An Efficient Ant Colony Optimization Approach for MPPT in Solar Photovoltaic Applications Under Shading Effects

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Abstract: ***Partially shaded PV devices show very non-linear and multimodal PV power-voltage characteristics which include multiple local maxima, making it very challenging to achieve an effective MPPT. It is well known that the deterministic MPPT and heuristic MPPTs both converge to sub-optimum operating point, thereby reducing the amount of energy generated by the system and the efficiency of the system. In this paper, a novel model of Ant Colony Optimization inspired global maximum extraction algorithm for PV systems under non-uniform irradiation is presented which overcomes these drawbacks under non-uniform irradiation is presented which overcomes these drawbacks. In the proposed approach, formulation of the MPPT problem is a constrained optimization problem with the duty cycle of the DC-DC converter as the optimization variable, and the instantaneous PV output power as the optimization objective. In order to keep a balance between exploration and exploitation, ACO algorithm adopts the probabilistic solution construction and the adaptive pheromone updating method and continuously narrows the search space. It features a memory-assisted duty cycle update mechanism that enhances the smoothness of convergence and minimizes oscillatory behavior at the optimum operating point. The suggested controller is strictly tested in terms of dynamically changing partial shading patterns, taking into account the fast irradiance changes and multiple peak conditions. The findings show that convergence reliability is better, global maximum identification time is lower and steady-state power oscillations are lower than those in conventional and modern MPPT methods. Moreover, the suggested approach is also very robust and flexible, which makes it very applicable to become part of smart energy management systems and advanced DC micro grid designs.***

Keywords: Photovoltaic, Maximum power point tracking, Global maximum power point, Hybrid, Optimization, Partial shading condition, Ant colony optimization

1. Introduction

The need for sustainable energy and green electricity has led to the fast adoption of PV systems in today's power network. In applications like smart grid, electric vehicles, and distributed energy systems, power electronic converter is playing an important role due to its high efficiency in power conversion and reliable energy delivering capability [1] [2]. But the load is tightly controlled and in converter-based systems is often represented as a constant power load (CPL), which is nonlinear and has negative impedances; this adversely affects the stability of the system and can cause undesirable oscillations [2]. PV systems are not only prone to instability issues, but they also rely on environmental parameters like solar irradiance and temperature. PV array power-voltage (P–V) characteristics have several peaks under partial shading, which lead to several LMPPs, and one GMPP. Such a phenomenon makes the extraction of maximum available power from the system very complicated [3, 4]. There are many conventional MPPT methods that are simple, have low implementation cost and are widely used including P&O and INC. However, these methods are not always effective in differentiating between local and global maximum in non-uniform irradiance, which results in less efficiency, steady-state oscillations and slow converging under dynamic irradiance [4]– [6]. In order to overcome these drawbacks, many intelligent and optimization-based MPPT algorithms have been suggested in the recent years. Fuzzy logic control and sliding mode control are two techniques that are more adaptive, but complex in terms of design and tuning [7, 8]. Also, metaheuristic optimization techniques such as PSO [9]–[10] and ANN, and Cuckoo Search (CS) algorithms enable better global search and tracking performance [11]. Nevertheless, problems like high complexity, instability caused by random search behaviour and slower convergence in dynamic environments still exist [11]– [13]. Moreover, these approaches are unable to strike the right balance between exploration and exploitation to ensure accurate and stable GMPP tracking. In this paper, an to overcome such problems, ACO based MPPT algorithm for PV system under partial shading (PS) condition is proposed. In the ACO algorithm inspired by the "social learning" of ants, a pheromone-based learning mechanism is added to avoid premature convergence in the search process to find the optimal solution [14, 15]. ACO is more structured than the traditional random search methods and more adaptive with respect to exploring the search space and allows it to converge faster and more accurately to track the search space. The approach suggested is to use ACO algorithm along with PV system with DC-DC converter to control the working point of the PV system for optimal extraction of PV power. The performance of the proposed method is compared to other existing proposed method is compared to other existing methods in terms of convergence speed, steady-state oscillation reduction and robustness under different irradiance conditions through simulation results. Hence, the ACO based MPPT technique is a potential approach for the future generation of the renewable energy system that needs intelligent and adaptive controls.

