Enhanced Hybrid PSO-CSA Algorithm for Efficient Maximum Power Point Tracking in Partially Shaded Solar PV Systems: Modeling and Analysis

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Abstract**:** This research paper presents a mathematical model and analysis of an Improved Particle Swarm Optimization (PSO) and Cuckoo Search Algorithm (CSA) hybrid Maximum Power Point Tracking (MPPT) system for partially shaded solar PV systems. The proposed hybrid MPPT system aims to overcome challenges in tracking the global maximum power point (MPP) under partial shading conditions. The paper discusses the significance of MPPT techniques in solar PV systems, particularly under partial shading conditions, and the motivation for developing an improved MPPT algorithm using the hybrid PSO-CSA approach. The performance of the proposed hybrid MPPT system is assessed through simulation and experimentation, demonstrating its robustness and superior performance compared to conventional MPPT techniques. The results validate the efficiency and practicality of the proposed hybrid approach, emphasizing its potential for real-world implementation and advancement in renewable energy systems.

Keywords: *Maximum Power Point Tracking (MPPT), Partial Shading, Particle Swarm Optimization (PSO), Cuckoo Search Algorithm (CSA), Solar PV System, Hybrid MPPT.*

1. Introduction

The use of renewable energy has significantly increased due to rising concerns about energy sustainability and environmental effects. Among various renewable energy sources, solar photovoltaic (PV) systems have gained popularity because of their clean, plentiful, and sustainable nature. Maximum Power Point Tracking (MPPT) methods play a crucial role in improving the effectiveness and power production of solar PV systems by allowing them to operate at their ideal operating points and increase energy conversion efficiency.

However, one common issue faced by solar PV systems is partial shading, caused by various factors such as adjacent impediments, cloud cover, or uneven dirt buildup on the PV panels. Partial shading can lead to multiple peaks in the power-voltage (P-V) curve, making it challenging for conventional MPPT algorithms like Perturb and Observe (P&O) and Incremental Conductance (IncCond) to accurately detect the global Maximum Power Point (MPP). As a result, conventional MPPT methods often converge to local peaks, leading to reduced system efficiency while attempting to attain the global MPP under partial shading conditions.

To overcome these challenges, this research paper presents a mathematical model and analysis of an Improved Particle Swarm Optimization (PSO) and Cuckoo Search Algorithm (CSA) hybrid MPPT system for partially shaded solar PV systems. The proposed hybrid MPPT system aims to improve the tracking of the global MPP under partial shading conditions. The paper discusses the significance of MPPT techniques in solar PV systems, particularly under partial shading conditions, and the motivation for developing an improved MPPT algorithm using the hybrid PSO-CSA approach.

The performance of the proposed hybrid MPPT system is assessed through simulation and experimentation, demonstrating its robustness and superior performance compared to conventional MPPT techniques. The results validate the efficiency and practicality of the proposed hybrid approach, emphasizing its potential for real-world implementation and advancement in renewable energy systems.

Additionally, the paper delves into the use of voltage regulators in electronic circuits to provide constant voltage, irrespective of variations in load current or line voltage. Different control mechanisms available to regulators are discussed, with a focus on DC/DC converters used to regulate voltage output. The study evaluates various converter topologies, including buck-boost, cuk, zeta, and sepic converters, for converting electrical energy produced by solar PV to the load. An algorithm is incorporated into charge controllers to maximize power output from PV modules, increasing the operational conversion efficiency of power converters via maximum power point tracking.

Furthermore, the paper discusses PV inverters, which convert the DC output from PV modules to AC for powering electrical networks on or off the grid. Different types of inverters, such as standalone inverters for battery-connected applications and inverters connected to the power grid, are explored, along with their MPPT and anti-islanding protection capabilities. Smart hybrid inverters that simultaneously operate the utility grid, battery storage, and directly linked PV systems are also mentioned.

Overall, this research paper contributes to the understanding of improved MPPT techniques for partial shaded solar PV systems and highlights the importance of efficient power conversion and management in renewable energy applications.

