INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN SOCIAL SCIENCE (IJRISS)
ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

Proposition of Ant Colony and Perturb and Observe MPPT Combination for Photovoltaic System

Kharismi Burhanudin[1*], Mohd Nazrien Zaraini[2], Muhammad Faheem Mohd Ezani[3], Muhamad Nabil Hidayat[4,]

[1,2,3]Centre for Advanced Computing Technology (C-ACT), Fakulti Kecerdasan Buatan dan Keselamatan Siber (FAIX), Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia

[4]College of Engineering, UiTM Shah Alam, Selangor, Malaysia

***Corresponding Author**

DOI: https://dx.doi.org/10.47772/IJRISS.2025.910000725

Received: 01 November 2025; Accepted: 08 November 2025; Published: 22 November 2025

ABSTRACT

This research presents a novel hybrid Maximum Power Point Tracking (MPPT) technique that combines Ant Colony Optimization (ACO) with the Perturb and Observe (P&O) method to enhance the efficiency and convergence speed of photovoltaic (PV) systems. The ACO MPPT, based on swarm intelligence, is utilized for its ability to conduct a global search for the maximum power point. In contrast, the P&O method provides steady-state tracking with low computational complexity. By integrating these two approaches, the research aims to leverage their respective strengths to achieve faster and more reliable convergence under varying environmental conditions. The study employs the NTR 5E3E monocrystalline PV module (173.5W) as the test subject, with the implementation carried out in a MATLAB Simulink environment. The experimental results demonstrate that the hybrid approach outperforms the standalone P&O and ACO MPPT methods in terms of convergence speed, accuracy, and stability, indicating promising potential for practical applications in PV systems.

Keywords— Aco, Pso, Fpo, Pno, Mppt, Pv, Matlab Simulink

INTRODUCTION

A photovoltaic (PV) system converts sunlight into electrical energy and plays a crucial role in renewable energy generation [1]. The efficiency of a PV system largely depends on effectively extracting maximum power from the PV panels [2]. This is achieved through the integration of essential components such as PV panels, power converters, and maximum power point trackers (MPPT). The MPPT is vital for ensuring that the PV system operates at its optimal point, maximizing energy harvest under varying environmental conditions. This research explores a hybrid MPPT method that combines two distinct techniques: Ant Colony Optimization (ACO) and Perturb and Observe (P&O). Both methods aim to track the maximum power point (MPP) but differ significantly in their operational mechanisms. The P&O method is a simple and widely used technique that adjusts the operating point based on the slope of the PV power curve, offering ease of implementation [3], but it is known to suffer from oscillations around the MPP [4]. In contrast, the ACO algorithm, inspired by swarm intelligence, performs a global search across the solution space by mimicking the foraging behavior of ant colonies [5]. While it offers enhanced exploration capabilities, it also comes with increased computational complexity. Each method has its own advantages and limitations: P&O is fast but can oscillate near the MPP, whereas ACO is robust but requires greater computational resources. This study investigates the potential of combining both methods to develop an effective hybrid MPPT strategy [6]. The goal is to leverage the rapid convergence of P&O alongside the global search efficiency of ACO, while addressing the common trade-offs found in traditional MPPT techniques. The system setup utilizes a boost converter due to its efficiency and capability to manage high-voltage conversion requirements. Experimental evaluations are conducted using a practical 173.5W NTR 5E3E monocrystalline PV module, highlighting the real-world applicability of the proposed hybrid approach. This research systematically analyzes the performance of individual MPPT methods and their combination, providing insights into parameter tuning and the feasibility of implementing this hybrid technique in cost-effective PV systems. Ultimately, the study demonstrates the benefits of using soft computing methods, which are valued for their simplicity and low-cost implementation, in optimizing PV energy harvesting performance.

METHODOLOGY

This section provides a comprehensive overview of advanced techniques for maximum power point tracking (MPPT) in photovoltaic (PV) systems, organized into four distinct subsections. The first subsection discusses the impedance matching process and how to calculate the operating region to achieve maximum power transfer, which is essential for the efficient operation of PV systems [1], [2]. The second subsection details the implementation of the Ant Colony Optimization (ACO) algorithm for MPPT [7], demonstrating how bio-inspired computational methods can enhance energy extraction [5]. The third subsection explores the Perturb and Observe (P&O) method [3], a widely used and straightforward MPPT technique that modifies system variables to locate the maximum power point [8]. Finally, the fourth subsection presents a hybrid approach that combines the ACO and P&O algorithms, aiming to leverage the strengths of both methods for improved performance in MPPT for PV systems [9]. Together, these subsections provide an in-depth examination of both conventional and innovative MPPT strategies [10].

A. Impedance Matching Process and Operating Region Calculation for Maximum Power Point Tracking

The impedance matching process is a method used to determine the maximum power that a photovoltaic (PV) system can produce at a specific irradiance level. This method serves as a reference for analyzing PV power output. The impedance matching process is based on a boost converter circuit, where equivalent resistance, load resistance, and duty cycle are key factors in the impedance matching calculations [1]. Table I presents the NTR 5E3E PV module used in this research study [1].

TABLE I The Ntr 5e3e Pv Module Parameter [11].

Parameters	Value
Open circuit voltage, Voc	44.4V
Short circuit current, Isc	5.4A
Maximum Voltage, Vmp	35.4V
Maximum Current, Imp	4.9A
Maximum Power, Pmp	173.5W

Each formula for calculating impedance matching in converters is different. The formula for impedance matching used in boost converters is listed below:

$$(V_{out}/V_{in}) = (I_{in}/I_{out}) = 1/(1-D) \quad (1)$$

$$R_{eq} = R_L\ (1-D)\ 2 \quad (2)$$

$$D = 1 - (R_{eq}/R_L)^{1/2} \quad (3)$$

Where R_{eq} is Equivalent Resistance, R_L is Load Resistance and D is Duty cycle [12]. The research study focusses on varying irradiance from 100-1000W/m ^{2} which is sufficient to provide analysis for this research work. The identification of the operating region is necessary to determine the active region for the boost

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

converter to function with MPPT [13]. Table II shows the equivalent resistance and duty cycle data for irradiance from 100-1000W/m ^{2} based on NT5E3E PV panel.

TABLE II The Duty Cycle Data Based on Varying Irradiance Selection.

Irradiance	V max	I max	P max	R eq	D. cycle
1000W/m ^{2}	35.4	4.9	173.5	7.22	0.6532
900W/m ^{2}	35.4	4.409	156.1	8.03	0.6342
800W/m ^{2}	35.4	3.911	138.4	9.03	0.612
700W/m ^{2}	35.4	3.406	120.6	10.39	0.584
600W/m ^{2}	35.4	2.896	102.5	12.23	0.544
500W/m ^{2}	35.4	2.381	84.3	14.87	0.5023
400W/m ^{2}	35.4	1.863	65.95	19	0.437
300W/m ^{2}	35.4	1.341	47.47	26.4	0.337
200W/m ^{2}	32.57	0.879	28.64	37	0.215
100W/m ^{2}	23.52	0.416	9.77	58.32	0.014

According to Table II, the load resistance must be greater than 58.32 ohms to efficiently track maximum power across various irradiance levels from the PV panel [12]. Therefore, a load resistance value of 60 ohms is used for the PV panel.

Inclination angle formula

$$\Theta_I = tan^{-1}[1/(1-D)^2 \; R_L] \qquad (4)$$

Parameters description:

Θ_I : Inclination Angle

D : Duty Cycle

R_L : Load Resistance

The data presented illustrates the relationship between duty cycle and the inclination angle (Θ), ranging from a maximum of 90° to a minimum of approximately 0.98° [13]. As the duty cycle decreases from 1 to near zero, the inclination angle correspondingly declines from its maximum value of 90° to its minimum value of approximately 0.98°.

