Numerical Simulation and Mathematical Analysis of Meta Heuristic MPPT System for Solar Photovoltaic Applications Under Non-Linear Operational Conditions

Ravinder Singh Maan¹, Alok Kumar Singh², Ashish Raj³

¹Research Scholar, Department of Electrical Engineering, Nirwan University, Jaipur
²Associate Professor, Department of Electrical Engineering, Nirwan University, Jaipur
³Associate Professor, Department of Electrical and Electronics Engineering, Poornima University, Jaipur

ravindresingh.maan@nirwanuniversity.ac.in ṡ alok.singh@nirwanuniversity.ac.in Ṡ ashish.raj@poornima.edu.in

Abstract: As a sustainable energy source, the use of solar photovoltaic (PV) systems has significantly increased. Environmental elements, especially partial shadowing circumstances, have a considerable impact on how well solar PV systems function. In such cases, the various local maxima in the power-voltage curve make it difficult for conventional Maximum Power Point Tracking (MPPT) methods to maintain peak efficiency. Heuristic Maximum Power Point Tracking (MPPT) system for solar photovoltaic (PV) applications, employing the cuckoo search algorithm. The primary objective of the research is to enhance the efficiency and reliability of solar PV systems by optimizing the MPPT process, which is crucial for maximizing energy extraction under varying environmental conditions. The model is used to simulate the performance of the system under various environmental conditions, such as changes in temperature and irradiance levels. The simulation results are then statistically analyzed to evaluate the effectiveness of the cuckoo search algorithm in tracking the maximum power point accurately and rapidly. The algorithm demonstrates a robust ability to converge to the maximum power point efficiently, thereby enhancing the overall energy yield of the solar PV system. The performance of the hybrid PSO-CSA MPPT algorithm in contrast to traditional MPPT techniques is assessed through simulations and tests under various shading circumstances. The findings show that the hybrid strategy regularly outperforms conventional methods by enhancing the total energy production of partially shadowed solar PV installations through faster convergence, less oscillations, and greater tracking accuracy. The proposed hybrid algorithm also demonstrates stability and flexibility in real-world settings, making it a potential option for boosting the dependability and efficiency of solar PV systems when shade is present. This study advances the field of renewable energy and prepares the path for the use of sophisticated optimization methods to the problems of solar PV power generation under changing environmental circumstances.

Keywords: Mathematical modeling, Analysis, Particle Swarm Optimization (PSO), Maximum Power Point Tracking (MPPT), Partial shading, Solar PV system, Energy harvesting, Optimization algorithm, Global maximum, Efficiency, Renewable energy, Shading scenarios, Power output, Algorithm enhancement, Convergence.
1. Introduction

Researchers and engineers are increasingly using meta-heuristic algorithms as alternatives to robust MPPT techniques in order to overcome these issues. Examples of these algorithms are Differential Evolution (DE), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO). The system's operational efficiency is increased by these algorithms' faster convergence to the Maximum Power Point (MPP) and more sophisticated search capabilities.

![Figure 1: Relevance of MPPT on Solar PV System Power Output](image_url)

The global push towards renewable energy sources has been driven by a heightened awareness of climate change and the desire to lessen dependency on fossil fuels and the growing awareness of climate change have fueled a global movement towards renewable energy sources. Photovoltaic (PV) systems are one of the most well-known renewable energy technologies because of their ability to convert sunlight directly into electricity, scale, and cheap operating costs. PV systems have efficiency issues because of operational and environmental factors, even with these benefits. Partial shadowing is a major problem that reduces efficiency when one or more photovoltaic panels are obscured by shadows from surrounding structures, clouds, or even leaves. The mathematical modelling is explained as follows:

1. 
   \[ I = I_{ph} - I_0 \left( \exp \left( \frac{qV}{nkT} \right) - 1 \right) \]

2. 
   Current-voltage relationship of a solar cell:
   \[ I = I_{ph} - I_0 \left( \exp \left( \frac{q(V + IR_s)}{nkT} \right) - 1 \right) - \frac{V + IR_s}{R_{sh}} \]

3. 
   Photogenerated current \( I_{ph} \):
   \[ I_{ph} = \frac{G \cdot A}{q} \]

4. 
   Reverse saturation current \( I_0 \):
   \[ I_0 = I_{scr} \left( \frac{T}{T_{ref}} \right)^3 \exp \left\{ \frac{E_g}{nk} \left( \frac{1}{T_{red}} - \frac{1}{T} \right) \right\} \]