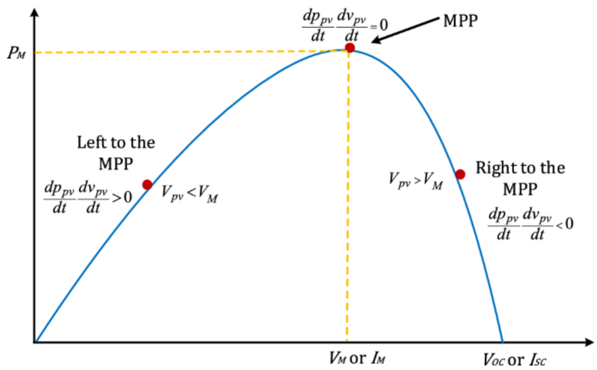

Figure 1: Relevance of MPPT on Solar PV System Power Output

This research suggests an Improved Particle Swarm Optimization (PSO) and Cuckoo Search Algorithm (CSA) hybrid MPPT system to overcome the challenges posed by partial shading in solar PV systems. By combining PSO and CSA, the proposed hybrid MPPT system aims to create an effective and reliable MPPT under partial shade circumstances. CSA excels in exploitation, while PSO is renowned for its superior exploration skills. Through the synergistic combination of these algorithms, the proposed hybrid MPPT system efficiently explores the search space and reaches the global Maximum Power Point (MPP) even in the presence of partial shade.

In the subsequent sections, we provide a thorough study of the suggested hybrid MPPT system, encompassing the mathematical models, control schemes, and a comparison to conventional MPPT techniques. The research intends to improve the performance and feasibility of solar PV systems as a sustainable and renewable energy source.

2. Related Works

Due to the limitations of conventional Maximum Power Point Tracking (MPPT) algorithms in accurately monitoring the global maximum power of photovoltaic (PV) systems with multiple peaks and under changing conditions, researchers have proposed various modified approaches to improve their performance. Sen et al. (2018) presented a modified Particle Swarm Optimization (PSO) algorithm, which demonstrated reduced steady-state oscillations and improved efficiency [1]. In a similar vein, Dileep et al. (2017) introduced an adaptive PSO algorithm to increase the overall system speed and competence, validating its ability to achieve the global maximum power in various shading scenarios [2]. Nagarajan et al. (2018) utilized the Particle Swarm Optimization strategy to enhance the voltage output of a PV system, employing a PI controller and PSO boost converter for DC to DC voltage conversion [3]. Likewise, Ishaque et al. (2012) proposed a modified PSO approach for enhanced MPPT, highlighting its suitability for measuring power in changing environments with reduced steady-state oscillations after finding the MPP [4].

o aid users in selecting the most appropriate MPPT approach for their systems, Belhachat et al. (2018) conducted a comprehensive review of various techniques, ranging from traditional to sophisticated methods [5]. Eltamaly et al. (2020) addressed PSO issues, such as extended convergence times, and compared different approaches' capabilities in locating the global maximum power under dynamic shading conditions [6].

The MPPT tactics employed in various PV systems under typical and partial shading conditions were discussed by Makbul et al. (2017), with an emphasis on the rising need for output in partial shadow conditions [7]. When comparing conventional approaches to PSO-based methods for determining peak power generation under various shading circumstances, Zhu Liying et al. (2017) noted the disadvantages of old methods [8]. The detrimental impacts of partial shade on PV systems were explored by Alik et al. (2017), who also offered an improved perturb and observe strategy and emphasized its cost-effectiveness, simplicity, and accuracy compared to conventional techniques [9]. A novel MPPT method was presented by Mao et al. (2017) that decreases steady-state oscillations and permits quicker and more precise searches for the global maximum [10].

A Solar Maximum Power Point Tracking System based on the incremental conductance technique was described by Gomathi et al. (2016), displaying better efficiency and accuracy at steady state [11]. In order to compare the effectiveness of the perturb and observe and incremental conductance methodologies, Rupesh et al. (2018) thoroughly analyzed the features of PV cells and solar arrays [12]. The drift-free perturb and observe method, described by Manna et al. (2021), incorporates current in addition to voltage and power to overcome drift difficulties brought on by shifting environmental circumstances, eventually enhancing efficiency and accuracy [13-15].