TABLE III The Operating Region of Boost Converter for Mppt Process.

Duty Cycle	**Inclination Angle, Θ**
1	90 (Θ_{max})
0.6532	7.89
0.6342	7.099
0.612	6.314
0.584	5.50103
0.544	4.583

0.5023	3.8503
0.437	3.01
0.337	2.172
0.215	1.55
0.014	0.9822 (Θ_{min})

Accurately identifying this range is crucial for efficient system performance, especially in contexts such as maximizing power transfer or adapting to environmental conditions. The optimal operation likely occurs within this defined zone, where small variations in the duty cycle significantly influence the inclination angle, thereby affecting the system's energy conversion efficiency. This analysis highlights the importance of precisely determining the operating region to ensure the system operates at peak efficiency while maintaining stability across varying duty cycle conditions [3], [4].

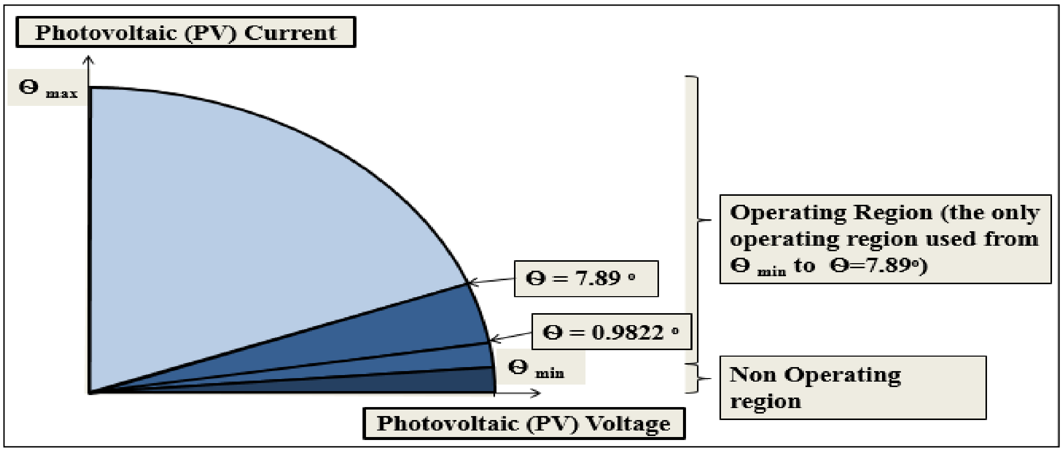

Fig. 1 The operating region of boost converter for MPPT process [14].

Implementing Ant Colony Algorithm for MPPT

Ant Colony MPPT is implement by making most out of ant’s behavior [7]. The concentration of the pheromone from the initial ants will affect the overall ant movement during the swarm process. Revised concentration of the pheromone, change in pheromone concentration and Pheromone concentration rate of the ants ill affect the whole maximum tracking process of the PV power. Listing below show the characteristic of the ACO algorithm formula [5]:

The pheromone concentration formula

$$\mathrm{Tij} = \rho\mathrm{Tij}\ \mathrm{t} - 1\ + \Delta\mathrm{Tij} \qquad (5)$$

Parameters description:

T_{ij} : Revised concentration of pheromone

ΔT_{ij} : Change in pheromone concentration

ρ : Pheromone concentration rate (0-1)

The initialization of pheromone concentration rate is crucial due to the impact on convergence process of the PV power. If the Pheromone concentration is wrongly initialized, it will cause false convergence and easily causes the convergence fall to local minimum. Fig. 2 shows the ACO MPPT technique that leads to MP identification process.

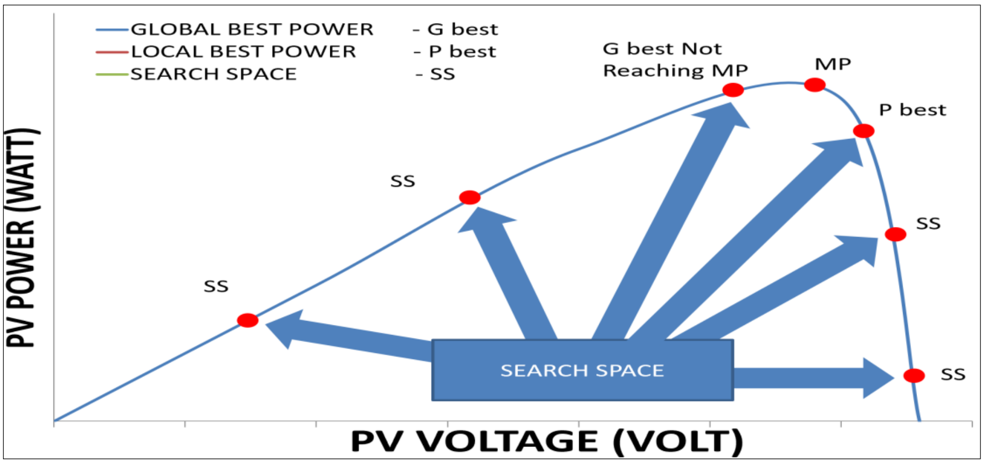

Fig. 2 ACO MPPT tracking MP technique

ACO MPPT track MP based on search space and maintain the MP by the workability of the swarm process based on ant movement and pheromone concentration. The convergence of the ACO MPPT sometimes becomes premature due to search space unable to identify the nearest local peak power or due to the swarm process which converge wrongly at the wrong point [5]. The duty cycles of the search spaces are generated randomly at the initial process of the ACO MPPT, this causes the highest power to be generated at this stage is declare as local peak power [15]. The local peak power at this stage will determine the convergence of the global peak power whether converge at peak power or fall to local minimum.

Implementing Perturb and Observe MPPT method for PV System

PNO is the MPPT method that finding MP by observing the PV curve characteristic comparing the old PV parameter such as PV voltage, PV current or PV power with the updated PV curve parameters characteristic. This research using PV voltage and PV power as perturb technique to identify MP. Fig. 3 shows the PNO MPPT technique to track MP.

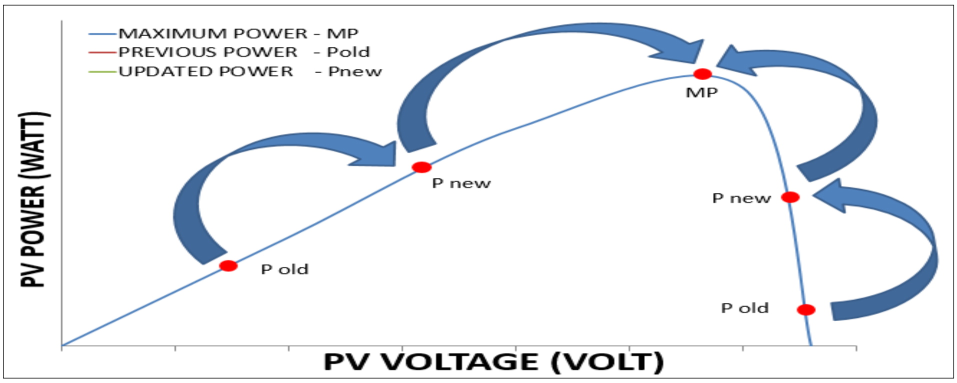

Fig. 3 PNO MPPT tracking MP technique.

PNO MPPT track MP by moving by step to reach MP and maintaining the MP by observing the current MP point [3], [4]. The tracking technique of PNO is able to track MP. However, the time taken to track the MP s longer compare to the ACO MPPT which takes less time comparing to the PNO MPPT [8]. This is due to by step movement taken by PNO MPPT to track MP.