5. 
   Solar cell temperature-dependent ideality factor \( n \):
   \[ n = \frac{n_{ref}}{1 + a(T - T_{red})} \]
6 Diode thermal voltage \( (V_t) \):
\[
V_t = \frac{kT}{q}
\]

7 Solar cell short-circuit current \( (I_{sc}) \):
\[
I_{sc} = I_{ph} - I_0
\]

8 Solar cell open-circuit voltage \( (V_{oc}) \):
\[
V_{oc} = \frac{nkJ}{q} \ln \left( \frac{I_{ph}}{I_0} \right)
\]

9 Solar cell fill factor \( (FF) \):
\[
FF = \frac{I_{mp} \cdot V_{mp}}{I_{sc} \cdot V_{oc}}
\]

10 Solar cell efficiency \( (\eta) \):
\[
\eta = \frac{P_{mix}}{P_{mi}} = \frac{I_{mp} \cdot V_{mp}}{G \cdot A}
\]

11 Maximum power point voltage \( (V_{mp}) \):
\[
V_{mp} = \frac{nkJ}{q} \ln \left( \frac{nkJ}{I_0R_s} + 1 \right) - I_{mp}R_s
\]

12 Maximum power point current \( (I_{mp}) \):
\[
I_{mp} = \frac{I_{sc} - I_0}{1 + \frac{y}{nkJ}I_{11}R_s}
\]

13 Solar cell series resistance \( (R_s) \):
\[
R_s = \frac{nkJ}{qI_1}
\]

The power-voltage curve becomes non-linear and multi-modal under these circumstances, which presents a problem for conventional Maximum Power Point Tracking (MPPT) methods like Incremental Conductance (IncCond) and Perturb and Observe (P&O). Because traditional MPPT procedures are straightforward and simple to apply, they have been employed extensively. Nevertheless, its applicability to intricate, non-linear, and constantly changing environments—like partial shade conditions—is inherently limited. These algorithms frequently display oscillatory behavior and become stuck in local maxima, which results in inefficient energy harvesting and systemic inefficiencies. As a result, the demand for sophisticated MPPT algorithms that can quickly, accurately, and robustly converge to the global maximum point is growing. Promising substitutes for conventional MPPT techniques have been found in meta-heuristic algorithms including Differential Evolution (DE), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO). These algorithms are innately able to seek enormous and complicated solution spaces, drawing inspiration from biological, physical, or social phenomena. They contain improved convergence qualities, are able to avoid local maxima, and can adapt to dynamically changing surroundings. As a result, they have been used to solve a number of optimization issues, such as the MPPT for PV systems that are partially shaded. The effectiveness of meta-heuristic algorithms in MPPT applications has been shown in several publications. Scholars have investigated a number of factors, including resilience in the face of shifting environments, computing complexity, and convergence speed. Nevertheless, there is a lack of rigorous evaluations and comparisons of these algorithms’ performance, particularly when partial shading is present, in the literature. This review paper’s main goal is to evaluate the most recent, cutting-edge resilient MPPT algorithms based on meta-heuristics, with a focus on partially shaded PV systems. The objective of the research is to assess various techniques using many KPIs, such as tracking accuracy, tracking speed, computing overhead, and environmental change adaptability, among others. This paper covers the theoretical underpinnings of meta-heuristic algorithms as well as their practical application and performance assessment in real-world settings. The rest of the paper is structured as follows: The next section offers a
detailed analysis of the difficulties related to PV systems that are partially shaded. After that, we go over the fundamental ideas and constraints of conventional MPPT methods. An overview of the meta-heuristic algorithms and how they are used in MPPT is provided in the next section. The concluding parts include recommendations for future study directions, a summary of findings, and a comparative analysis. This paper offers a thorough analysis of robust MPPT algorithms based on meta-heuristics, with the goal of advancing ongoing research efforts to maximize the operational efficiency of partially shaded PV systems. Our goal is to elucidate the optimal circumstances for every algorithm and pinpoint avenues for future progress in this domain.

2. Objectives

The following objectives and strategies have been outlined to guide this endeavor:

- To design and understand mathematical modelling of solar photovoltaic system.
- To analyze electrical and operational characteristics of solar panel.
- To develop improved Meta heuristic optimization based maximum power point tracking System under different operating conditions.
- To review and simulate and analyze the maximum power point tracking system for solar photovoltaic system under dynamic operational conditions.
- To model the schedule of charging of electric vehicle keeping identification of grid requirement and EV charging requirement.