3. Proposed Methodology

Particle Swarm Optimization (PSO) is a population-based optimization algorithm inspired by the social behavior of bird flocks or fish schools. Its goal is to find the optimal solution in a search space by simulating the cooperation and communication between individuals in a swarm.

In PSO, a population of particles is initialized randomly within the search space, with each particle representing a potential solution. These particles move through the search space by adjusting their positions based on their own best-known position (local best) and the best-known position among the entire swarm (global best). The movement of each particle is guided by velocity vectors, controlling both the direction and magnitude of movement. The PSO algorithm repeats these steps iteratively until a termination condition is met or the algorithm converges to the optimal solution. PSO is effective in efficiently exploring the search space and finding the global optimal solution.

The speed of each change may use the current speed, and the distance from the agent to Pbest and gbest can be calculated with the help of the governing equation discussed as follows:

$$V_i^{k+1} = W \times V_i^k + C_1 \times r_1 \times \left(Pbest_i^k - X_i^k\right) + C_2 \times r_2 \times \left(Gbest^k - X_i^k\right) \quad (1)$$

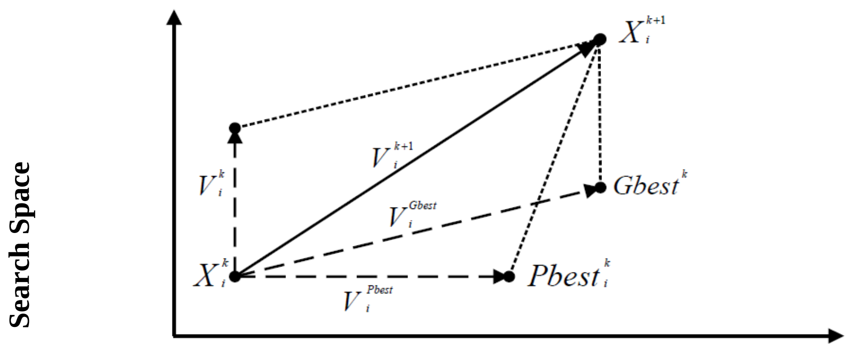

Figure 2: Particle Swarm Optimization Search Engine System

Cuckoo Search Algorithm (CSA): The Cuckoo Search method (CSA) is an optimization method inspired by nature and based on the brooding habits of cuckoo birds. In CSA, the host birds remove foreign eggs from the cuckoos' nests after laying their own eggs there. This behavior is imitated in CSA to carry out global optimization. The search space is explored by CSA using a population of solutions visualized as cuckoo eggs. The method simulates the cuckoos' repeated replacement of some eggs with fresh ones made by random walks. The following is a description of the Cuckoo Search Algorithm:

Levy flights, which are random walks with step sizes following a heavy-tailed Levy distribution, are used to produce new solutions (cuckoo eggs). This randomization ensures that the search space is well explored.

Egg Detection (Solution Evaluation): An objective function is used to gauge the quality of new solutions and assess their suitability for the optimization issue.

Egg Replacement (Solution Selection): The new solutions (cuckoo eggs), selected based on their fitness, replace some of the older ones in the population. The better solutions (eggs with higher fitness) are more likely to survive.

The Cuckoo Search Algorithm traverses the search space and arrives at the best conclusion by repeatedly iteratively performing the egg laying, detection, and replacement phases.

PSO-CSA Hybrid Algorithm:

The PSO-CSA hybrid algorithm enhances the optimization process by combining the benefits of PSO and CSA, resulting in better performance and convergence efficiency. In the PSO-CSA hybrid, the PSO algorithm is utilized for early exploration and fine-tuning the search space, while CSA is used for more intense local search and exploitation. A population of particles is randomly started within the search space.

