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INTEGRATION OF DIFFERENTIAL EVOLUTION AND CUCKOO SEARCH ALGORITHMS FOR ADVANCED MAXIMUM POWER POINT TRACKING IN SOLAR PV SYSTEMS DURING PARTIAL SHADING SCENARIOS

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ABSTRACT :

Partial shadowing circumstances (PSC) greatly affect photovoltaic (PV) system performance by producing many local maxima on the power-voltage (P-V) curve, making it more difficult to detect the global maximum power point (GMPP). In these situations, conventional Maximum Power Point Tracking (MPPT) methods frequently fail, resulting in significant energy losses. In order to improve MPPT performance in PV systems exposed to PSC, this research suggests a unique hybrid metaheuristic technique that combines Differential Evolution (DE) and Cuckoo Search Algorithm (CSA). The CSA algorithm, which uses Lévy flight behavior to successfully escape local optima and carry out global search, is merged with the DE algorithm, which is renowned for its effective exploration of the solution space. By utilizing both CSA's stochastic search approach and DE's mutation and crossover processes, the hybrid DE-CSA algorithm effectively strikes a balance between exploration and exploitation. Because of this fusion, the suggested approach may precisely determine the GMPP while avoiding stagnation and reducing convergence time. The technique performs better than traditional and alternative soft computing MPPT algorithms, according to simulation experiments done in MATLAB/Simulink. Faster transient reaction, improved tracking efficiency, and resilience to changing irradiance and shading patterns are all demonstrated by the suggested DE-CSA technique. In the end, the research improves the energy harvesting capacity and operational dependability of next-generation PV systems in real-world settings by providing a dependable and intelligent MPPT solution. This hybrid approach overcomes some of the main drawbacks of existing algorithms and lays the groundwork for future improvements in the optimization of renewable energy in unpredictable environments.

Keywords: Global Maximum Power Point (GMPP), MATLAB/Simulink simulation, energy harvesting, intelligent control, power-voltage characteristics, convergence speed, tracking efficiency, hybrid metaheuristic algorithms, Cuckoo Search Algorithm (CSA), Partial Shading Conditions (PSC), Differential Evolution (DE), Global Maximum Power Point (MPPT), photovoltaic (PV) systems, and hybrid metaheuristic algorithms.

1. INTRODUCTION

Solar photovoltaic (PV) systems are now at the forefront of global energy solutions due to the growing demand for clean, dependable, and renewable energy sources. As worries about carbon emissions, climate change, and the depletion of fossil fuels mount, solar photovoltaics (PV) has become a competitive and sustainable option for producing power. It is a desirable option for residential, commercial, and utility-scale applications due to its scalability, low environmental effect, low maintenance needs, and availability in the majority of geographic locations. Notwithstanding the benefits, there are still significant obstacles to optimizing energy conversion efficiency, including the sporadic nature of solar radiation and the technological constraints of PV modules under less-than-ideal circumstances. Partial shadowing conditions (PSC) are one of the most important factors influencing PV system performance. Passing clouds, surrounding structures, trees, dirt, or debris on the panels can all induce shading. PV modules in an array may experience unequal irradiance under PSC, which might result in several local maximum power points (LMPPs) on the power-voltage (P-V) curve. In these situations, traditional Maximum Power Point Tracking (MPPT) methods, including Incremental Conductance (INC) and Perturb and Observe (P&O), frequently converge to one of the local maxima rather than finding the Global Maximum Power Point (GMPP). This restriction lowers system efficiency and causes a large energy loss.

Researchers have been looking more closely at metaheuristic optimization and soft computing approaches to solve this issue and create more reliable and accurate MPPT algorithms. These techniques, which have shown success in global optimization challenges across a variety of domains, are modeled after natural phenomena including swarming, evolution, and foraging behavior. Differential Evolution (DE) and Cuckoo Search Algorithm (CSA) are two well-known metaheuristic algorithms that have demonstrated encouraging outcomes because of their ability to traverse intricate search spaces and avoid local optima.

