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Unveiling global MPP: ACO-driven MPPT strategy for partially shaded PV arrays

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Abstract---Maximizing the efficiency of photovoltaic (PV) arrays requires operation at their maximum power point (MPP). Traditional maximum power point tracking (MPPT) techniques perform well under uniform irradiance but falter when partial shading introduces multiple MPPs, often failing to identify the global MPP. To tackle this issue, we introduce an ant colony optimization (ACO)-based MPPT scheme for PV systems. This heuristic algorithm not only ensures the identification of the global MPP but also simplifies the control scheme and reduces system costs. We validated the feasibility of the proposed method through simulations under various shading patterns and compared its performance to that of traditional MPPT techniques, such as Constant Voltage Tracking (CVT), Perturb and Observe (P&O), and Particle Swarm Optimization (PSO).Results indicate that the proposed ACO-based algorithm effectively tracks the global MPP and exhibits robustness across different shading scenarios, thus offering a reliable and cost-effective solution for enhancing the efficiency of PV systems.

Keywords--- Ant Colony Optimization, Enhanced System Efficiency, Maximum Power Point Tracking, Partial Shading Mitigation, Photovoltaic Optimization.

INTRODUCTION

Background and Motivation

The increasing urgency to shift towards renewable energy sources stems from the finite nature of fossil fuels and escalating environmental concerns related to their combustion. Solar energy systems have gained significant traction due to their advantages such as low maintenance requirements, minimal post-production pollution, and advancements in semiconductor and power electronic devices. Among these systems, photovoltaic (PV) technology stands out as it directly converts sunlight into electricity through the PV effect.

A typical PV system comprises solar modules connected in series or parallel to form large-scale PV arrays, which capture solar energy on a commercial scale. However, the relationship between the PV array's output voltage and current is nonlinear, resulting in a unique maximum power point (MPP) in its power-voltage (P-V) characteristics under uniform irradiance conditions. Optimizing the PV system to operate at this MPP is critical for maximizing energy harvested from solar modules.

Challenge of Partial Shading

Researchers have long studied MPPT algorithms, effective under uniform sunlight. However, real-world scenarios often involve partial shading due to clouds, trees, or dirt, causing multiple peaks in PV array power-voltage curves [2]. Traditional methods like P&O and Incremental Conductance struggle here, getting stuck in local maxima and losing significant energy (up to 70%) [1]. This challenge demands robust MPPT solutions capable of accurately tracking the global MPP. Two-stage controllers, observational approaches, and AI-based techniques have been explored but no universal solution fits all shading conditions [3-4].

Ant Colony Optimization (ACO) for MPPT

Ant colony optimization (ACO) is a nature-inspired heuristic algorithm based on the foraging behaviour of ants. It has been widely used in various fields, such as scheduling, image processing, and power electronic circuit design [5]. In this paper, we propose an ACO-based MPPT scheme for large-scale PV systems operating under partial shading conditions. The proposed method not only ensures the identification of the global MPP but also simplifies the control scheme and reduces system costs by requiring only one pair of current and voltage sensors.[7,8].The basic principle of ACO involves a population of artificial ants traversing the search space and depositing pheromones along their paths [9,10].

Contributions of the Paper

The main contributions of this paper are:

1. Novel ACO-Based MPPT Algorithm: Introduces an innovative ACO-based algorithm for tracking the global MPP in PV systems under partial shading conditions, utilizing ant colony intelligence to efficiently explore the P-V curve.

2.Simplified Control Scheme: Minimizes the number of required sensors, reducing system cost and complexity.

3.Robustness and Efficiency: Extensive simulations show the algorithm's robustness against various shading patterns, fast convergence, and independence from initial conditions.

Structure of Paper

The remainder of this paper is organized as follows: Section 2 briefly presents the main principles of the ACO algorithm and its application to MPPT for PV systems [11,12]. Section 3 presents the experimental results and a discussion of the proposed approach. Lastly, Section 4 concludes the paper and proposes avenues for future research.