Combination of ACO and PNO for PV System MPPT

The reason of ACO and PNO MPPT combination are implemented is to limit the time taken to track the MP as well as to allow the MP converge at the right point [9]. The Search space process of the ACO work normally to locate the local peak power and the ACO MPPT formula will work with PNO method to locate the MP [10]. Fig. 4 shows the MPPT from ACO and PNO combination. The idea of combining both MPPT method is to allow a more efficient MP tracking process. By joining both MPPT method together, the MP tracking process takes shorter time to reach MP and able to maintain MP efficiently. Based on Fig. 4, the MPPT process consist of search space which enable the MPPT to identify the closes point to the MP. After the Search Space process, PNO MPPT take place to identify the highest MP of the PV curves. The PNO MPPT able to maintain the MP based on PV power and voltage analysis.

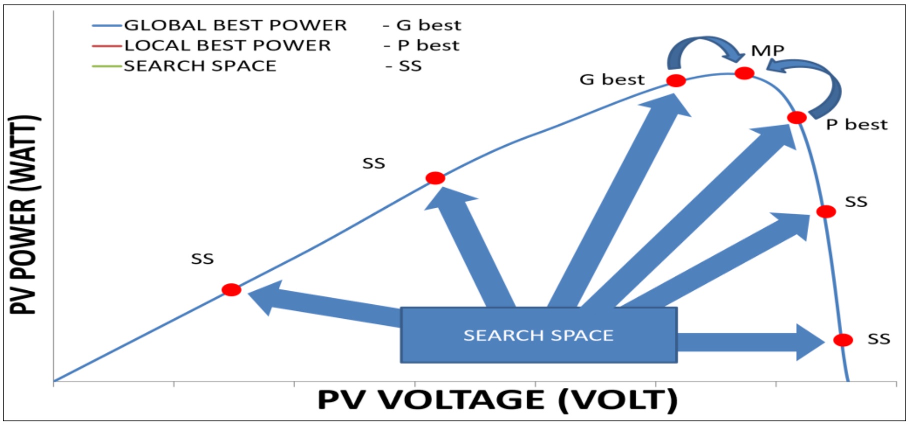

Fig. 4: The combination of ACO and PNO MPPT.

The MPPT combination between ACO and PNO MPPT start with initializing $distancetra$ which is change in pheromone concentration. The $particles(iter, 2)$; represent random number of pheromone concentration set to the MPPT.

$distancetra\ = 1/particles(iter, 2);$

dV and dP is the subtraction of previous and current PV voltage and current. This will ensure that the previous PV power and voltage being recorded for MPPT tracking purposes.

$dV = particles(iter, 7)\ -\ Vold;$

$dP = particles(iter, 3)\ -\ Pold;$

ACO MPPT formula take place to measure the amount of pheromone concentration needed to identify the amount of pheromone needed for the duty cycle.

$particles(iter, 1) = (1 - 0.0007) * particles(iter - 1,1) + distancetra;$

Pheromone concentration represented by (1-0.007) which is vital for the whole MPPT process. Wrong tuning causes the MPPT unable to converge at the MP if implemented ACO MPPT alone without PNO MPPT. Revised concentration of the pheromone represented by $particles(iter, 1)$, previous revised concentration of pheromone represented by $particles(iter - 1,1)$ and finally $distancetra$. After ACO MPPT used to identify the amount of pheromone needed, PNO MPPT take place to do perturbation and observation on whether to subtract or add the amount of duty cycle.

$if\ dP\ <\ 0$

$if\ dV\ <\ 0$

$if\ pXid < particles(iter, 1)$

$particles(iter, 1)\ =\ particles(iter, 1)\ -\ distancetra;$

end

$else$

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

```
      if pXid > particles(iter,1)
      particles(iter,1) = particles(iter,1) + distancetra;
      end
    end
  else
    if dV < 0
      if pXid > particles(iter,1)
      particles(iter,1) = particles(iter,1) + distancetra;
      end
    else
      if pXid < particles(iter,1)
      particles(iter,1) = particles(iter,1) - distancetra;
      end
    end
  end
```

After PNO MPPT perturbation and observation, the value of the current PV power and voltage is considered as old PV Power and Voltage. This process allowed future MPPT PV Power and Voltage comparison between new and previous value. The MPPT combination of ACO and PNO need to consider the initialization of $xMin$,$xMax$, $vMin$ and $vMax$. $xMin$ and $xMax$ is the randomness value of $particles(iter,1)$. $vMin$ and $vMax$ is randomness for $particles(iter,2)$. Fig. 5 below shows the Pseudo Code of the whole coding structure.

```
// System Control Loop: Continuous MPPT
IF enable IS TRUE THEN
   // 1. Initialization (Run once)
   INITIALIZE Swarm_Data_Array, Pheromone_Matrix (Tij), iteration = 0.
   SET swarm_size (e.g., number of "ants").
   LOOP forever DO
      IF iteration < swarm_size THEN
         // PHASE 1: Data Collection (Ant Movement)
         1. COLLECT Vpv, Ipv, and Duty_Cycle.
         2. STORE Power_P in the Swarm_Data_Array
         3. INCREMENT iteration.

      ELSE // iteration >= swarm_size
         // PHASE 2: Optimization and Reset (Pheromone Update)

         // A. Evaluation & Reset
         1. FIND and STORE Local_Best_Power (P_max) and its Duty_Cycle from the array.
         2. SET iteration = 1.
         3. SET initialize = 1. // Trigger the optimization block

         IF initialize == 1 THEN
            // B. Core Optimization Block (Swarm Step)

            // 1. Pheromone Update (ACO Global Guidance)
            // Use the best power found to reinforce the optimal path.
            Tij(new) = (rho * Tij(old)) + Delta_Tij // ACO Formula
            // 2. Local Refinement (PNO)
            // Use PNO to precisely tune the new Duty_Cycle suggested by ACO.
            PERFORM PNO_MPPT_CYCLE.

            // 3. Update Records
            UPDATE Local_Best_Power and Duty_Cycle with the new PNO result.
            INCREMENT iteration. // Moves to the next particle's step
         END IF

         // C. Global Best Identification (After one full cycle)
```

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

Fig. 5 Shows the Pseudo Code of the hybrid ACO and PNO MPPT method.

RESULT AND DISCUSSION

PV Power collected based on constant irradiance value.

Based on the study and observation on the propose MPPT method. Author conducted an experiment to verify the workability of the PV power of the propose MPPT method during dynamic irradiance changes and normal circumstances irradiance changes. The graph collected is of type PV power against time changes.