3. Methods

Velocity vectors govern the motion of individual particles, governing their direction and quantity. Until a termination condition is satisfied or the algorithm converges to the ideal solution, the PSO algorithm repeatedly repeats these phases. PSO finds the global optimum solution and effectively explores the search space. Every change's speed may be determined using the current speed, and the governing equation shown below may be used to compute the agent's distance from Pbest and gbest:

\[
V_i^{k+1} = W \times V_i^k + C_1 \times r_1 \times (P_{best_i}^k - X_i^k) + C_2 \times r_2 \times (G_{best}^k - X_i^k)
\]

![Figure 2: Particle Swarm Optimization Search Engine System](image)

Partial Shading Analysis:

\[ P_{i,t} = P_{i,t} - P_{i,t} \times I_{shad,k} \]

Photovoltaic Module Current (I) Calculation:

\[ I = \frac{V}{R_{sh}} + \frac{V - V_{oc}}{R_s} \]

PV Module Voltage (V) Calculation:

\[ V = V_{oc} - I \times R_s \]

Total Output Power (P) Calculation:

\[ P = V \times I \]
19 Change in Power (dP) Calculation:
\[ dP = P^t_i - P^{t-1}_i \]

20 Update Reference Voltage for MPPT:
\[ V_{ref}^{t+1} = V_{ref}^t + K_p \cdot dP \]

21 Update Reference Current for MPPT:
\[ I_{ref}^{t+1} = I_{ref}^t + K_i \cdot P^t_i \]

22 PV Module Temperature Calculation:
\[ T = T_{ambient} + \frac{P^t_i \cdot R_{th}}{A_{module}} \]

23 Change in Temperature (dT) Calculation:
\[ dT = T - T_{previous} \]

24 Change in Voltage Reference (dV) Calculation:
\[ dV = -\alpha \cdot dT \]

25 New Voltage Reference for MPPT:
\[ V_{ref}^{t+1} = V_{ref}^t + dV \]

26 PV Module Current (I) Calculation with Temperature Compensation:
\[ I = \frac{V}{R_{sh}} + \frac{V - V_{oc}}{R_s} + \frac{T - T_{ref}}{R_{th}} \]

27 PV Module Voltage (V) Calculation with Temperature Compensation:
\[ V = V_{oc} - I \cdot R_s \]

Figure 3: CSA-Particle Swarm Optimization MPPT System
The theory behind the methodology of the improved PSO-based MPPT tracking under a partially shaded PV system integrates the principles of Particle Swarm Optimization (PSO) with the intricacies of Maximum Power Point Tracking (MPPT). Let's unpack this step-by-step:

1. **Particle Swarm Optimization (PSO):**
   PSO is a heuristic optimization method inspired by the social behavior of birds flocking or fish schooling. It involves a number of particles (potential solutions) moving around in the search space. Each particle has a position and velocity and adjusts its movements based on its personal best position and the global best position found by the swarm. The aim is to explore the search space to find the most optimal solution.

2. **Maximum Power Point Tracking (MPPT):**
   Solar PV systems produce the maximum power when operated at a particular point called the Maximum Power Point (MPP). MPPT techniques are developed to track this MPP under different environmental conditions. Since the PV output is nonlinear and affected by external factors like temperature and irradiance, MPPT algorithms adjust the operating point of the system to ensure it's close to MPP.

3. **Challenges with Partial Shading:**
   Partial shading is when only a part of the solar array is shaded. It creates multiple power-voltage (P-V) curves with multiple peaks, including local and global maxima. Traditional MPPT algorithms like P&O can get stuck in local maxima, leading to suboptimal performance.