2. ANT COLONY OPTIMIZATION FOR MPPT IN A PV SYSTEM

The Ant-Colony Optimization (ACO) algorithm was adapted to solve the Maximum Power Point Tracking (MPPT) problem in photovoltaic (PV) systems [5,6][12]. The objective is to find the optimal current settings for each PV string to maximize the power output under various conditions, such as partial shading.

ACO Algorithm Steps

1. Initialization: Randomly generate (K) solutions and store them in an archive. These solutions are then ranked based on their power output values.

2. Gaussian Sampling: For each dimension, a new solution is generated by sampling from a Gaussian kernel defined as:

$$[G_i(x) = \sum_{l=1}^{K} \omega_l g_i^l(x) = \sum_{l=1}^{K} \omega_l \frac{1}{\sigma_i^l \sqrt{2\pi}} \exp\left(-\frac{\left(x-\mu_i^l\right)^2}{2\left(\sigma_i^l\right)^2}\right)] \tag{12}$$

Here, (μ_i^l) and (σ_i^l) are the mean and standard deviation for the (i)-th dimension of the (l)-th solution, and (ω_l) is the weight of the (l)-th solution.

3. Updating Gaussian Parameters:

- Mean:

$$[\mu_i = \{\mu_i^1, \mu_i^2, \dots, \mu_i^K\} = \{s_i^1, s_i^2, \dots, s_i^K\}] \tag{13}$$

- Standard Deviation:

$$[\sigma_i^l = \frac{\sum_{j=1}^{K} \left|s_i^j - s_i^l\right|}{K-1}] \tag{14}$$

- Weight:

$$[\omega_l = \frac{1}{QK\sqrt{2\pi}} \exp\left(-\frac{(l-1)^2}{2Q^2K^2}\right)] \tag{15}$$

4. Solution Generation: Generate (M) new solutions by sampling the Gaussian kernel for each dimension, and update the archive with these new solutions.

5. Iterations and convergence: The process of generating new solutions and updating the archive until the maximum number of iterations is reached or the power output remains stable within a small range over successive iterations.

Reinitialization: The algorithm incorporates a reinitialization step to adapt to varying environmental conditions. The search process restarted periodically or when a significant change in irradiance is detected:

$$[\frac{\left|I(s_{i+1}) - I(s_i)\right|}{I(s_i)} > I_{threshold}] \tag{16}$$

2.1 Flowchart and Parameters

The flowchart for the ACO-based MPPT algorithm involves initializing the archive, sensing PV array parameters, generating and evaluating new solutions, updating the archive, and iterating until convergence or reinitialization is needed. The key parameters include the number of ants (M), archive size (K), the convergence speed constant (ϵ), and the locality parameter (Q). These parameters balance convergence speed and accuracy, avoid local maxima and ensure efficient global MPP tracking.