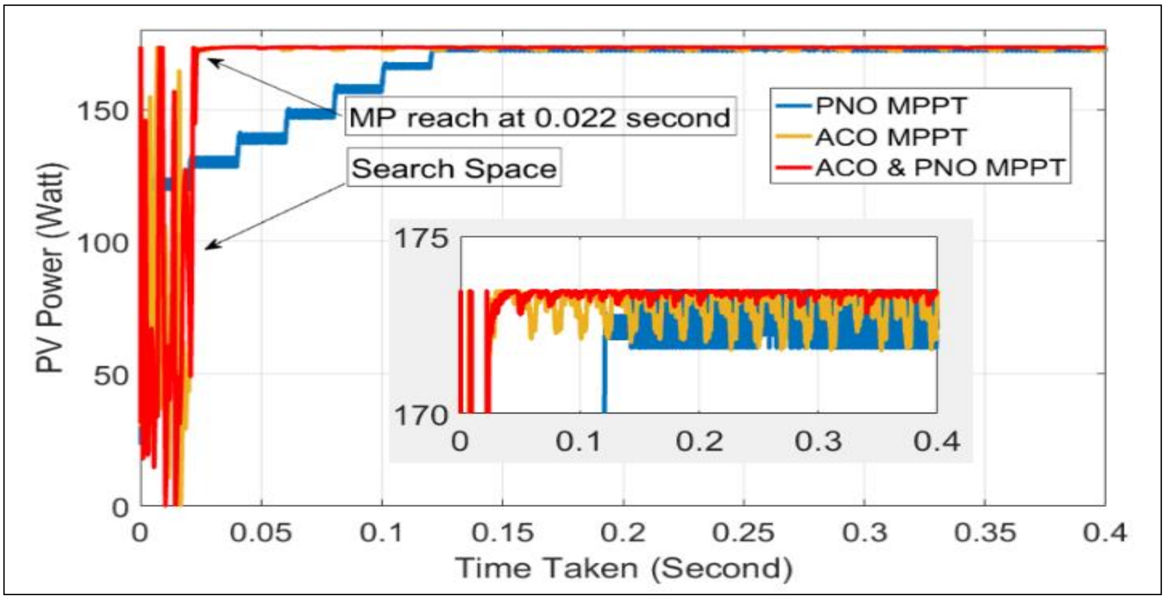

Fig. 6 Comparison of PV Power collected between proposed, ACO and PNO MPPT at 1000 W/m^2 at time taken between (0-0.2) and (0.198-0.2) second.

The workability of the propose MPPT method be able to converge better compare to the normal ACO MPPT method. The irradiance value tested is from 100-1000 W/m^2. Based on Table II, the calculated PV power is use to compare with the actual PV power collected from the analysis.

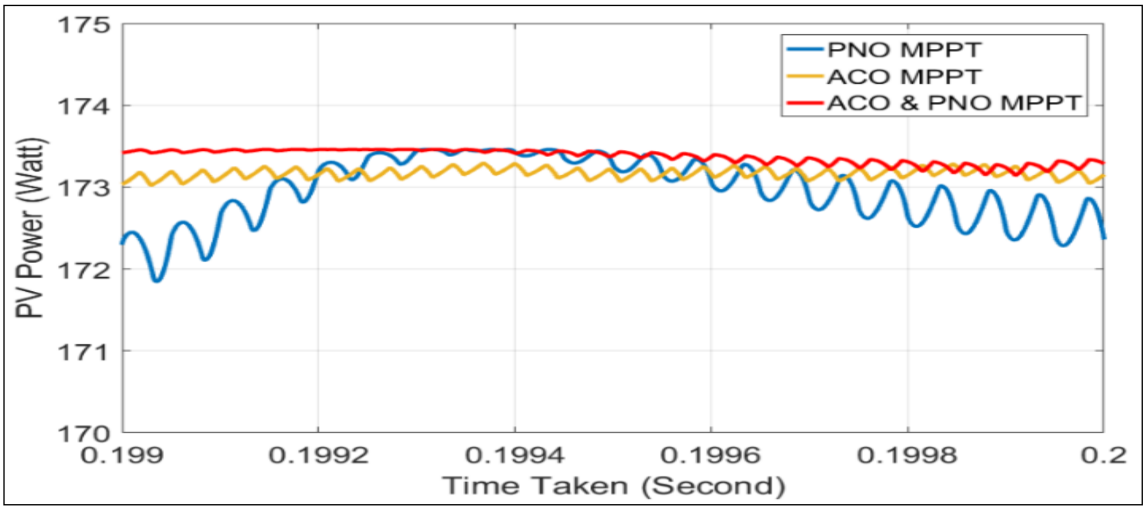

Fig. 7 Comparison of PV Power collected between ACO & PNO, ACO and PNO MPPT at 1000 W/m^2 at time taken between ((0.199-0.2) second.

Based on Fig. 6 and Fig. 7 it is clear that the proposed MPPT method converge better compare to the ACO and PNO MPPT. Fig. 7 shows that the ACO MPPT converge near the MP while PNO and proposed MPPT method able to converge at MP. Proposed MPPT method able to maintain at the MP better compare to the PNO MPPT.

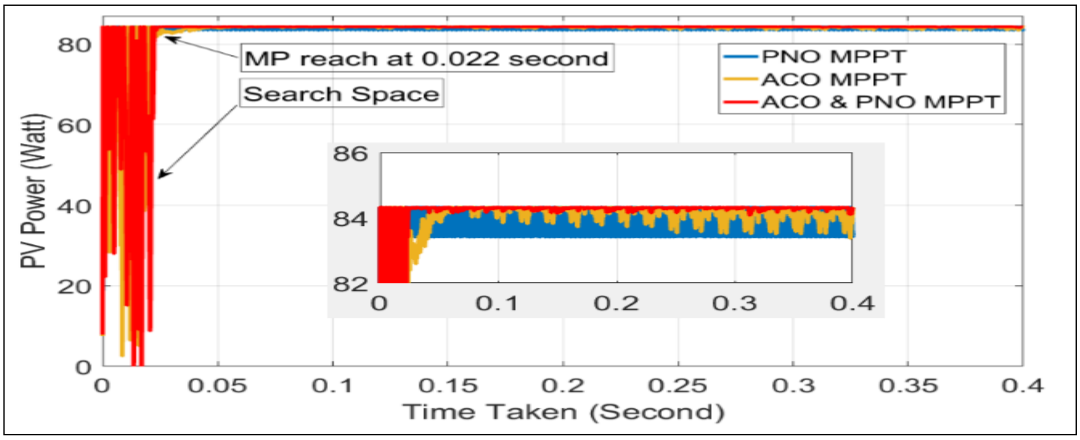

Fig. 8 Comparison of PV Power collected between proposed, ACO and PNO MPPT at 500 W/m^2 at time taken between (0-0.2) and (0.198-0.2) second.

PNO MPPT require more time to be able to reach the MP and the convergence is sometimes slip due to perturb and observe character of the PNO MPPT. Fig. 8 and Fig. 9 show the characteristic of the PV power track at the irradiance of 500 W/m^2.

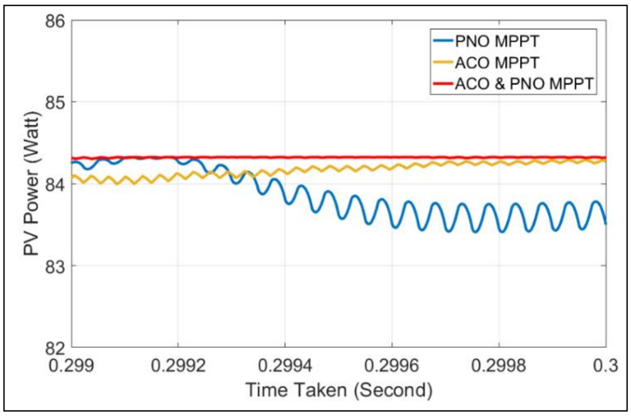

Fig. 9 Comparison of PV Power collected between proposed, ACO and PNO MPPT at 500 W/m^2 at time taken between (0.199-0.2) second.

Fig. 8 and Fig. 9 show the characteristic of the PV power collected at the irradiance of 500 W/m^2. The convergence of the 3 methods able to converge at the MP. However, the proposed method able to converge better compare to the ACO and PNO MPPT method. Table IV provide the detail of the average PV power based on varying irradiance value.

TABLE IV The Average Pv Power Data Based on Varying Irradiance.

