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# OPTIMIZING MAXIMUM POWER POINT TRACKING ON PHOTOVOLTAIC ARRAYS USING ANT COLONY OPTIMIZATION AND PARTICLE SWARM OPTIMIZATION ALGORITHMS

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## ABSTRACT

Solar power plants, in general, cannot produce maximum power by themselves; the characteristics of the PV voltage generally follow the battery voltage or the load that is connected directly to the PV. The intensity of light received by the PV modules does not all get uniform irradiation, so the power produced is not optimal and causes multi-peak. A Maximum Power Point Tracking (MPPT) system is needed to optimize power from PV. However, the often used methods are still trapped in local peaks and long convergence times. In this study, we compare the performance of each algorithm to find the maximum power point (MPP) and tracking time using two methods, namely Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO). This study uses 6 selected cases that can occur in 6 solar panel modules arranged in series. Characteristic curves in 6 cases were generated using MATLAB SIMULINK for tracking to find the maximum power point using the ACO and PSO algorithms. The ACO has an efficiency of 99.4910% and tracking failure 7 times in 6 cases in 10 trials of each case, while the PSO algorithm has an efficiency of 99.1043% and tracking failure seven times in 6 cases in 10 trials each case. The efficiency comparison of the ACO algorithm is 0.39% better than the PSO algorithm, while the PSO method is faster in tracking.

**Keywords** Ant Colony Optimization; Particle Swarm Optimization; Maximum Power Point Tracking; Convergent Time.
**Paper type** Research paper

## INTRODUCTION

In general, PV cannot produce optimally because the PV voltage will usually follow the battery's voltage connected to the PV. Maximum Power Point Tracking (MPPT) technology can help control the PV module to work at the maximum power point or Maximum Power Point (MPP) to produce optimal PV power. For PV to produce a higher maximum current and voltage, it is necessary to use several PV modules connected in series or parallel to get a higher current and voltage. The modules connected in parallel or series are called PV arrays. Suppose shadows of trees partially cover the PV array modules, clouds, buildings and so on. In that case, not all of the modules get the same irradiation, where each PV module has different or unbalanced results, so the total output power of the PV array is very high decrease. In addition, the hot-spot effect caused by partial shading tends to damage the PV cells and affect the safety of the PV system [1]. Therefore, more comprehensive tracking is needed when experiencing partial shadows. Conventional methods widely used for MPPT include Perturb and Observe (P&O), fractional open-circuit voltage, and incremental conductance. This conventional method has a slow response and is unsatisfactory in solving the problem of rapid environmental change and overcoming the non-linearity of PV. The rapid change in irradiation due to weather factors, the P&O method failed to track MPP [2].

The latest research related to the manufacture of the MPPT algorithm in Partial Shading conditions is using Artificial Intelligence (AI) based control methods such as Artificial Neural Network [3] *Adaptive-Neuro-Fuzzy Inference System* [4] and Fuzzy Logic Control [5]. However, the very large data is needed for fuzzification process in fuzzy logic control will burden the computational process. Likewise, the large amount of data makes the training process slow with the neural network method.

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Several researchers then proposed several methods to improve the quality of MPPT tracking, such as extremum-seeking control, ripple correlation control, etc. These methods can accurately track MPPs and improve dynamic and steady-state tracking performance. However, these methods cannot overcome the output curve with multi-peak caused by partial shadow conditions in the PV array [6]. Therefore, it is very important to develop an algorithm that accurately tracks the global MPP on a complex and non-linear output curve.

The MPPT problem under partial shadow becomes an optimization problem. The metaheuristic algorithm can obtain global peaks using a randomization number to avoid local peaks. Metaheuristic algorithms imitate animal behavior intending to find optimization of a function. Popular metaheuristic algorithms include Genetic Algorithm (GA), Harmony Search (HS), Aritical Bee Colony (ABC), Ant Colony Optimization (ACO) [7].

This study will compare efficiency and tracking time of each Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) algorithms in MPPT under partial shadow. According to Purnomo [8], Ant Colony Optimization (ACO) is a metaheuristic optimization algorithm. This algorithm was inspired in finding the path from the colony to the food. So, this algorithm solves a computational problem that can be solved through the shortest and fastest path. Particle Swarm Optimization (PSO) is a metaheuristic algorithm that researchers widely use because it is simple, flexible, and easy to implement. Animals, namely birds, inspire this algorithm.