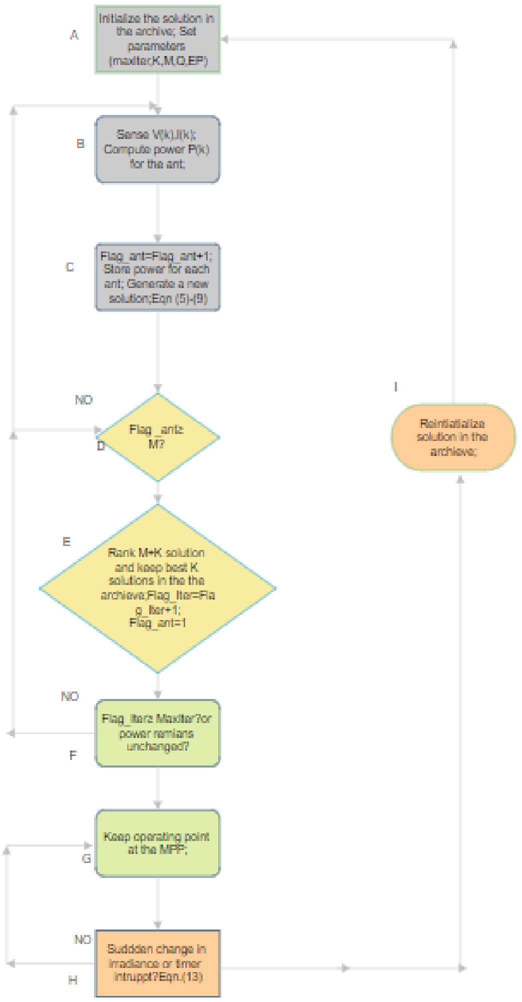


Fig.3 ACO flowchart to find MPPT

Summary

The ACO-based MPPT algorithm effectively finds the global MPP in a PV system under varying conditions by leveraging probabilistic sampling and iterative solution improvement [5-7]. The algorithm's ability to reinitialize and adapt to changing conditions ensures optimal performance and power output.

3. EXPERIMENTAL RESULTS

This section demonstrates the effectiveness of the proposed ACO-based MPPT algorithm in MATLAB simulations. The algorithm's performance is compared with other MPPT methods under different irradiance conditions.

3.1 Experiment 1

The first experiment tests the ACO-based MPPT's ability to track the global maximum power point (MPP) under both steady and transient shading conditions. To verify the algorithm's capability, we selected several shading patterns in table I and II.

I: Experimental Shading Patterns

Pattern No.	Shading Pattern (W/m²)
SP1	[1000, 1000, 1000; 1000, 1000, 1000]
SP2	[1000, 800, 400; 1000, 400, 200]
SP3	[500, 200, 400; 800, 400, 200]
SP4	[600, 1000, 1000; 800, 400, 200]

II: Algorithm Parameters

Parameter	Symbol	Value
Solution Archive Size	K	8
Number of Ants per Iteration	M	5
Problem Dimension	N	3
Convergence Speed Constant	β	0.83
Locality of Search Process	Q	0.46

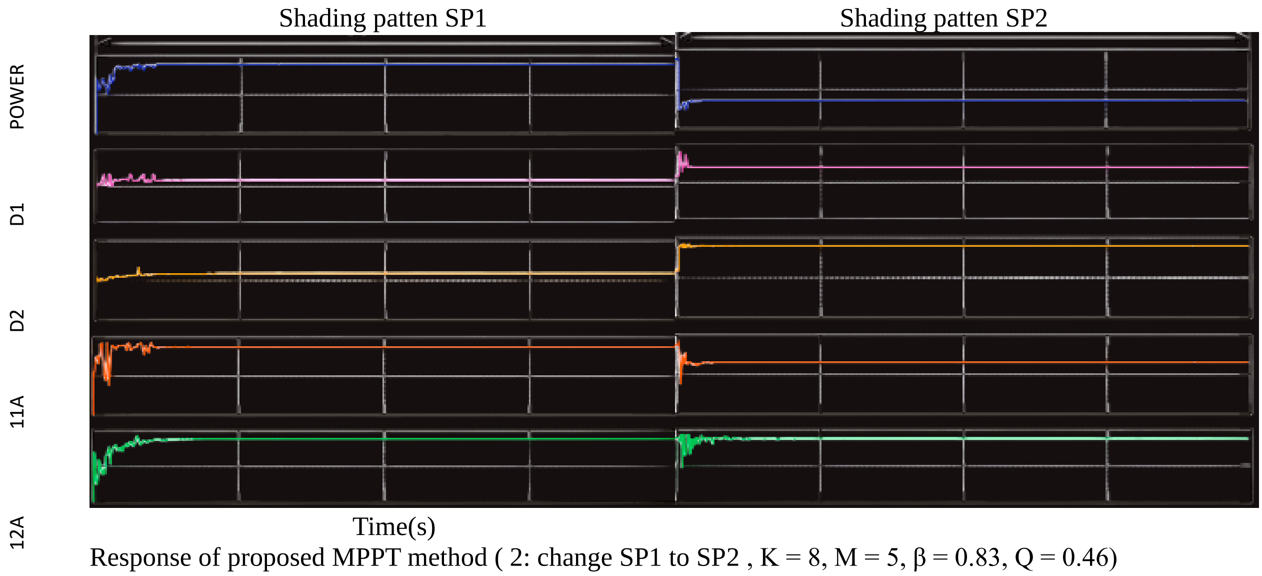
Using the ACO-based MPPT algorithm, the currents for each PV string (I1 and I2), ideal power (P_ideal), and average power measured over 200 runs (P) for each shading pattern are listed in Table III