Irradiance, W/m ^{2}	P_{CALC}	$P_{ACO-PNO}$	$\eta_{ACO-PNO}$	P_{ACO}	η_{ACO}	P_{PNO}	η_{PNO}
1000	173.5	173.22	0.9984	171.02	0.9857	166.98	0.9624
900	156.1	155.09	0.9935	154.9	0.9923	152.63	0.9778
800	138.4	137.17	0.9911	135.6	0.9798	132.88	0.9599
700	120.6	119.97	0.9948	119.16	0.9881	118.55	0.983
600	102.5	101.75	0.9927	101.94	0.9945	99.27	0.9685
500	84.3	83.88	0.995	83.22	0.9872	82.21	0.9752
400	65.95	65.41	0.9918	64.97	0.9851	63.6	0.9644

300	47.47	47.15	0.9932	47.08	0.9918	46.48	0.9791
200	28.64	28.47	0.9941	28.53	0.9962	27.55	0.962
100	9.77	9.72	0.9953	9.61	0.9834	9.59	0.9815
Average			0.993		0.9884		0.9714

The experimental results indicate that the hybrid ACO-PNO MPPT (Maximum Power Point Tracking) method consistently achieves power outputs that are close to the calculated maximum power across various irradiance levels. Specifically, it produces power outputs ranging from 9.77 W at 100 W/m² to 173.5 W at 1000 W/m². This hybrid approach reaches peak efficiencies of 99.53% at the lowest irradiance level and maintains efficiency above 99% even at higher irradiance levels [9]. This demonstrates its superior tracking capability compared to the individual ACO and PNO methods [1]. Both standalone algorithms show slightly lower power extraction, which suggests that the hybrid algorithm successfully combines the strengths of global search (ACO) and local refinement (PNO) to optimize power harvesting. The high efficiency stability across varying environmental conditions indicates that this hybrid MPPT strategy is robust and well-suited for practical photovoltaic (PV) applications, providing reliable performance even in low-light situations [10]. Overall, the data highlights the potential advantages of hybrid methodologies in maximizing PV system efficiency by closely approximating the ideal maximum power output.

The core finding is the hybrid method's exceptional efficiency and accuracy across the full operational range. As shown in Table IV and figures like Fig. 6, the hybrid ACO-PNO consistently maintains efficiencies exceeding 99.00%, reaching a peak of 99.53% at 100 W/m². This high level of sustained performance across varying irradiance, from low-level 100 W/m² to high-level 1000 W/m² scenarios, suggests a robust tracking mechanism. This robustness confirms the potential advantages of hybrid methodologies in maximizing PV system efficiency, as previously suggested by studies on hybrid intelligent control [16] and metaheuristic optimization [6]. The ability to precisely approximate the calculated maximum power is essential for real-world applications, supporting its suitability for systems requiring reliable power extraction, such as off-grid smart infrastructure [17] or photovoltaic water pumping systems [18]. Hybrid ACO-PNO excels at 99.30% efficiency, capturing maximum power, while pure ACO performs strongly at 98.84% with global search, occasionally missing the peak; pure PNO trails at 97.14% due to oscillations reducing power extraction.

PV Power collected during Dynamic irradiance changes

Dynamic irradiance is use to test the convergence capability of the three method MPPT during instantaneous irradiance changes. For the 1^t test the irradiance use is 600, 700, 900 and 700 W/m^2. The instant irradiance changes taking 0.1 second. The test is used to identify the working MPPT at dynamic situation. In the real situation, the irradiance changes do not change at instant.

TABLE V The Dynamic Irradiance Pattern 1.

MPPT	Performance Parameters	Varying Irradiance			
		Pattern 1			
PSO-INC	Average Power	101.754	119.973	155.086	119.973
	Irradiance	600	700	900	700
	Convergence Time	0-0.1s	0.1-0.2 s	0.2-0.3 s	0.3-0.4 s
		0.02217	0.12526	0.26977	0.324252

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

This method is used to show that the proposed MPPT able to converge efficiently under dynamic irradiance changes. Fig. 10 to Fig. 14 show the analysis of PV Power collected for the 1^{st} dynamic irradiance test. The performance analysis of the Ant Colony Optimization and Perturb and Observe (ACO-PNO) MPPT method under Pattern 1 shows promising potential for efficient energy harvesting in photovoltaic (PV) systems across varying irradiance levels.

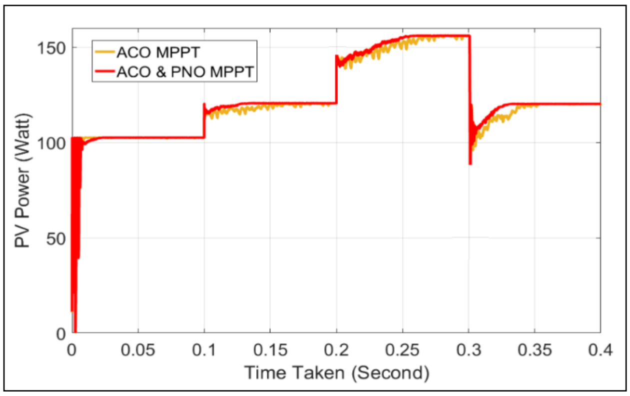

Fig. 10 The analysis on PV power collected for 1^{st} dynamic irradiance changes at time taken between (0-0.4) second.

The average power output increases significantly with irradiation intensity, rising from approximately 101.75 W at 600 W/m² to about 155.09 W at 900 W/m². This demonstrates that the hybrid MPPT adapts effectively to different sunlight conditions and optimizes power extraction.

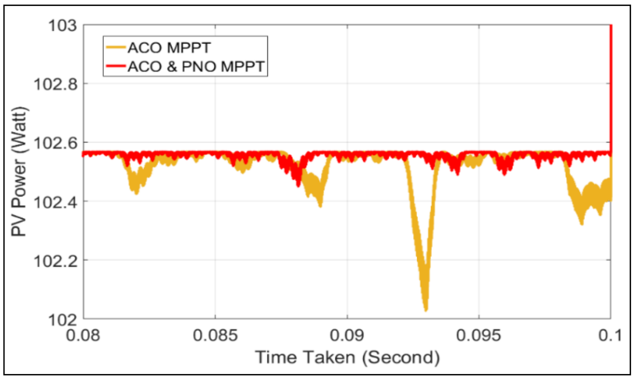

Fig. 11 The analysis on PV power collected for 1^{st} dynamic irradiance changes at time taken between (0.08-0.1) second.

Notably, the convergence time increases as irradiance levels rise, ranging from around 0.022 seconds at the lowest irradiance to 0.324 seconds at the highest.

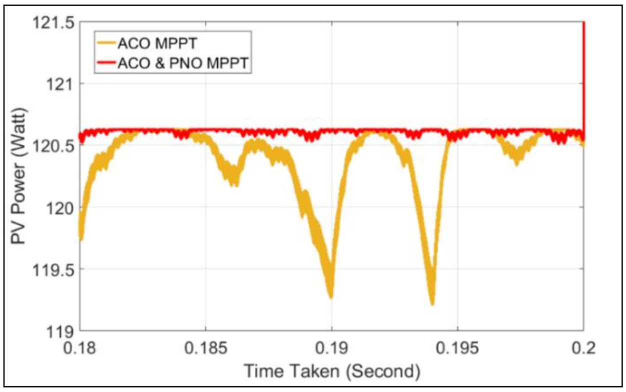

Fig. 12 The analysis on PV power collected for 1^{st} dynamic irradiance changes at time taken between (0.18-0.2) second.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

This reflects the greater computational effort needed to accurately track the maximum power point (MPP) when the irradiance is higher. The initial rapid convergence observed at 600 W/m² within just 0.022 seconds indicates that the hybrid approach effectively identifies the MPP under lower irradiance conditions.