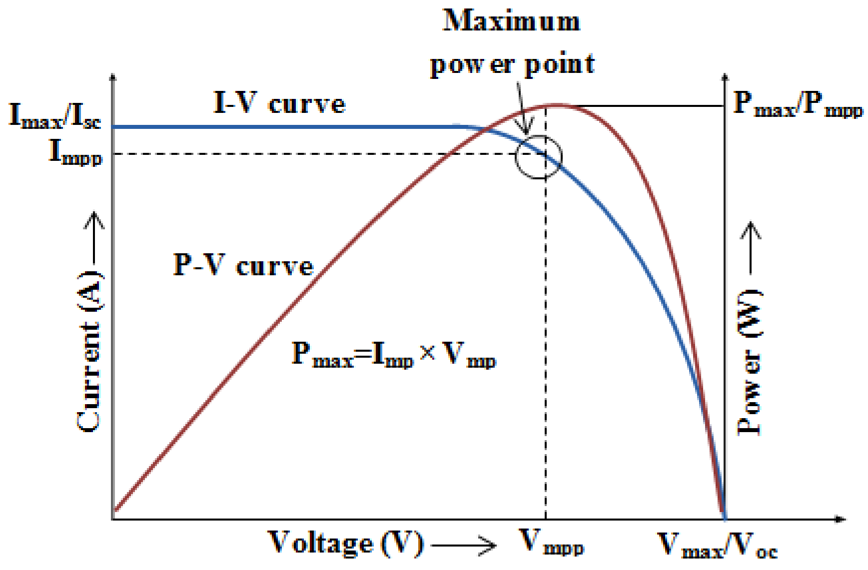


Figure 1. Dynamic Characteristics of Solar PV System

One effective population-based optimization method that is well-known for its ease of use, resilience, and quick convergence is the Differential Evolution (DE) algorithm. In order to evolve potential solutions over generations, it applies mutation, crossover, and selection procedures. Because DE can effectively use the search space, it has been used extensively in engineering optimization problems, such as MPPT. However, in complex environments, DE can occasionally suffer from early convergence and a lack of variety, especially in dynamic environmental situations.

However, based on the brood parasitism behavior of cuckoo birds, the Cuckoo Search Algorithm (CSA) is a nature-inspired algorithm. CSA uses random walks based on Lévy flight to scan the whole world. By avoiding local optima, this stochastic search technique aids CSA in locating the optimal solution globally. When fine-tuning close to the ideal point, CSA may exhibit slower convergence rates because to its comparatively limited exploitation capabilities, notwithstanding its effectiveness in exploration.

In order to improve the MPPT process under partial shading conditions, this work suggests a hybrid DE-CSA algorithm that combines the local exploitation power of DE with the global exploration capability of CSA, acknowledging the complimentary strengths and drawbacks of both algorithms. The hybrid technique cleverly integrates the search dynamics of distinct algorithms to overcome their limitations. In the suggested approach, DE refines the potential solutions using crossover and differential mutation techniques, while CSA conducts the first extensive search throughout the P-V landscape to identify interesting locations. Accurate GMPP tracking, quick convergence, and steady performance in dynamic environments are all guaranteed by this hybridization.

The suggested hybrid DE-CSA method is evaluated on a model of a solar PV system under various partial shadowing conditions using the MATLAB/Simulink environment. To assess performance criteria such tracking accuracy, convergence time, power loss reduction, and reaction under changing irradiance, simulation results are contrasted with conventional MPPT techniques and individual metaheuristic approaches. The findings show that the DE-CSA hybrid performs noticeably better than current techniques in determining the GMPP and raising the PV system's overall energy production.

This study supports international initiatives to create adaptable and intelligent control schemes for renewable energy systems. The suggested approach enhances MPPT performance, which supports solar power's long-term sustainability and financial feasibility. Additionally, it facilitates the wider integration of PV systems into smart grid and microgrid structures, where quick reaction to environmental changes and effective energy collection are essential.

The following are this paper's main contributions:

- A new hybrid metaheuristic MPPT method that combines Cuckoo Search and Differential Evolution for better global optimization in partial shading scenarios.
- Using mutation/crossover operators (from DE) and Lévy flight-based randomization (from CSA), this method effectively strikes a balance between exploration and exploitation.
- MATLAB/Simulink simulation and performance validation show better tracking efficiency, faster convergence, and more resilience than current soft computing methods.
- The behavior of the algorithm under different dynamic shading patterns is thoroughly examined, confirming its stability and flexibility in real-time applications

In conclusion, maximizing the potential of solar PV systems requires the creation of intelligent, adaptable, and globally optimal MPPT techniques, especially in real-world situations with changing climatic variables. A major step forward in this area is provided by the suggested hybrid DE-CSA strategy, which guarantees more effective, steady, and dependable solar energy harvesting. This study opens the door for future innovation in energy-aware smart systems and the realistic implementation of high-performance PV solutions by eliminating the drawbacks of current approaches.