4. **Methodology Theory:**
   Given the above principles, the methodology for the improved PSO-based MPPT can be conceptualized as follows:
   - **Initialization:** Start by setting PSO parameters like swarm size, maximum iterations, and inertia weight. This phase essentially prepares the algorithm for the optimization process.
   - **Swarm Initialization:** Particles, representing potential solutions, are initialized with their positions and velocities. These positions can be thought of as potential operating points of the PV system.
   - **Evaluation:** Each particle's position corresponds to a potential MPP. By evaluating the power output at each position, we can gauge the efficiency of each potential solution.
   - **Position Updates:** Particles adjust their positions based on their individual best-found positions and the swarm's overall best-found position. This iterative process ensures that the swarm collectively moves closer to the global MPP.
   - **Integration with CSA:** While PSO provides the exploration capability to search for the global MPP, the Cuckoo Search Algorithm (CSA) refines the solution. By integrating the CSA's exploitation mechanism, the algorithm can fine-tune particle positions, ensuring a more accurate MPP tracking.
   - **Convergence Check:** The process iteratively continues until a satisfactory solution (MPP) is found or until a predefined number of iterations are reached.
   - **Outcome:** The result is an optimized tracking of the MPP, even under partial shading conditions, ensuring the PV system operates near its peak efficiency.

The proposed algorithm is an advanced variant of the traditional PSO and CSA, addressing some of its inherent limitations. By enhancing its sensitivity to the rate of change of power concerning voltage or current, it achieves a more refined tracking capability. Nevertheless, under challenging partial shading conditions, the algorithm may still be misled by multiple local maxima.
maxima, potentially leading to suboptimal performance points. Table 1.1 highlights the improved performance of the algorithm under different shading conditions.

**Table 1.1: Comparative Analysis of In P&O Performance**

<table>
<thead>
<tr>
<th>Shading Condition</th>
<th>Efficiency (%)</th>
<th>Convergence Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Shading</td>
<td>98.9</td>
<td>Very Fast</td>
</tr>
<tr>
<td>Partial Shading (1PV)</td>
<td>84.7</td>
<td>Moderate</td>
</tr>
<tr>
<td>Partial Shading (2PV)</td>
<td>78.2</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

The advanced method incorporates adaptive techniques to better interpret incremental changes in conductance, thereby determining the MPP with increased precision. Its performance metrics, although impressive under steady-state conditions, still present challenges when navigating partial shading. Table 1.2 presents the nuanced performance metrics of the Advanced IncCond method.

**Table 1.2: Advanced IncCond Performance Metrics**

<table>
<thead>
<tr>
<th>Shading Condition</th>
<th>Efficiency (%)</th>
<th>Convergence Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Shading</td>
<td>99.5</td>
<td>Fast</td>
</tr>
<tr>
<td>Partial Shading (1PV)</td>
<td>86.4</td>
<td>Moderate</td>
</tr>
<tr>
<td>Partial Shading (2PV)</td>
<td>79.9</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

**Figure 4:** Analysis of Convergence Speed

**Figure 5:** Analysis at Normal Operational Condition
Introducing the Hybrid PSO-CSA MPPT algorithm - a strategic fusion of the Particle Swarm Optimization's exploration strategy with Cuckoo Search Algorithm's exploitation mechanism. The stepwise operational methodology is as follows:

Step 1: Set the PSO parameters: including the swarm's dimensions, iteration boundaries, and inertia coefficient.

Step 2: Commence the swarm of particles by randomly setting their positional coordinates and velocity vectors.

Step 3: Assess the power efficiency of each particle considering its current coordinates.

Step 4: Update each particle's optimal position and the collective best position based on the efficiency readings.

Step 5: Transition the PSO particles based on the local and collective optimum points.

Step 6: Incorporate the CSA's strategic exploitation to enhance particle coordinates.

Step 7: Reiterate Steps 3-6 till optimal convergence or the predefined iteration threshold is met.

Validating the hybrid algorithm's efficiency was imperative. The analysis was realized through MATLAB simulations, embodying realistic irradiance and shading patterns. Table 1.3 draws a comparative analysis of diverse MPPT algorithms against different shading environments.
Table 1.3: Comparative Analysis of MPPT Algorithms

<table>
<thead>
<tr>
<th>MPPT Algorithm</th>
<th>Efficiency (%)</th>
<th>Convergence Speed</th>
<th>Shading Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP&amp;O</td>
<td>84.7</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Advanced IncCond</td>
<td>86.4</td>
<td>Fast</td>
<td>Moderate</td>
</tr>
<tr>
<td>FSCC</td>
<td>83.1</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>MP&amp;O</td>
<td>86.2</td>
<td>Fast</td>
<td>High</td>
</tr>
<tr>
<td>Hybrid PSO-CSA</td>
<td>97.3</td>
<td>Very Fast</td>
<td>Exceptional</td>
</tr>
</tbody>
</table>

The analysis of the Maximum Power Point Tracking (MPPT) algorithms for solar photovoltaic applications, based on the generated graphs, reveals significant insights:

1. **Efficiency Comparison**: The Hybrid PSO-CSA algorithm demonstrates superior efficiency across various shading conditions, notably excelling in no shading scenarios. Advanced IncCond also shows high efficiency, particularly under no shading, but slightly less than the Hybrid PSO-CSA. In P&O, while efficient in no shading, drops significantly in efficiency under partial shading conditions.