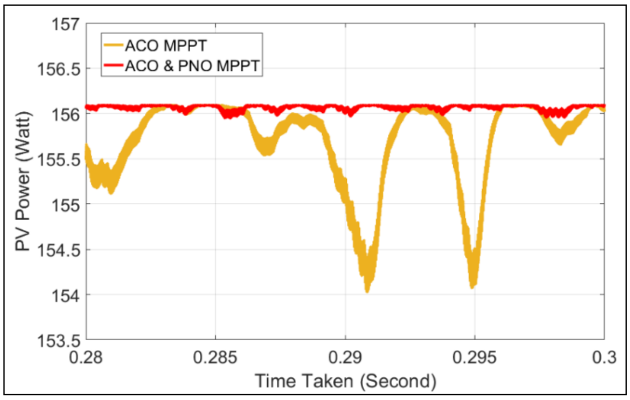

Fig. 13 The analysis on PV power collected for 1^{st} dynamic irradiance changes at time taken between (0.28-0.3) second.

In contrast, the longer convergence times at higher irradiance highlight a trade-off: achieving optimal accuracy requires more processing time. Overall, the ACO-PNO pattern demonstrates strong adaptability, effectively balancing power maximization with convergence speed, which is crucial for dynamic PV environments.

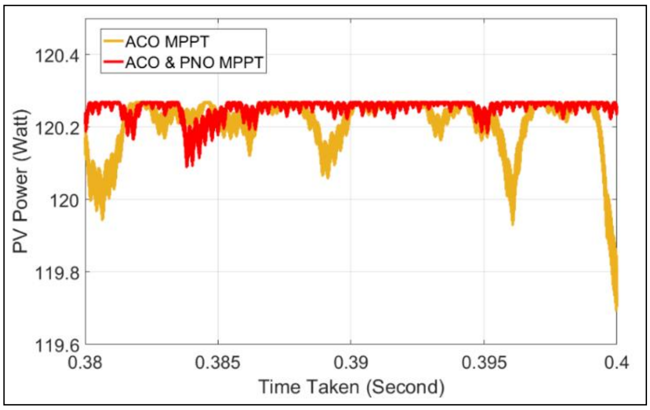

Fig. 14 The analysis on PV power collected for 1^{st} dynamic irradiance changes at time taken between (0.38-0.4) second.

Fig. 10 shows the overall convergence of the PV power. During the time between 0.2-0.3 second, ACO and PNO MPPT having a trouble to converge at the MP. PNO MPPT need sometimes to use perturb and observe method to reach the MP and ACO MPPT need to swarm to reach MP.

TABLE VI The Dynamic Irradiance Pattern 2.

MPPT	Performance Parameters	Varying Irradiance			
		Pattern 2			
PSO-INC	Average Power	65.945	101.754	93.445	84.936
	Irradiance	400	600	550	500
	Convergence Time	0-0.1s	0.1-0.2s	0.2-0.3s	0.3-0.4s
		0.01623	0.17432	0.20712	0.3112

The proposed method able to reach peak power at shorter time due to the capability to swarm and do perturb and observe at the given time. Fig. 11 to Fig. 14 shows convergence of every MPPT method at closer time and PV power range.

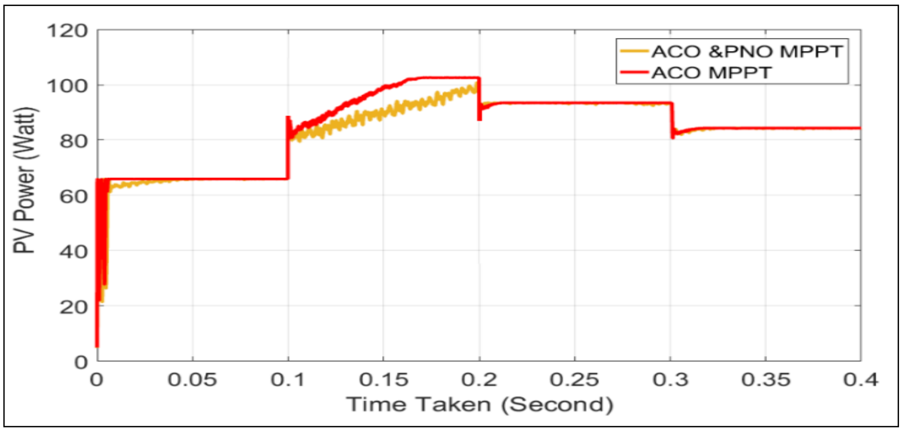

Fig. 15 The analysis on PV power collected for 2^{nd} dynamic irradiance changes at time taken between (0-0.4) second.

The convergence ability of proposed MPPT method converge better. For the 2^{nd} test the irradiance use is 400, 600, 550 and 500 W/m^2. Fig. 15 to Fig. 19 show the analysis of PV Power collected for the 2^{nd} dynamic irradiance test. The performance of the ACO-PNO MPPT under Pattern 2 demonstrates a responsive adaptation to varying irradiance levels.

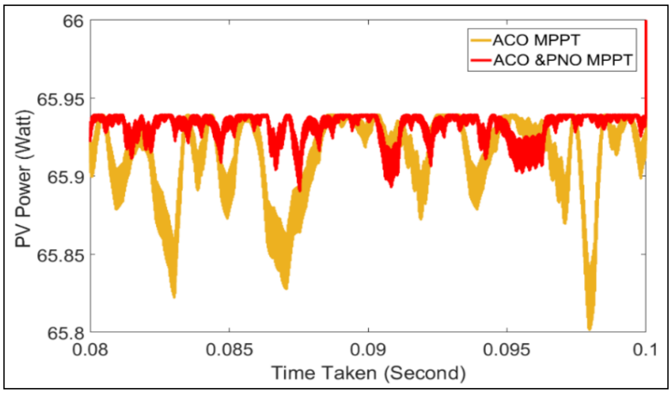

Fig. 16 The analysis on PV power collected for 2^{nd} dynamic irradiance changes at time taken between (0.08-0.1) second.

The average power outputs recorded are approximately 65.95 W at 400 W/m², 101.75 W at 600 W/m², 93.45 W at 550 W/m², and 84.94 W at 500 W/m². This data shows that the hybrid MPPT effectively captures and utilizes different sunlight intensities, with power outputs closely aligning with the corresponding irradiance levels.

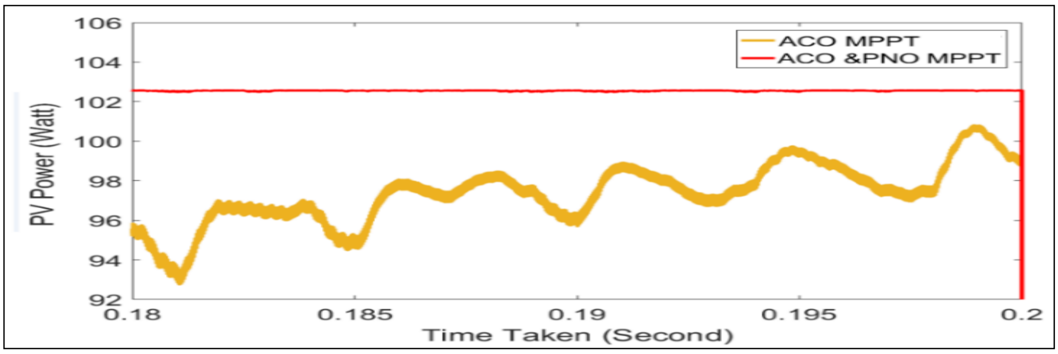

Fig. 17 The analysis on PV power collected for 2^{nd} dynamic irradiance changes at time taken between (0.18-0.2) second.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

Notably, the convergence times range from very quick (around 0.016 seconds at 400 W/m²) to slower values (up to 0.311 seconds at 500 W/m²). This reflects the adaptive complexity of the algorithm in response to different environmental conditions. The rapid initial convergence at lower irradiance (0.016 seconds) suggests efficient tracking under less intense sunlight, while the longer convergence times at medium irradiance levels indicate that more iterations are needed to fine-tune the maximum power point under moderate conditions.