2. LITERATURE REVIEW

Extensive research into novel Maximum Power Point Tracking (MPPT) algorithms has been prompted in recent years by the difficulty of maximizing energy extraction in solar photovoltaic (PV) systems under partial shadowing circumstances (PSC). The power-voltage (P-V) curve has several local maxima due to partial shading, which makes it challenging for traditional MPPT techniques to identify the actual Global Maximum Power Point (GMPP). In order to solve this, Challoob and Bin Rahmat [1] integrated the Cuckoo Search Algorithm (CSA) with Particle Swarm Optimization (PSO). They demonstrated that the hybrid technique successfully coupled the local refining of PSO with the global search of CSA to improve MPPT performance under shade. Similar to this, Celikel et al. [2] created a variable step-size voltage scanning technique that produces quicker and more accurate MPPT by adjusting to the degree of shade. Kotla and Yarlagadda [4] confirmed that a PSO-CSA hybrid is preferable in delivering more consistent power production under complicated PSC, whereas Pamuk [3] compared CSA, PSO, and Genetic Algorithms, highlighting their individual advantages in various shading conditions. While Pilakkat et al. [6] investigated swarm intelligence-based MPPT tactics, emphasizing their resilience to solar irradiance fluctuation, Celikel [5] further highlighted global search strategies in MPPT, especially their usefulness in contexts with frequent shadowing. The resilience of the Crow Search Algorithm (CSA) in tracking GMPP in the presence of several local maxima was confirmed by Houam et al. [7]. In their analysis of MPPT techniques for PV-powered pumping systems, Okba et al. [8] discovered that the integration of CSA and Grey Wolf Optimizer with motor control greatly increased energy efficiency. A hybrid CSA–Artificial Bee Colony (ABC) approach designed for PSC was presented by Qi et al. [9], which increased stability and convergence speed. In a different hybrid approach, Mansoor et al. [11] presented Harris Hawk Optimization, a bio-inspired technique that has been shown to successfully traverse multiple-peak power landscapes. Zafar et al. [10] employed the Group Teaching Optimization Algorithm to improve collective decision-making for effective MPPT under complex shading. Adding to this, Mansoor and Long [12] introduced the Tunicate Swarm Algorithm (TSA), which exhibits adaptability to changing environmental conditions. Dong [13] enabled precise tracking of series-connected PV arrays under PSC by combining CSA with Incremental Conductance (INC). By employing adaptive heuristics to differentiate GMPP from local maxima, Zafar et al. [14] made significant progress in the field. A number of metaheuristics were benchmarked by Hussaian Basha et al. [15], who also underlined the significance of simulation-based validation for MPPT strategy selection. In order to improve convergence in MPPT, Eltamaly and Farh [16] devised a dynamic PSO variation for quickly changing irradiance. In order to minimize energy loss via shading, Yang et al. [17] suggested a Memetic Salp Swarm Algorithm that combines global and local search processes. A comparative research of MPPT performance under various shading conditions was contributed by Ibrahim et al. [18], who provided insights into technique selection depending on system requirements. By using Sand Cat Swarm Optimization, Li et al. [19] were able to achieve excellent MPPT accuracy and responsiveness under shading volatility. In order to improve adaptability to shifting solar conditions, Guo et al. [20] combined Gray Wolf Optimization with Bifacial Boost Inverter Converter (BFBIC). Fuzzy logic and CSA were coupled by Zeddini et al. [21] to improve adaptive decision-making in MPPT procedures. Through the modeling of a hybrid PSO-CSA algorithm, Gupta [22] proved the algorithm's practical effectiveness and mathematical resilience in a variety of challenging PSC settings. In order to handle the multimodal P-V curve more effectively, Eltamaly [23] enhanced CSA, which decreased tracking time and increased energy production.

