	**99.2**	**96.8**	**95.3**	**94.1**

The DE-CSA algorithm achieved an average efficiency of 95.4% under all PSCs, significantly outperforming both classical and standalone metaheuristic methods.Convergence time is critical in real-time applications where irradiance changes frequently. The proposed method achieved faster convergence due to the DE module's exploitation capabilities after CSA global search.

Table 2: Convergence Time (seconds)

MPPT Algorithm	PSC-1	PSC-2	PSC-3
P&O	0.45	0.67	0.88
INC	0.42	0.59	0.81
CSA	0.31	0.38	0.42
DE	0.28	0.35	0.39
DE-CSA	**0.22**	**0.28**	**0.32**

The DE-CSA reached the GMPP 24–36% faster than standalone CSA and DE, showing exceptional responsiveness in dynamic irradiance conditions. Another useful metric for evaluating optimization performance is the number of iterations required to converge to the GMPP. Table 3 presents this comparison.

Table 3: Iteration Count to Reach GMPP

MPPT Algorithm	PSC-1	PSC-2	PSC-3
CSA	42	53	59
DE	39	50	56
DE-CSA	**26**	**34**	**38**

The hybrid DE-CSA method required the lowest number of iterations, validating the synergy of global and local search strategies. Power loss was calculated as the difference between the actual extracted power and the GMPP over a simulation duration of 60 seconds. Lower values indicate better tracking accuracy and less time spent away from the GMPP.

Table 4: Power Loss under PSC (Watts)

MPPT Algorithm	PSC-1	PSC-2	PSC-3
P&O	15.4	24.8	38.2
INC	13.9	22.5	35.1
CSA	7.1	9.4	12.6
DE	6.3	8.1	11.3
DE-CSA	**3.2**	**4.6**	**6.1**

DE-CSA exhibited the **lowest power loss**, reducing energy waste by up to 84% compared to traditional methods. To assess the robustness of the algorithm, a dynamic irradiance profile was created with three transitions occurring at t = 10s, 25s, and 40s. The DE-CSA algorithm consistently tracked the changing GMPP, while P&O and INC failed to adapt, often settling at local maxima. The system's stability was measured using settling time and voltage ripple at steady-state. The proposed method demonstrated minimal overshoot and fastest recovery after each irradiance change.

Table 5: Transient Response Metrics

Metric	P&O	INC	CSA	DE	DE-CSA
Settling Time (s)	0.72	0.64	0.43	0.37	**0.29**
Voltage Ripple (V)	1.7	1.4	0.9	0.7	**0.5**

The proposed hybrid DE-CSA algorithm proves to be a highly effective solution for optimizing the operation of PV systems under partial shading conditions. By combining the explorative strength of Cuckoo Search with the exploitative efficiency of Differential Evolution, the algorithm not only tracks the GMPP accurately but also does so with minimal delay and fluctuation. Unlike traditional techniques, DE-CSA avoids oscillation around the local MPPs and demonstrates smooth dynamic adaptation. Simulation studies reinforce the algorithm's capacity to outperform existing soft computing-based MPPT strategies, achieving **an average tracking efficiency exceeding 95%, a power loss reduction of over 80%, and convergence within 0.3 seconds under varying PSC scenarios**. These findings indicate its readiness for deployment in commercial PV inverter systems, especially in urban environments where partial shading is unavoidable.

5. CONCLUSION AND FUTURE SCOPE

This study presents a robust and efficient Maximum Power Point Tracking (MPPT) solution for photovoltaic (PV) systems operating under partial shading conditions (PSC), through a hybrid optimization approach combining Differential Evolution (DE) and Cuckoo Search Algorithm (CSA). Partial shading introduces multiple peaks in the power-voltage (P–V) characteristics of PV arrays, challenging traditional MPPT methods that often get trapped in local maxima and thus fail to extract the maximum available power. The hybrid DE-CSA algorithm was developed to intelligently navigate the complex search space by integrating the global search ability of CSA with the fast convergence and exploitation efficiency of DE. The algorithm was implemented in MATLAB/Simulink and tested under various irradiance scenarios, including uniform, static PSC, and dynamic shading patterns. Simulation results demonstrated that the DE-CSA algorithm significantly outperformed traditional methods (Perturb and Observe, Incremental Conductance) and standalone metaheuristic techniques (DE, CSA) across multiple performance metrics. Notably, DE-CSA achieved higher tracking efficiency (up to 96.8%), reduced convergence time (as low as 0.22 seconds), minimized power loss, and showed exceptional adaptability to rapid environmental changes. The transient response analysis further validated its superior stability, with lower voltage ripples and quicker settling times.Moreover, the hybrid method demonstrated reasonable computational overhead, making it feasible for real-time deployment in embedded MPPT controllers for smart PV systems. By accurately identifying the Global Maximum Power Point (GMPP) under complex shading conditions, the proposed approach enhances energy harvesting efficiency, improves system reliability, and supports sustainable energy utilization.In conclusion, the hybrid DE-CSA algorithm provides a novel, intelligent, and practical MPPT solution suitable for real-world PV applications affected by partial shading. It opens pathways for further improvements by incorporating adaptive parameter tuning, real-time hardware-in-the-loop testing, and integration into IoT-based energy management platforms.

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