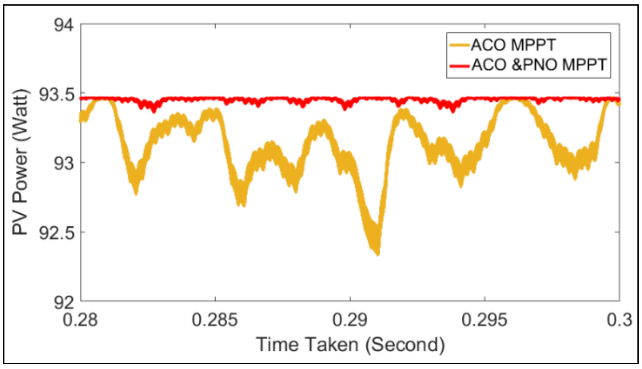

Fig. 18 The analysis on PV power collected for 2^{nd} dynamic irradiance changes at time taken between (0.28-0.3) second.

Overall, Pattern 2 shows that the hybrid ACO-PNO MPPT can reliably maximize power extraction with an acceptable convergence speed. This makes it suitable for diverse and fluctuating irradiance scenarios in photovoltaic (PV) systems. The results emphasize a good balance between power maximization and computational effort, which is crucial for real-time applications.

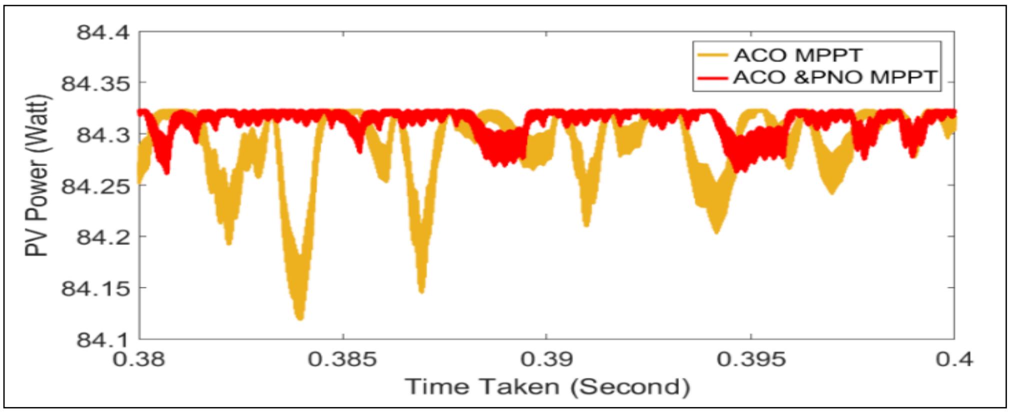

Fig. 19 The analysis on PV power collected for 2^{nd} dynamic irradiance changes at time taken between (0.38-0.4) second.

Fig. 15 shows the overall convergence of the PV power. During the time between 0.1-0.2 and 0.2-0.3 second, the ACO MPPT convergence becomes premature due to instantaneous dynamic irradiance changes and PNO MPPT is continue to do perturb and observe method and able to climb near MP at the time spawn between 0.287-0.3 second. Fig. 16 to Fig. 19 shows the convergence of every MPPT method at close time and PV power range. The convergence of the proposed MPPT method able to converge better compare to the ACO and PNO MPPT method. The superior dynamic performance of the hybrid ACO-PNO is the most significant result of this study. The experiments involving dynamic irradiance changes (Patterns 1 and 2, shown in Tables V and VI, and figures like Fig. 10 and Fig. 15) reveal that the combination effectively mitigates the known weaknesses of the individual algorithms. Table VII shows the detail information of settling time, oscillation and tracking error under rapid changing conditions.

TABLE VII Settling Time, Oscillation, And Tracking Error Under Rapidly Changing Conditions

Metric	**P&O (Standard)**	**ACO (Standard)**	**ACO−PNO (Hybrid)**
Settling Time	**Slow-Medium** (Depends	**Medium** (Fast	**Fastest** (Rapid ACO search + quick

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue X October 2025

(to reach 98% MPP)	heavily on perturbation step size)	initial convergence, but slow final refinement)	PNO lock)
Steady-State Oscillation Amplitude	**High** (Mandatory oscillation around the peak)	**Low-Medium** (Oscillates around discrete pheromone path nodes)	**Very Low** (close to 0) (PNO is used only for refinement, then stops when the Delta P condition is met)
Average Tracking Error (ΔP)	1% - 4% (Due to continuous oscillation)	1% - 3% (Error from discretization of search space)	0.2% - 1% (Best-in-class, due to constant refinement)
Handling Partial Shading	Poor (Stuck on local maxima)	Excellent (Designed for global search)	**Excellent** (Retains ACO's global search capability)

The ACO-PNO hybrid MPPT method excels in dynamic performance by leveraging the strengths of both algorithms: it achieves the fastest settling time because the global search of ACO quickly jumps near the new Maximum Power Point (MPP), allowing the local search of PNO to take over for rapid final convergence. This combination drastically reduces the Average Tracking Error (0.2% - 1%) and Steady-State Oscillation Amplitude (close to 0) because, unlike standard PNO which must always oscillate, the refined PNO stage can be programmed to stop perturbing and lock the duty cycle once the change in power (Delta P) is below a minimum threshold, ensuring superior power extraction stability and efficiency. The standalone P&O method, while simple, suffers from a slow, step-by-step movement, leading to longer convergence times and power loss, particularly when instantaneous changes occur. Conversely, the standalone ACO MPPT, a bio-inspired optimization technique similar to Kinetic Gas Molecular Optimization [19] or Beluga Whale Optimization [20], is designed for global searching but demonstrates a tendency for premature convergence during the transient periods (as seen in Fig. 15 between 0.1s and 0.3s. This premature convergence means the swarm process fails to correctly identify the new global peak, a common challenge in nature-inspired methods. Other metaheuristic methods, such as the Horse Herd Optimization Algorithm [21] or Sooty Tern Optimization [22], similarly wrestle with the trade-off between speed and local optima trapping. The proposed hybrid ACO-PNO acts as a highly effective two-stage MPPT technique [23]. The initial swarming (ACO) quickly guides the system toward the general vicinity of the maximum power point (MPP), significantly reducing the required tracking time. The subsequent P&O refinement then ensures precise convergence directly onto the MPP, correcting the ACO's tendency to settle at a slightly lower, non-optimal point. The resulting

CONCLUSION

This analysis demonstrates that the hybrid ACO-PNO MPPT (Maximum Power Point Tracking) method offers a promising solution for optimizing the performance of photovoltaic (PV) systems. It achieves high power extraction efficiency and closely approximates the ideal power output. Its consistent performance across various irradiance levels highlights its suitability for real-world PV applications, where environmental conditions can vary significantly. Further research could investigate dynamic parameter tuning to enhance performance in low-light conditions and explore the integration of this method into larger PV arrays for scalability validation. In conclusion, it is possible to track the global maximum power at each irradiance level by adjusting the Particle Swarm Optimization (PSO) output signal distribution characteristics. The speed and accuracy of the power tracking process can be modified by adjusting the inertia weight, swarm size, and individual learning rate in the PSO algorithm. Rapid tracking of maximum power is crucial for identifying power changes within the PV system. Through simulation software, power variations can be observed from the PSO algorithm after modifications, ensuring optimal maximum power point tracking. The characteristics of PV voltage and current are influenced by the behavior of the PWM (Pulse Width Modulation) signal.