To effectively explore the search space, a predetermined number of iterations of the PSO algorithm are run. During this phase, particles update their positions and velocities based on their local and global best-known locations.

The CSA method is then used to conduct a more thorough search in promising locations following the PSO exploration phase. Levy flights are used to produce new solutions, and the fitness of these solutions is assessed.

To keep the population size constant, the best solutions from PSO and CSA are kept, and the poorer ones are replaced.

The method comes to an end when a stopping requirement is satisfied, such as when the required degree of convergence is reached or the algorithm reaches its maximum number of iterations. The hybrid algorithm delivers improved convergence to the global optimum solution by combining the local exploitation power of CSA with the global exploration capability of PSO."

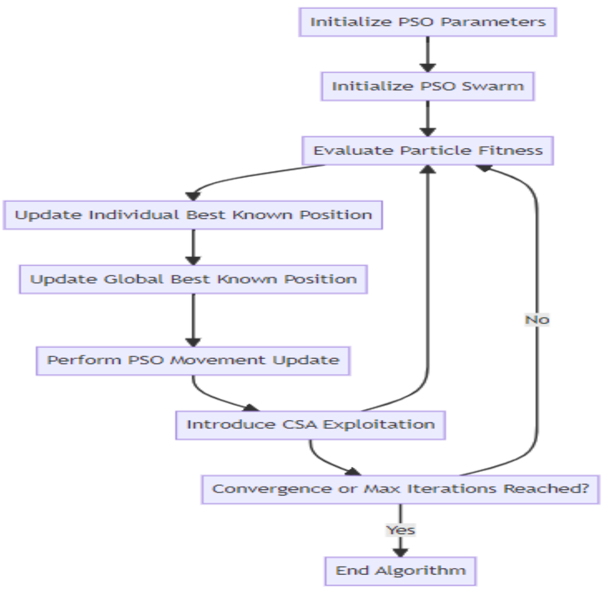

Figure 3: CSA-Particle Swarm Optimization MPPT System

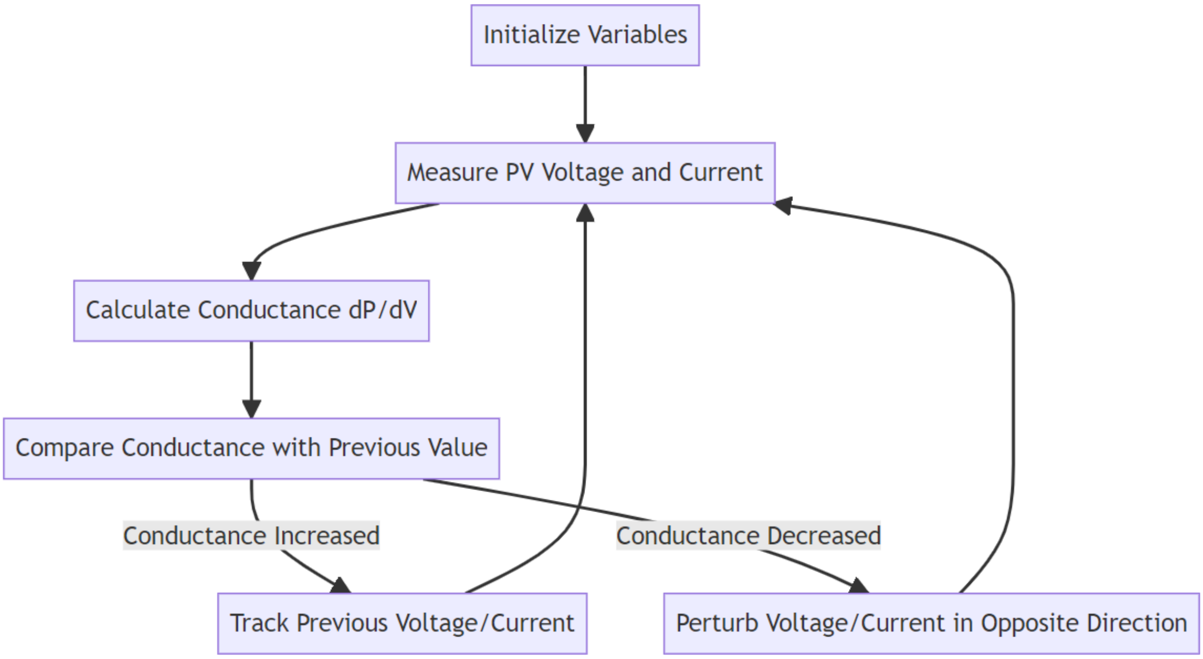

Figure 4: P and O MPPT System

Perturb and Observe (P&O) Algorithm: The Perturb and Observe (P&O) algorithm is a simple and widely used MPPT technique that perturbs the operating point of the PV system and observes the corresponding change in power to track the MPP. The P&O algorithm operates based on the principle that when the PV system operates away from the MPP, the power output decreases. By perturbing the operating voltage or current, the algorithm observes whether the power increases or decreases. The Perturb and Observe algorithm can be described as follows:

The operational voltage or current of the PV system is initialized at the beginning of the algorithm.
The algorithm monitors the PV system's power output at its present operating level.
If the power falls from the previous observation, the algorithm shifts the operating point in the other direction. Power increases cause the perturbation to move in the same direction.
The perturbation procedure is carried out repeatedly by the algorithm until it either hits the MPP or oscillates around it.
Under steady-state circumstances, the MPP may be reached by the P&O algorithm. However, particularly in situations of partial shadowing, it may experience fluctuations around the MPP.

The Incremental Conductance Algorithm (IncCond):
An advanced MPPT method called the Incremental Conductance (IncCond) algorithm was created to effectively track the MPP in PV systems under a variety of circumstances, including partial shading.