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2. System Description

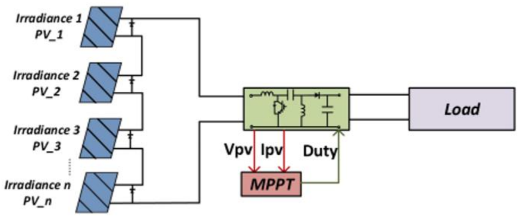

Figure 1: SEPIC Converter with MPPT Algorithm Schematic

SEPIC Converter with MPPT-Based Photovoltaic System

1) ***PV Array under PS: 1.2***
   The PV is composed of a number of solar modules (PV_1, PV_2, PV_3, and PV_n) with different level of irradiation. This configuration is produced in the actual application of partial shading, in which the input power is not uniform and there are many power peaks and power efficiency reduction
2) ***SEPIC Converter Configuration***
   The output from the PV is connected to a SEPIC, that can step up and step down the voltage. It is the capacity of a regulator to hold a constant output voltage regardless of the input voltage that it receives. The PV array is used as an interface to the load with the converter.
3) ***MPPT Strategy***
   An MPPT controller is used to get the maximum energy extraction. The controller continually tracks the MPP by measuring PV Vpv and Ipv and calculates the optimal operating point of the MPPT.
4) ***Duty Cycle Generation and Control***
   The MPPT algorithm is used to determine an optimum duty cycle and fed to the SEPIC converter. The operation of the switching function of the converter is controlled by this duty cycle and hence the energy flowing from the PV array to the load is controlled.
5) ***System Operation and Power Delivery***
   Closed loop control is employed which makes this PV system work at its optimum efficiency in different environmental conditions. The regulated power is passed to the load where the stability, loss and overall performance of the system is improved.

3. Control Topology

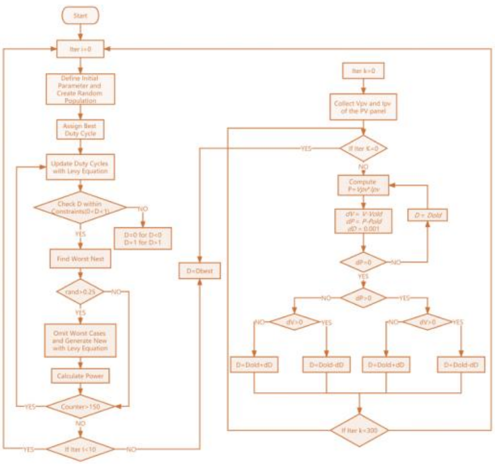

Figure 2: P&O-CS MPPT Algorithm Operational Flowchart

Explanation of Proposed Hybrid MPPT Flowchart

A hybrid MPPT controller is introduced which is based on optimization method (Levy based search) and incremental decision mechanism to solar systems with high accuracy and within a short period of time

1) Initialization Stage

The process starts with initializing the iterations counter to 0 and assigning the values for the parameters of the system. Random population of duty cycles is generated and explored to explore the search space. Of these, initial best duty cycle is selected based on a performance criteria.

2) Optimization Using Levy-Based Search

The duty cycles are iteratively updated to obtain global exploration by using a Levy flight equation. The new duty values are now tested for validity ($0 < D < 1$). They are corrected if there are constraints violated. The algorithm finds out the poorest solutions and substitutes them with new ones in order to get closer to the best duty cycle.

3) Power Evaluation and Selection

The PV power is calculated for each of the updated duty cycles. The maximum power output is used to select the best duty cycle (D best). This continues until a certain number of iterations is reached (defined in advance).

4) Incremental Adjustment Mechanism

Once the optimized duty cycle is obtained, the controller enters into a fine tuning stage. In this instance, the electricity supply (current) and potential (volt) of the PV is measured and the power output calculated. Given that the signs of ΔP and ΔV are known:

- The dutycycle is incremented or decremented
- If no change power is observed, the previous duty cycle is retained

5) Convergence and Output

Repeats until the max. Number of iterations is reached. Finally, the converter is controlled by a duty cycle operation to control the converter to operate at the global maximum power point (MPP) with minimum oscillation.