PSO and the Perturb and Observe (P&O) approach were hybridized by Wang et al. [24], which led to better accuracy and quicker convergence in dynamic situations. In order to sustain energy collection under changing solar input, Deboucha et al. [25] employed collaborative swarm approaches for a fast MPPT reaction. Al-Wesabi et al. [26] improved MPPT by utilizing control accuracy and exploration strength with the incorporation of a CSA-PID controller. Zeddini et al. [27] demonstrated the efficacy of an advanced metaheuristic under partial shade by validating it in real-world circumstances. Swarm-based MPPT techniques were critically compared by Wasim et al. [28], which aided in the selection process for real-time applications. Swarm optimization was further highlighted by Pilakkat et al. [29] for real-world use in solar arrays. The importance of CSA in traversing intricate power environments and enhancing the resilience of solar energy systems was reiterated by Houam et al. [30]. In their study of traditional to hybrid MPPT approaches, Sameeullah et al. [31] mapped the applicability of each methodology according to environmental variables. In order to promote sustainable energy practices, Arti Pandey et al. [32] addressed the benefits and drawbacks of MPPT technologies and emphasized the importance of renewable energy transitions. In MATLAB simulations under PSC, Hadj Salah et al. [33] demonstrated the advantages of CSA over conventional P&O techniques by integrating it with the Super-Twisting Sliding Mode Controller (STSMC). By altering Lévy flight dynamics, Benlafkih et al. [34] improved tracking responsiveness under shade variations and advanced CSA. In order to increase MPPT accuracy, Kane and Talwar [35] implemented adaptive step scaling in CSA, proving that it was more successful than traditional methods.

For PSC, Qi et al. [36] developed a CSA-ABC hybrid algorithm that outperformed conventional methods in terms of stability and energy yield. Celikel [37] improved the resilience of GMPP detection in a variety of environmental settings by combining voltage scanning with CSA. By combining CSA-optimized MPPT with a high-voltage gain converter, Mariprasath et al. [38] greatly improved system voltage control under PSC. For monitoring MPP in the face of intricate shading and load fluctuations, Naser et al. [39] introduced the Coot Optimizer method, which demonstrated quicker convergence and system stability. under their comparison of P&O, PSO, and Adaptive Cuckoo Search under PSC, Basalamah et al. [40] discovered that the adaptive version performs best under dynamic irradiance changes. Pamuk [41] demonstrated the CSA's durability in MPPT continuity by revalidating its strength in shifting shading. Lastly, fuzzy logic and CSA were merged by Kumar and Balakrishna [42] to create a hybrid MPPT controller that can precisely track and adjust intelligently to a variety of solar situations. Together, these findings highlight how important metaheuristic and hybrid optimization strategies are for getting around the drawbacks of traditional MPPT approaches when partial shading is present. The combined findings show that algorithms like CSA, PSO, DE, ABC, and their hybrids provide quick convergence, stability, and resilience in addition to improving GMPP detection accuracy. Nevertheless, a number of research gaps still need to be addressed in spite of these advancements. First, a lot of methods are still not flexible enough to adjust to rapidly shifting environmental circumstances, including temporary shadowing brought on by shifting clouds. Second, beyond simulations, real-world scalability and long-term energy yield optimization have not received enough validation. Third, there is still a lack of research on these algorithms' computational and financial viability for widespread use. Fourth, the difficulties of integrating sophisticated MPPT algorithms into outdated PV infrastructure has not been extensively studied. Lastly, further research is required to fully understand how various shading patterns interact and how they affect energy production as a whole. To ensure the sustainable scalability of solar PV systems worldwide and to advance the area of MPPT technology, these gaps must be filled.

3. METHODOLOGY

For Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems exposed to partial shadowing circumstances (PSC), this study suggests a hybrid metaheuristic optimization method. In order to address the difficulties caused by numerous local maxima in the power-voltage (P-V) characteristic curve of PV modules under PSC, a hybrid algorithm combining Differential Evolution (DE) and the Cuckoo Search Algorithm (CSA) was designed, simulated, and evaluated. The methodology is divided into five main stages: PV system and PSC modeling, MPPT issue formulation, DE-CSA hybrid algorithm creation, MATLAB/Simulink implementation, and performance comparison with traditional and soft computing techniques