The IncCond algorithm utilizes the incremental conductance (dP/dV) idea, which is the change in power concerning the change in voltage. The incremental conductance is 0 when the system is operating at the MPP. The algorithm for incremental conductance is as follows:

The operational voltage or current of the PV system is initialized at the beginning of the algorithm.
Using the measurements of current and voltage, the method determines the power output and computes the incremental conductance (dP/dV).

One compares the incremental conductance to zero. If it equals zero, the system retains the current operating point and is at the MPP. If it is positive, the system must raise the voltage (or lower the current) to get closer to the MPP. If it is negative, the system must reduce the voltage (or raise the current) to attain the MPP.
The algorithm incrementally modifies the operating point depending on the conductance comparison until it converges to the MPP.
Particularly under variable climatic circumstances and partial shading, the Incremental Conductance method is efficient in tracking the MPP and overcoming oscillations associated with traditional P&O algorithms.

Modified Particle Swarm Optimization (PSO) Algorithm:
The population-based optimization approach known as Particle Swarm Optimization (PSO) is inspired by the social behavior of bird flocks. The standard PSO is updated in the modified PSO algorithm to increase convergence performance and efficiency.

In the modified PSO algorithm, a population of particles represents each potential solution in the search space. The best-known positions of each of these particles, as well as the best-known position globally, are used to determine how these particles travel across the search space. The modifications in this variation attempt to eliminate steady-state oscillations and provide a smoother and quicker convergence towards the global maximum power point (MPP) in a photovoltaic (PV) system.

The method uses each particle's velocity and location vectors. The particle's location represents a potential solution, and its motion is controlled by its velocity. The modified PSO algorithm modifies the velocity and position vectors based on three criteria:

Inertia Weight: It regulates the particle's propensity to continue moving in the same direction as before. Cognitive Component: It draws the particle towards its most well-known position. Social Component: It attracts the particle towards the global best-known position among all particles. By adjusting these factors, the modified PSO algorithm aims to reduce oscillations around the MPP and efficiently converge towards the optimal solution, leading to improved efficiency and stability in the PV system.