Table III: Performance of ACO-based MPPT under Different Shading Patterns

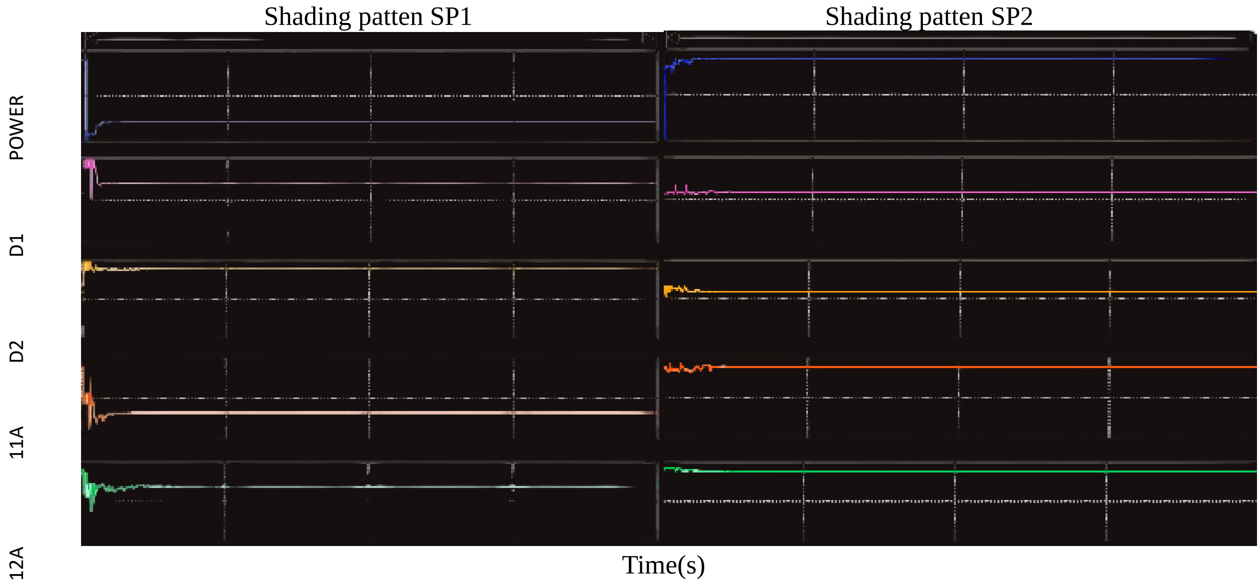
Pattern No.	I1 (A)	I2 (A)	P_ideal (W)	P (W)
SP1	3.488	3.488	359.10	359.09
SP2	2.843	3.459	150.10	150.08
SP3	1.376	1.381	95.20	95.17
SP4	3.497	1.382	164.47	162.62

The results demonstrate that the ACO-based MPPT algorithm successfully tracks global MPP, achieving power outputs that are very close to ideal values for all shading patterns [3]. This assumption assumes that no power losses due to DC-DC converter inefficiencies, wire losses, or other factors reduce the actual power harvest in a real system.