2. **Convergence Speed**: The Hybrid PSO-CSA and In P&O algorithms exhibit a "Very Fast" convergence speed under no shading, indicating their quick responsiveness to changing conditions. Advanced IncCond, although fast, is slightly slower compared to the Hybrid PSO-CSA.

3. **Shading Resilience**: The Hybrid PSO-CSA stands out with exceptional shading resilience, indicating its robustness and reliability in varying solar irradiance conditions. Other algorithms like MP&O and Advanced IncCond show moderate to high resilience.

4. **Performance Under No Shading**: In scenarios without shading, the Hybrid PSO-CSA and Advanced IncCond algorithms demonstrate high efficiency and fast convergence, marking them as suitable choices for consistent solar conditions.

5. **Performance Under Partial Shading**: Under partial shading, both In P&O and Advanced IncCond exhibit moderate efficiency and convergence speed, highlighting the challenges posed by fluctuating solar conditions.

Overall, the Hybrid PSO-CSA emerges as the most promising algorithm, offering a balance of high efficiency, rapid convergence, and exceptional shading resilience, making it an optimal choice for solar PV applications across varying environmental conditions.

6. **Conclusion**

The comprehensive analysis of the performance of various Maximum Power Point Tracking (MPPT) algorithms in solar photovoltaic applications, particularly focusing on the newly proposed Hybrid PSO-CSA algorithm, provides insightful conclusions. The Hybrid PSO-CSA algorithm, integrating the exploration capabilities of Particle Swarm Optimization with the exploitation mechanisms of the Cuckoo Search Algorithm, exhibits outstanding performance across multiple parameters. Its efficiency under no shading conditions is remarkable, registering close to 97.3%, which is a testament to its effectiveness in optimal solar energy harvesting. The algorithm's exceptional shading resilience is a critical feature, as it ensures stable performance even under fluctuating solar irradiance, a common challenge in real-world solar applications. In comparison, the Advanced IncCond method shows significant improvements over traditional methods like In P&O, especially in efficiency under various shading conditions. However, it falls slightly short of the Hybrid PSO-CSA's performance, particularly in terms of convergence speed and shading resilience. The traditional In P&O algorithm, while still relevant, is outperformed by these advanced methods in almost all aspects. Its moderate efficiency and convergence speed under partial shading conditions indicate its limitations in handling complex solar irradiance patterns. The statistical and comparative analysis underlines the importance of algorithmic efficiency and convergence speed in maximizing energy extraction from photovoltaic systems. The resilience to shading conditions is particularly crucial, as it determines the system's reliability and consistency in energy output under real-world environmental variations. In conclusion, the Hybrid PSO-CSA algorithm emerges as a superior choice for MPPT in solar PV systems. Its balanced approach in effectively harnessing solar energy, coupled with its robustness against shading effects, makes it a
highly promising solution for enhancing the efficiency and reliability of solar photovoltaic systems. This advancement holds significant implications for the renewable energy sector, offering a pathway to optimize solar energy utilization and contribute to sustainable energy solutions.

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, Feburary 2018


[10] Mingxuan Mao, Li Zhang, QichangDuan, 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


[16] BennisGhita, Karim Mohammed and Lagrioui Ahmed, “Comparison between the conventional methods and PSO method for maximum power point extraction in photovoltaic systems under partial shading condition”, International journal of power electronics and drive system, vol. 9, no. 631-640, June 2018

[17] ThanikantiSudhakarBabu and Prasanth Ram, NatranjanRajeskarandFredeBlaabjerg, “Particle swarm optimization based solar PV array reconfiguration of the maximum power extraction under partial shading”, Sustainable energy, IEEE, vol. 9, no. 74-85, January 2018


[27] T. Diana and Dr. K Rama Sudha, “Maximum power point tracking of PV system by particle swarm optimization algorithm”, International research journal of engineering and technology, vol. 6, no. 126-130, September 2019


https://internationalpubls.com