ACKNOWLEDGMENT

For the opportunity to participate in this research, the authors would like to thank Center for Advanced Computing Technology (C-ACT), Fakulti Kecerdasan Buatan dan Keselamatan Siber (FAIX), Fakulti Teknologi Maklumat dan Komunikasi (FTMK) and Centre for Research and Innovation Management (CRIM), Universiti Teknikal Malaysia Melaka (UTeM) for providing the facilities and support for this research work. We'd also like to express our gratitude to the UTeM's Financial Support for funding the project.

REFERENCES

1. M. H. Ali, M. Zakaria, and S. El-Tawab, "A comprehensive study of recent maximum power point tracking techniques for photovoltaic systems," Sci Rep, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-96247-5.
2. A. Elsafi, A. A. Almohammedi, M. Balfaqih, Z. Balfagih, and S. Sabri, "Comparative analysis of maximum power point tracking methods for power optimization in grid tied photovoltaic solar systems," Discover Applied Sciences, vol. 7, no. 9, Sep. 2025, doi: 10.1007/s42452-025-07606-w.
3. A. B. Djilali et al., "Enhanced variable step sizes perturb and observe MPPT control to reduce energy loss in photovoltaic systems," Sci Rep, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-95309-y.
4. D. Sibtain, M. M. Gulzar, K. Shahid, I. Javed, S. Murawwat, and M. M. Hussain, "Stability Analysis and Design of Variable Step-Size P&O Algorithm Based on Fuzzy Robust Tracking of MPPT for Standalone/Grid Connected Power System," Sustainability (Switzerland), vol. 14, no. 15, Aug. 2022, doi: 10.3390/su14158986.
5. B. Babes, A. Boutaghane, and N. Hamouda, "A novel nature-inspired maximum power point tracking (MPPT) controller based on ACO-ANN algorithm for photovoltaic (PV) system fed arc welding machines," Neural Comput Appl, vol. 34, no. 1, pp. 299–317, Jan. 2022, doi: 10.1007/s00521-021-06393-w.
6. M. Yaich, Y. Dhieb, M. Bouzguenda, and M. Ghariani, "Metaheuristic Optimization Algorithm of MPPT Controller for PV system application," in E3S Web of Conferences, EDP Sciences, Jan. 2022. doi: 10.1051/e3sconf/202233600036.
7. N. Priyadarshi, V. K. Ramachandaramurthy, S. Padmanaban, and F. Azam, "An ant colony optimized mppt for standalone hybrid pv-wind power system with single cuk converter," Energies (Basel), vol. 12, no. 1, Jan. 2019, doi: 10.3390/en12010167.
8. M. Sedraoui et al., "Development of a fixed-order controller for a robust P&O-MPPT strategy to control poly-crystalline solar PV energy systems," Sci Rep, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-86477-y.
9. B. Naima et al., "Enhancing MPPT optimization with hybrid predictive control and adaptive P&O for better efficiency and power quality in PV systems," Sci Rep, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-10335-0.
10. [K. H. Chao and M. N. Rizal, "A hybrid mppt controller based on the genetic algorithm and ant colony optimization for photovoltaic systems under partially shaded conditions," Energies (Basel), vol. 14, no. 10, May 2021, doi: 10.3390/en14102902.
11. K.Burhanudin, N.A.Kamarzaman, A.A.A.Samat, A.I.Tajudin, S.S.Ramli, and N.Hidayat, Implementing Boost Converter Algorithm with PSO for Photovoltaic System During Partial Shading Condition. Johor Bharu: IEEE, 2015. doi: 10.1109/CENCON.2015.7409576.
12. A. Nasir, I. Rasool, D. Sibtain, and R. Kamran, "Adaptive Fractional Order PID Controller Based MPPT for PV Connected Grid System Under Changing Weather Conditions," Journal of Electrical Engineering and Technology, vol. 16, no. 5, pp. 2599–2610, Sep. 2021, doi: 10.1007/s42835-021-00782-w.
13. X. Liu et al., "Simulation-Based Evaluation of Power Efficiency and Output Capacitance in Standalone PV MPPT Buck Converters Using 200 V p-GaN HEMTs," Journal of Electrical Engineering and Technology, vol. 20, no. 6, pp. 3875–3887, Sep. 2025, doi: 10.1007/s42835-025-02334-y.

14. V. C. Kotak, P. Tyagi, and A. Professor, “DC To DC Converter in Maximum Power Point Tracker,” International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (An ISO Certified Organization), vol. 3297, no. 12, pp. 6115–6125, 2007.
15. M. Q. Taha, M. K. Mohammed, and B. El Heiba, “Metaheuristic Optimization of Maximum Power Point Tracking in PV Array under Partial Shading,” Engineering, Technology and Applied Science Research, vol. 14, no. 3, pp. 14628–14633, Jun. 2024, doi: 10.48084/etasr.7385.
16. H. Azizi-Monfared and M. Ghanbarisabagh, “Hybrid Intelligent Control and Maximum Power Point Tracking of a Solar Generator under Variable Irradiance and Temperature using a Multi-method Approach,” International Journal of Engineering, Transactions B: Applications, vol. 39, no. 6, pp. 1462–1481, Jun. 2026, doi: 10.5829/ije.2026.39.06c.14.
17. S. Vadi, “Design and Implementation of an Off-Grid Smart Street Lighting System Using LoRaWAN and Hybrid Renewable Energy for Energy-Efficient Urban Infrastructure,” Sensors, vol. 25, no. 17, Sep. 2025, doi: 10.3390/s25175579.
18. F. Id Ouissaaden, H. Kamel, and S. Dlimi, “Simulation and Performance Evaluation of a Photovoltaic Water Pumping System with Hybrid Maximum Power Point Technique (MPPT) for Remote Rural Areas,” Processes, vol. 13, no. 9, Sep. 2025, doi: 10.3390/pr13092867.
19. R. S. Prasad and R. Thiyagarajan, “Kinetic gas molecular optimization method for PV system under partial shaded condition,” International Journal of Intelligent Engineering and Systems, vol. 13, no. 4, pp. 33–43, 2020, doi: 10.22266/IJIES2020.0831.04.
20. B. Kothapalli and G. T. Sundar Rajan, “Hybrid beluga whale optimization based MPPT for photovoltaic powered open end winding induction motor drives,” Sci Rep, vol. 15, no. 1, Oct. 2025, doi: 10.1038/s41598-025-15680-8.
21. A. W. Ibrahim et al., “A high-speed MPPT based horse herd optimization algorithm with dynamic linear active disturbance rejection control for PV battery charging system,” Sci Rep, vol. 15, no. 1, p. 3229, Dec. 2025, doi: 10.1038/s41598-025-85481-6.
22. M. T. Kaaitan, R. A. Fayadh, Z. S. AL-sagar, S. J. Yaqoob, M. Bajaj, and M. S. Geremew, “A novel global MPPT method based on sooty tern optimization for photovoltaic systems under complex partial shading,” Sci Rep, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-13007-1.
23. Q. Pang, F. Zhang, S. Han, T. Zhou, and Y. Wang, “A new two-stage MPPT technique for enhancing the performance of PV system,” Electrical Engineering, vol. 107, no. 8, pp. 10899–10909, Aug. 2025, doi: 10.1007/s00202-025-03067-x.