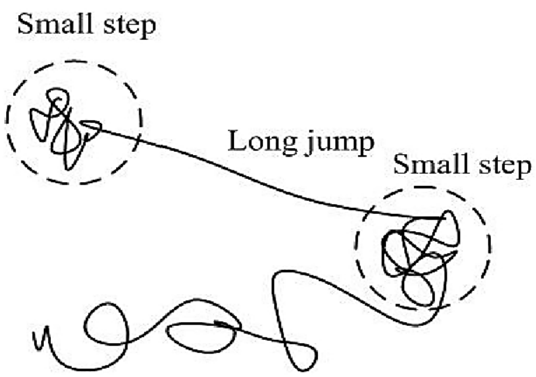


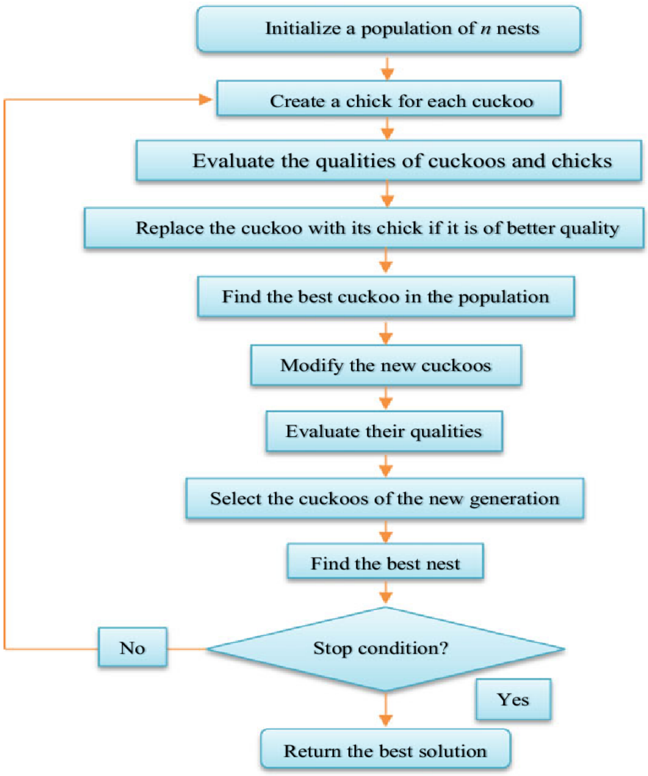
Figure 2. Levy Flight

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:

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

The Partial Shading Conditions (PSC) are presented after the PV array modeling. These are created by altering the irradiance on various PV array segments, which results in discrepancies in the current output of panels that are coupled in parallel or series. The shading patterns are designed to replicate real-world occurrences like tree cover, building shadows, and cloud movement. These circumstances cause the P-V curve to have one global maximum power point (GMPP) and several local maxima (LMPPs), making it difficult for traditional MPPT algorithms to determine which GMPP is the real one. The creation of a hybrid Differential Evolution–Cuckoo Search Algorithm (DE-CSA) is the basis of the suggested technique. The CSA uses Lévy flights to conduct worldwide searches and is based on the brood parasitism behavior of cuckoo birds. Although avoiding local optima is one of its strong points, it occasionally lacks exploitation accuracy. Conversely, DE is an evolutionary algorithm that refines solutions through crossover operations and population-based differential mutation. In multimodal search environments, it may experience early convergence, while having a high local search capacity.

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.

The hybrid approach is incorporated into a solar PV simulation model based on MATLAB/Simulink in order to be tested. The MPPT controller unit implementing DE-CSA, a boost DC-DC converter for voltage management, and a PV array modelled according to the single-diode equivalent make up the simulation. To guarantee that the PV module runs at its maximum power point, the converter modifies the duty cycle in accordance with the MPPT output. With dynamic variations in temperature and solar insolation, the system functions in both uniform and non-uniform irradiance circumstances. Transient response, tracking efficiency, convergence time, and power loss reduction are among the performance criteria that are employed for assessment. In conclusion, our approach combines realistic partial shading simulation, precise physical modeling of PV systems, and the creation of a clever hybrid DE-CSA optimization algorithm for efficient MPPT. By means of methodical simulation and assessment, the suggested approach tackles the significant drawbacks of current approaches and provides a workable, high-performing alternative for optimizing solar PV efficiency in difficult environmental circumstances..