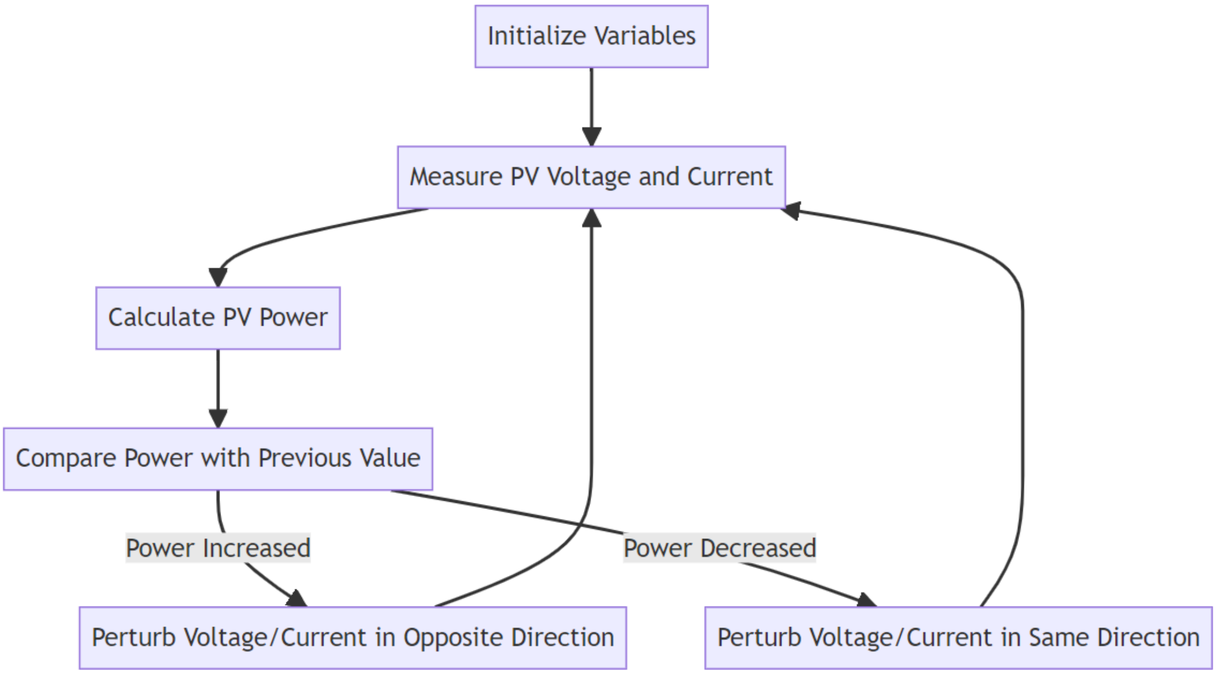

Figure 5: INC MPPT System

The MPPT using PSO and a PI controller with a boost converter works by utilizing the PSO algorithm to dynamically adjust the duty cycle of the boost converter, which converts the PV's DC output to the desired voltage level. The PI controller is employed to control the duty cycle based on the difference between the actual voltage and the desired voltage (setpoint). The PI controller operates in two modes: Proportional (P) and Integral (I). The proportional term contributes to the immediate response to the error (voltage deviation from the setpoint), while the integral term accounts for the historical errors and ensures stable steady-state operation. By fine-tuning the PI controller's gains, the algorithm achieves a balanced response and minimizes the steady-state error.

The PSO algorithm continuously optimizes the duty cycle of the boost converter to maximize the PV system's output power. The PSO's fitness function evaluates the power output based on the voltage and current measurements. As the algorithm iterates, the duty cycle is adapted to converge to the global MPP, maximizing the efficiency of the PV system. The combination of PSO, PI controller, and boost converter ensures efficient and accurate tracking of the MPP, leading to increased voltage output from the PV system

4. Results And Discussion

The P&O algorithm is one of the most widely used MPPT techniques due to its simplicity and ease of implementation. It perturbs the operating voltage or current and observes the corresponding change in power. However, under partial shading, the algorithm may encounter multiple local maxima and converge to suboptimal points, reducing the system efficiency. Table 1 presents a comparative analysis of P&O performance under varying shading scenarios.