Overall Insight

This approach allows to implement both global search (with Levy optimization) and local search (with the incremental logic), giving
Rise Faster convergence
Reduced steady-state oscillations
Greater visibility in partial shade. Better tracking in partial shade

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Flowchart of MATLAB Plotting Process

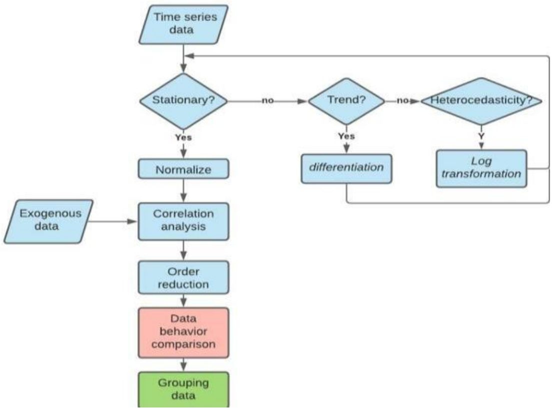

Figure 3: Flowchart for Comparative Analysis of MPPT Algorithms

The provided MATLAB code is used to compare the performance of the different mpp methods in terms of power output using visual plotting. First, figure (1) is used to form a figure window. The power output of the ACO algorithm is displayed in cyan colour, and then again the Hybrid algorithm in black colour is displayed.

Multiple plots will be plotted on the same graph without overwriting previous plots by using the hold on command. In addition, 3 other signals (MPP_1, MPP_2, MPP_3) are plotted, the points of which are mean power point levels in comparison to the theoretical maximum power point levels for different conditions. These are represented by red, green and blue respectively, and are used as a standard for comparison of performances.

The graph is enhanced using grid on for better readability. The x axis and y axis are labelled as time (s) and Power (W). The axis limits are set to make the interval of 0 to 0.3 seconds and the power range 0 to 100W, which makes it very clear in a transient analysis. Last but not least, a legend is added to differentiate between the ACO and Hybrid methods. Overall this code shows the visual proof of the conversion speed, tracking accuracy and stability of various MPPT techniques.

4. Proposed Method

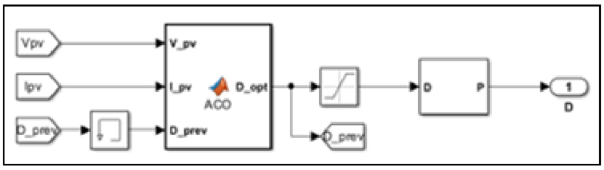

Figure 4: Ant Colony Optimization Algorithm

Controller Description (ACO-Based MPPT Controller)
The controller presented is designed to maximise the power the PV system can produce via an optimisation- based approach. In particular, the ACO algorithm is used. This controller optimizes the duty cycle of the DC-DC converter to achieve the best working point of the PV system under different environmental conditions.

The controller has three major inputs:

- Vpv (PV voltage) Represents the voltage of the solar panel at each instant
- Ipv (PV current) Represents the current generated by the PV system
- D prev (Previous duty cycle) Provides memory of the previous operating condition

These inputs help the controller understand the current operating state of the PV system.

Role of ACO Algorithm
The heart of the controller is an intelligent optimization block (ACO). It simulates the movement of ants to determine the shortest route to food. Where:

- Different duty cycle values are treated as possible “paths”
- The algorithm evaluates which duty cycle gives better power output
- Over iterations, it converges toward the optimal duty cycle (D opt)
- These inputs assist the controller to know the current operating condition of the PV system.

Duty Cycle Optimization Process

- The ACO block generates an optimum duty cycle (D opt) based on PV
- This value is then passed to a limiter/saturation block, to ensure the duty cycle does not go beyond safe operating limits.
- The previous duty cycle (D prev) is also fed back to the system for smooth transitions and to avoid sudden changes.

After optimization:

- The processed duty cycle is sent to a PWM generation block.
- This block converts the duty cycle into switching pulses
- These pulses control the DC-DC switch, regulating the PV output

Overall Function
The controller continuously:

- Monitors PV voltage and current
- Uses ACO to find the best duty cycle
- Adjusts the converter switching accordingly
- Maintains maximum power extraction under dynamic conditions

Key Advantages

- Accelerated mppt
- Less performance drop during partial shading and performance drift.
- Reduced oscillations compared to conventional methods
- Smart and adaptive control behavior

5. Simulation Results & Discussion

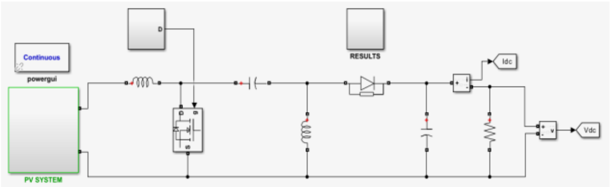

Figure 5: Simulation diagram

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During A C O Algorithm:

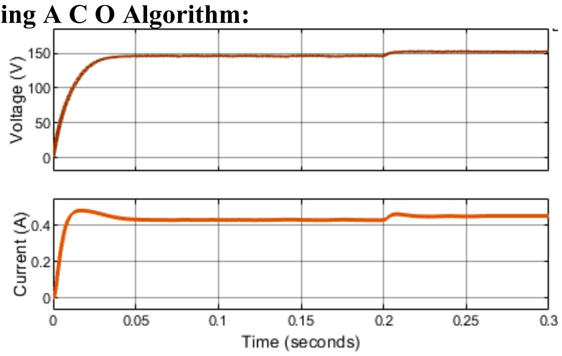

Figure 6: PV Volt and current

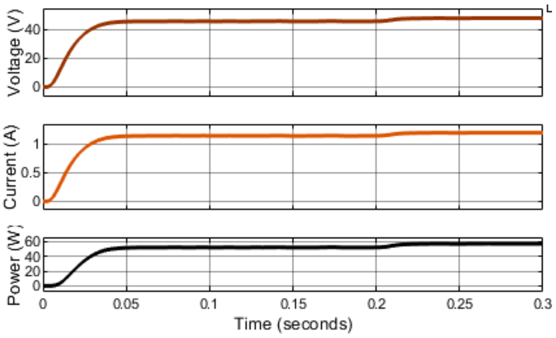

Figure 7: DC Link/Output Voltage, Current and Power meter

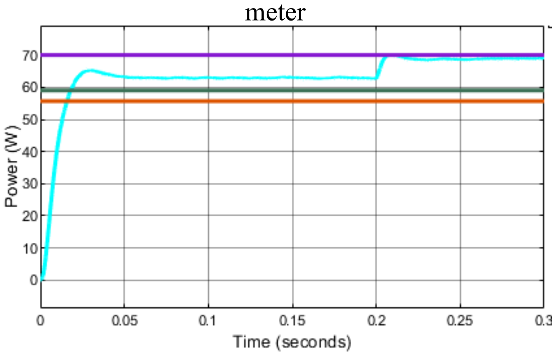

Figure 8: ACO Algorithm's dynamic response

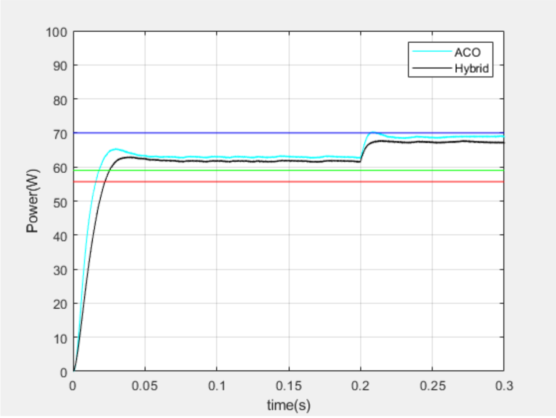

Figure 9: Graphical representation between different methods

In terms of output power tracking, the suggested hybrid technique and the traditional ACO -based MPPT are compared in the figure. The hybrid approach shows quicker convergence toward the MPP during the first transient (0–0.05 s), whereas the ACO strategy shows slower response with discernible oscillations. Both approaches operate close to the MPP in the steady-state zone prior to disturbance (0.05–0.2 s); however, the hybrid technique consistently delivers somewhat higher power with lower ripple, indicating improved tracking accuracy.

A disturbance, signifying a shift in irradiance or partial shadowing, is introduced at about 0.2 seconds. With little oscillation and a shorter settling period, the hybrid controller reacts quickly and smoothly to achieve the new operating point. On the other hand, the ACO approach exhibits slower enhanced transient volatility and adaptability.

When compared to the Pand O and Cuckoo search algorithms, The Hybrid P&O-Cuckoo Search algorithm did well. However, the settling time is still delayed. Here, Ant Colony Optimization was employed to shorten that settling time. After that, there were no more oscillations in the waveform as it converged to Second GMPP (70 W).

While the ACO method shows residual oscillations in the ultimate steady-state, the hybrid strategy retains higher power production with better stability. The convergence speed, tracking efficiency and robustness in dynamic conditions are generally higher for hybrid MPPT compared to traditional ACO.

6. Conclusion

In conclusion, this paper suggests using ACO to tackle the issue of MPPs in different shading conditions. The ACO algorithm explores the solution space by mimicking how ants behave, which helps find the GMPP. By using a group of artificial ants, the algorithm can quickly move toward the best power output. The results show that the ACO algorithm has minimal overshoot and steady-state error, leading to fast, optimized output with fewer oscillations. Additionally, the ACO algorithm can Properly control the output of photovoltaic panels so that they track the power well under any shading condition.

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