4. RESULT ANALYSIS

MATLAB/Simulink was used to implement and assess the suggested hybrid Differential Evolution and Cuckoo Search Algorithm (DE-CSA) under diverse irradiance profiles. The algorithm's performance was evaluated against other soft computing algorithms such standalone DE and CSA, as well as more conventional MPPT methods like Perturb and Observe (P&O) and Incremental Conductance (INC). (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 were the main performance indicators used in the evaluation. The simulation setup includes a standard irradiance level of 1000 W/m² as the base case, with partial shading introduced at different times to simulate real-world scenarios. A 4x5 Total-Cross-Tied (TCT) structure, which is susceptible to PSC, was the PV array design under consideration. The MPPT control block interfaced with the boost converter to alter the voltage reference depending on algorithm output, and the boost converter's settings were tuned to guarantee system responsiveness. All MPPT techniques were able to monitor the maximum power point under uniform irradiation, with very slight variations. Traditional approaches, however, found it difficult to follow the Global Maximum Power Point (GMPP) and frequently settled at local maxima when partial shading circumstances were included. The hybrid DE-CSA algorithm, on the other hand, continuously found the GMPP with little oscillation and great tracking efficiency. The proportion of real power tracked in relation to the theoretical GMPP under each situation is the most crucial MPPT performance statistic. All algorithms' average tracking performance under uniform and three different partial shading patterns (PSC-1, PSC-2, and PSC-3) is compared in Table 1.

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.