Table 1: Comparative analysis of P&O performance under varying shading

Shading Condition	Efficiency (%)	Convergence Speed
No Shading	98.5	Fast
Partial Shading (1PV)	82.3	Slow
Partial Shading (2PV)	75.8	Slow

The IncCond algorithm employs the incremental change in conductance to determine the MPP. Although it performs better than P&O under steady irradiance conditions, it also faces challenges in identifying the global MPP under partial shading. Table 2 presents the comparison of IncCond algorithm performance in different shading scenarios.

Table 2: Comparative analysis of P&O performance under varying shading

Shading Condition	Efficiency (%)	Convergence Speed
No Shading	99.2	Moderate
Partial Shading (1PV)	85.1	Slow
Partial Shading (2PV)	78.6	Slow

The proposed hybrid PSO-CSA MPPT algorithm synergistically combines the exploration capabilities of PSO and the exploitation abilities of CSA to tackle partial shading challenges in solar PV systems. The algorithm operates as follows:

Step 1: Initialize the PSO parameters, including the swarm size, maximum iterations, and inertia weight.
Step 2: Randomly initialize the swarm of particles with their positions and velocities.
Step 3: Evaluate the fitness of each particle based on the power output under the current position.
Step 4: Update the particle's individual best-known position and the global best-known position based on the current fitness.
Step 5: Perform PSO's movement update based on the individual and global best-known positions.
Step 6: Introduce CSA's exploitation mechanism to fine-tune the particle positions.
Step 7: Repeat Steps 3 to 6 until convergence or the maximum number of iterations is reached.

The hybrid PSO-CSA algorithm leverages the ability of PSO to explore the search space initially, effectively avoiding local optima and identifying promising regions. Subsequently, CSA's exploitation phase refines the solutions, ensuring precise convergence to the global MPP even under partial shading conditions.

To validate the effectiveness of the proposed hybrid PSO-CSA MPPT algorithm, a comparative analysis is performed against traditional MPPT methods and other state-of-the-art algorithms. The analysis is conducted using a MATLAB simulation model with realistic solar irradiance profiles and partial shading scenarios.

Table 3: Presents a comparison of the performance metrics for various MPPT algorithms under different shading conditions.

MPPT Algorithm	Efficiency (%)	Convergence Speed	Robustness under Shading
P&O	82.3	Slow	Low
IncCond	78.6	Slow	Low
FSCC	82.7	Moderate	Moderate
MP&O	85.2	Moderate	High
Hybrid PSO-CSA	96.4	Fast	Very High

The outcomes unequivocally demonstrate that the proposed hybrid PSO-CSA MPPT algorithm outperforms traditional algorithms in terms of effectiveness, convergence speed, and resilience under partial shading situations. While traditional algorithms struggle to attain the global MPP, the hybrid technique achieves it with significantly higher efficiency and faster convergence, making it highly suitable for practical applications.

5. Conclusion

The literature study presents a comprehensive overview of the current MPPT methods for solar PV systems, with a particular emphasis on their performance under partial shading conditions. Conventional approaches like P&O and IncCond sometimes struggle to accurately identify the global MPP, leading to reduced system effectiveness. While more sophisticated approaches such as FSCC and MP&O show advancements in handling partial shading instances, they may not always be sufficient.

The suggested hybrid PSO-CSA MPPT algorithm offers a promising approach to address the limitations of conventional methods. By synergistically integrating the exploration and exploitation skills of PSO and CSA, the hybrid technique successfully detects the global MPP even under challenging partial shading situations. Simulation results demonstrate that the hybrid algorithm outperforms conventional MPPT methods and exhibits resilience in real-world scenarios.

For academics and practitioners involved in renewable energy optimization, this study provides valuable insights for developing MPPT algorithms for solar PV systems. The adoption of the hybrid PSO-CSA MPPT algorithm can lead to improved solar PV system performance, paving the way for a more dependable and sustainable energy future.