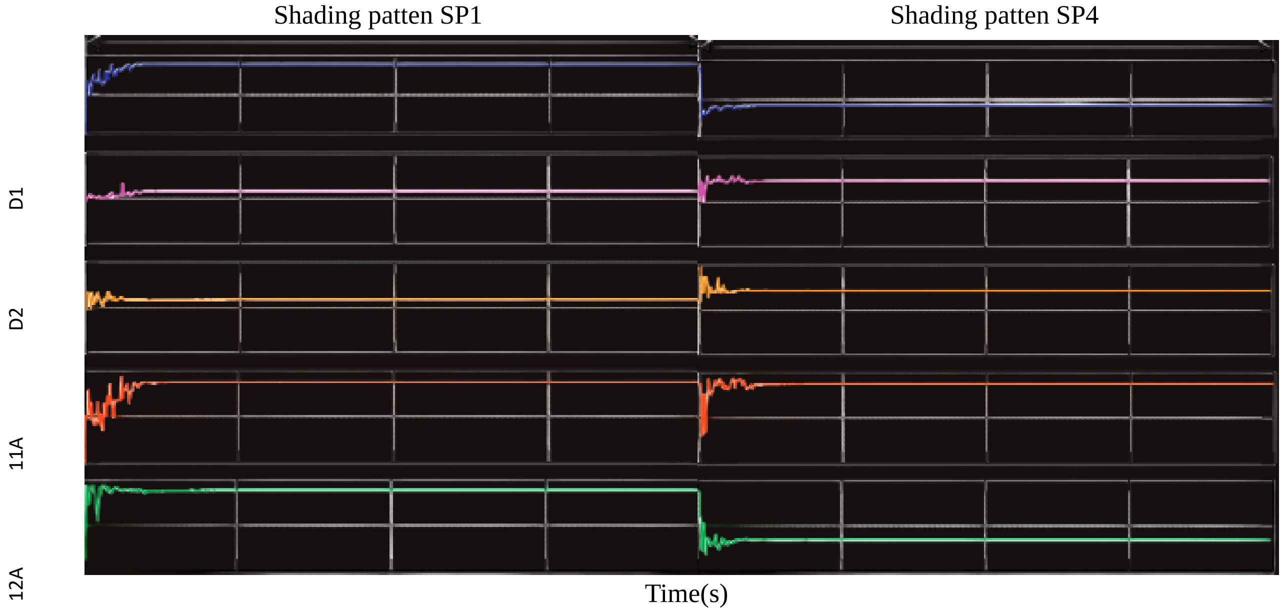
The box-plot distribution of the extracted power over 200 runs for each shading pattern indicates that the algorithm consistently locates the global MPP regardless of the initial search conditions. This robustness is crucial in regions with frequent weather changes, such as tropical area



Response of proposed MPPT method (2: change SP1 to SP2 , K = 8, M = 5, β = 0.83, Q = 0.46)



Response of proposed MPPT method (2: change SP1 to SP3, K = 8, M = 5, β = 0.83, Q = 0.46)



Response of proposed MPPT method (3: change SP1 to SP4, K = 8, M = 5, β = 0.83, Q = 0.46)

Dynamic Shading Condition Test

To evaluate the algorithm's performance under changing shading conditions, three cases were tested:

- 1: Pattern of shading changes from SP1 to SP2
- 2: Pattern of shading changes from SP1 to SP3
- 3: pattern of shading changes from SP1 to SP4

The sampling period for the MPPT algorithm is set to 0.01 seconds. The results are in below table

Table IV: Power Obtained by different MPPT Algorithms under Various Shading Patterns

Case	Ideal Power (W)	CVT (W)	P&O (W)	PSO (W)	ACO (W)
SP1 - SP2	151.1	111.30	104.40	150.09	151.1
SP1-SP3	95.30	69.74	67.10	95.18	96.20
SP1-SP4	165.47	144.23	157.60	164.48	165.43

The power transient characteristics, duty cycle, and current variables of each PV string are shown for each case. The ACO-based MPPT algorithm effectively tracks the global MPP, with power outputs closely matching ideal values [10]. The algorithm converges in less than 15 iterations, averaging 7.3 ms per iteration, achieving the global MPP in under 0.4 s. This quick response is crucial for PV systems in regions with rapidly changing irradiance, like tropical areas [11-12].

4 FUTURE SCOPE

Our future work will focus on moving from simulations to practical implementation by developing and testing a physical prototype of the ACO-based MPPT algorithm [13] This step is essential to validate its performance in real-world conditions and confirm its efficiency in optimizing PV system power output under varying environmental conditions. This transition aims to bridge the gap between research and practical application, advancing reliable MPPT technique for solar energy systems and promoting sustainable energy use.

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