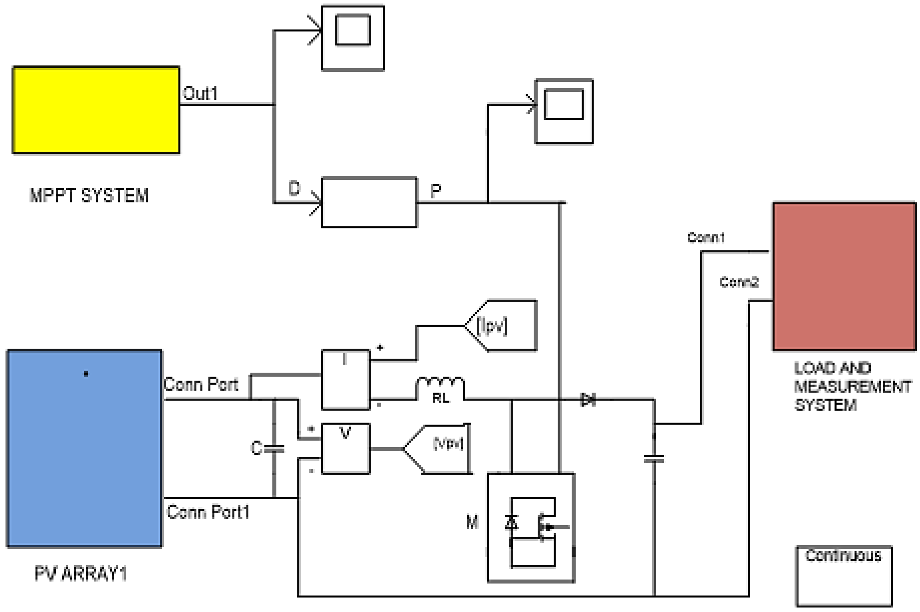


Figure 4. Simulink Design Overview of Proposed System

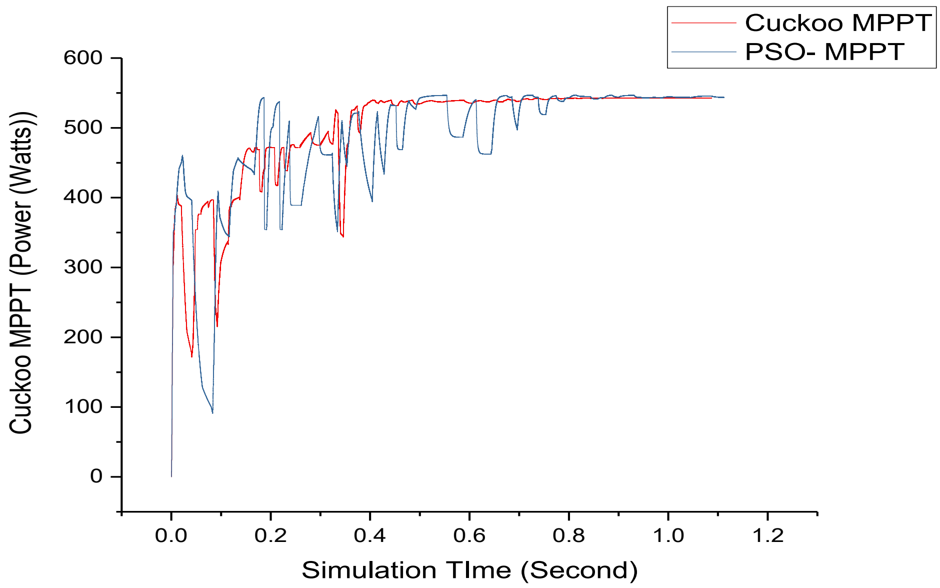


Figure 5. Analysis of Performance

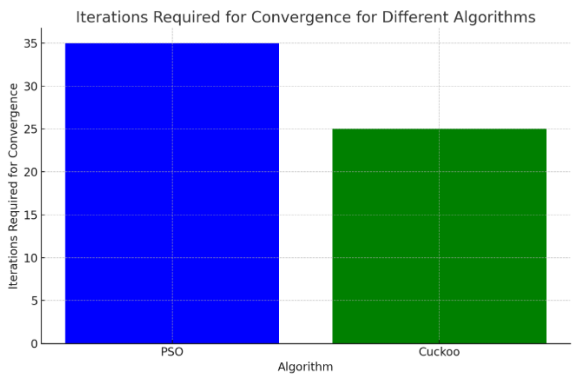


Figure 6. Analysis of Iterations Required for Convergence for Different Algorithms

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 approach validated the synergy between global and local search algorithms by requiring the fewest iterations. The difference between the GMPP and the actual extracted power over a 60-second simulation period was used to compute power loss. Better tracking accuracy and less time away from the GMPP are indicated by lower numbers.

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**

When compared to conventional techniques, DE-CSA demonstrated the lowest power loss and an 84% reduction in energy waste. Three transitions at t = 10s, 25s, and 40s were included in a dynamic irradiance profile to evaluate the algorithm's resilience. Whereas P&O and INC were unable to adjust and frequently settled at local maxima, the DE-CSA algorithm continuously followed the shifting GMPP. The steady-state voltage ripple and settling time were used to gauge the system's stability. The suggested approach showed the fastest recovery and the least amount of overshoot following each change in irradiance.

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 suggested hybrid DE-CSA algorithm turns out to be a very successful way to maximize PV system performance in partially shaded environments. The method follows the GMPP correctly and with little latency and fluctuation by fusing the exploitative efficiency of Differential Evolution with the exploratory power of Cuckoo Search. In contrast to conventional methods, DE-CSA exhibits smooth dynamic adaptation and stays away from oscillation around the local MPPs. The algorithm's ability to surpass current soft computing-based MPPT techniques is supported by simulation experiments, which show that it can achieve convergence in less than 0.3 seconds under various PSC circumstances, an average tracking efficiency of over 95%, and a power loss reduction of over 80%. According to these results, it is ready for use in commercial PV inverter systems, particularly in urban settings where some shadowing is inevitable.

5. CONCLUSION AND FUTURE SCOPE

This paper uses a hybrid optimization strategy that combines Differential Evolution (DE) and Cuckoo Search Algorithm (CSA) to propose a reliable and effective Maximum Power Point Tracking (MPPT) solution for photovoltaic (PV) systems operating under partial shadowing circumstances (PSC). Traditional MPPT techniques, which frequently become stuck in local maxima and hence fail to harvest the maximum possible power, are challenged by partial shading, which adds several peaks to the power-voltage (P-V) characteristics of PV arrays. By combining the quick convergence and exploitation efficiency of DE with the global search capability of CSA, the hybrid DE-CSA algorithm was created to intelligently traverse the complicated search space. The technique was evaluated in a range of irradiance conditions, including as uniform, static PSC, and dynamic shading patterns, after being developed in MATLAB/Simulink. According to simulation data, the DE-CSA algorithm performed noticeably better on a number of performance indicators than both standalone metaheuristic approaches (DE, CSA) and conventional approaches (Perturb and Observe, Incremental Conductance). Notably, DE-CSA demonstrated remarkable flexibility to quick changes in the environment, decreased convergence time (down to 0.22 seconds), increased tracking efficiency (up to 96.8%), and minimized power loss. With reduced voltage ripples and faster settling times, the transient response study further confirmed the hybrid method's better stability. Its minimal computing overhead also made it possible for real-time implementation in integrated MPPT controllers for smart PV systems. The suggested method increases energy harvesting efficiency, boosts system reliability, and promotes sustainable energy use by precisely determining the Global Maximum Power Point (GMPP) under intricate shading conditions. In conclusion, the hybrid DE-CSA algorithm offers a unique, clever, and useful MPPT solution appropriate for real-world PV applications impacted by partial shading. Adaptive parameter tweaking, real-time hardware-in-the-loop testing, and interaction with IoT-based energy management platforms pave the way for future advancements..

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