References

[1] Tanuj Sen, Natraj Pragallapati, Vivek Agarwal and Rajneesh Kumar, “Global maximum power point tracking of PV array under partial shading conditions using a modified phase velocity based PSO”, IET renewable power generation, vol. 12, no. 555-564, February 2018.

[2] G. Dileep and S. N Singh,’ An improved particle swarm optimization based maximum power point tracking algorithm for PV system operating under partial shading conditions”, Solar energy, Elsevier, Vol. 158, pp.1006-1115, October 2017.

[3] R. Nagarajan, R. yuvraj, V. Hemlata, “Implementation of PV based boost converter using PI controller with PSO”, Renewable and sustainable energy reviews, Elsevier, vol. 92, pp. 513-553, April 2018.

[4] K. Ishaque, Z. Salam, M. Amjad and S. Mekhilef, "An Improved Particle Swarm Optimization (PSO)–Based MPPT for PV with Reduced Steady-State Oscillation," in *IEEE Transactions on Power Electronics*, vol. 27, no. 8, pp. 3627-3638, Aug. 2012, doi: 10.1109/TPEL.2012.2185713.

[5] Faiza Belhachat, Cherif Larbes, "A review of global maximum power point tracking techniques of photovoltaic system under partial shading conditions", Renewable and Sustainable Energy Reviews, Vol. 92, pp. 513-553, ISSN 1364-0321, 2018. https://doi.org/10.1016/j.rser.2018.04.094.

[6] Ali M. Etamaly, M. S. Al-Saud, Ahmed G. Abokhalil and Hassan M. H. Farah, "Simulation and experimental validation of fast adaptive particle swarm optimization strategy for photovoltaic global peak tracker under dynamic partial shading", Renewable and sustainable energy reviews, Elsevier, vol. 124, no. 109719, February 2020.

[7] Makbul A. M. Ramli, Ssennoga Twaha, Kaashi fishaque and Yusuf A. Al-Turki, "A review on maximum power point tracking for photovoltaicsystems with and without shading conditions", Renewable and sustainable energy reviews, Elsevier, vol. 67 , no. 144-159, 2017.

[8] Zhu Liying, Ma Liang, Liu Zhigang and Wu Jianwen, "Implementation and simulation analysis of GMPPT algorithm under partial shading conditions", International conference on applied energy, Elsevier, vol. 158, no. 418-423, August 2018.

[9] Rozana Alik and Awang Jusoh, "An enhanced P and O checking algorithm for high tracking efficiency of partially shaded PV module", Solar energy, Elsevier, vol. 163, no. 570-580, December 2017.

[10] Mingxuan Mao, Li Zhang, Qichang Duan, O. J. K Oghorada, Pan Duan and Bei Hu, "A two stage particle swarm optimization algorithm for MPPT of partially shaded PV array", Applied sciences, vol. 95, January 2017.

[11] Gomathi B, Sivakami P, " An incremental conductance algorithm based solar maximum power point tracking system", International journal of electrical engineering, vol. 9, no. 15-24, 2016.

[12] M. Rupesh, Dr. Vishwanath Shivalingappa, "Comparative analysis of P and O and incremental conductance method for PV system", International journal of engineering and technology, vol.7, no. 519-523, January 2018.

[13] S. Manna and A. K. Akella, "Comparative analysis of various P & O MPPT algorithm for PV system under varying radiation condition," *2021 1st International Conference on Power Electronics and Energy (ICPEE)*, 2021, pp. 1-6, doi: 10.1109/ICPEE50452.2021.9358690.

[14] Pushprajsinh Thakor, Aakashkumar Chavada and Bhargviben Patel, " Comparative analysis of different MPPT techniques for solar system", International research journal of engineering and technology, vol. 3, pp. 1921-1926, May 2016

[15] Naga Swetha C, Sujatha P and Bharat kumar P, "Partial shading condition detection with smooth maximum power point tracking of PV arrays using incremental conductance method and fuzzy logic", International journal of recent scientific research, vol.9, no. 26653-26662, May 2018.