## METHOD

The output of PV voltage and current has non-linear characteristics, as the irradiation and temperature change, causing the peak point of the maximum PV power to vary. PV cannot work automatically to find its maximum power point so it needs control to find its maximum power point. So the role of MPPT is needed to track the maximum power point of the PV.

*Data retrieval*

This study uses 6 PV modules installed in series, the purpose of installing PV modules in series is to get a graph with 6 varying peaks. This PV module is modeled using Matlab Simulink software and simulated by changing the solar irradiation in each PV module to get a PV graph of current and voltage and the location of different maximum power points. The PV module used in PV array modeling with SIMULINK is the SunPower SPR-X20-250-BLK module. The specifications for the SunPower SPR-X20-250-BLK module at STC, namely the light intensity of 1000 W/m² and the module temperature of 25°C, are shown in Table 1.

TABLE I. PV MODULE SPECIFICATIONS.

| | |
|---|---|
| Rated maximum power ($P_{mp}$) | 249,952 W |
| Voltage at Pmax ($V_{mp}$) | 42,8 V |
| Current at Pmax ($I_{mp}$) | 5,84 A |
| Open-circuit voltage ($V_{oc}$) | 50,93 V |
| Short-circuit current ($I_{sc}$) | 6,2 A |

The purpose of this MPPT is to obtain $V_{ref}$, which will be compared with V from the PV array so that an error is obtained, which is the input of the PI controller. This PI controller will later adjust the duty cycle of the Boost Converter to control the PV array output voltage.

*MPPT simulation using ACO and PSO algorithms*

The ACO algorithm is modeled like the behavior of foraging ants. The concept of the ACO algorithm is based on communication between ants. When ants search for food, these ants leave footprints (pheromones), these footprints will be information for other ants to reach the food source. The closer the distance between the food, the less evaporation will occur, increasing the amount of pheromones. The more pheromones, the ants will follow the footprints [9]. The MPPT control flowchart using the ACO algorithm is shown in Figure 1.

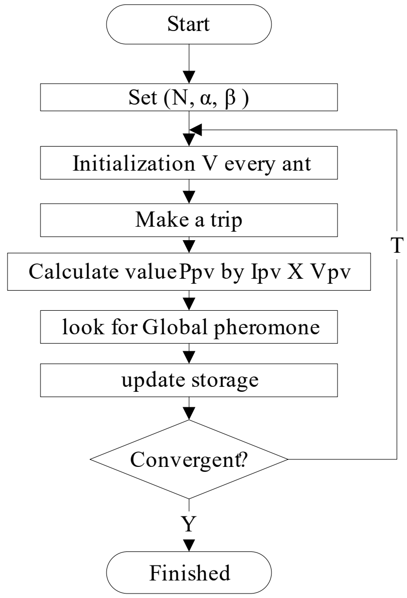


Figure 1. MPPT Flowchart with ACO

TABLE II. ACO PARAMETER SETTING.

| Parameter | Value |
|---|---|
| number of ants (k) | 5 |
| Pheromone ($\tau$) | 1 |
| Evaporasi ($\rho$) | 0.5 |
| Pheromone effect ($\alpha$) | 1 |
| Pheromone effect ($\beta$) | 2 |
| Tolerance ($\varepsilon 1$) | 1 |

The steps for the PSO calculation process are as follows.

1. The initialization of the parameter value of the algorithm of the number of ants (N), the effect of the magnitude of the pheromone value ($\alpha$, $\beta$).
2. Calculate the distance between $D_i$ each $V_i$ with the chosen solution (i = 1 … m) and the best solution $V_{best}$ in storage.

$$D_i = |V_i - V_{best}| \tag{1}$$

3. Place ants randomly at each point.
4. Arrangement of the route of the visit of each ant that has been distributed to each point.
5. Calculation of the route length of each ant between points for the next cycle.
6. Empty the tabu list, and repeat from step 3 if needed, the tabu list needs to be emptied to be filled again with a new order in the next cycle, if the maximum number of cycles has not yet converged.

Probability to visit [8].

$$Pij = \frac{\tau_{ij}^{\alpha} \times \eta_{ij}^{\beta}}{\sum \tau_{ij}^{\alpha} \times \eta_{ij}^{\beta}} \tag{2}$$

The PSO algorithm modeled the behavior of a flock of birds in foraging. The population in the PSO is called the swarm and the individual is called the particle. Each particle moves at a speed adapted from the search area and stores it as the best position ever reached. PSO is based on the social behavior of flocks of birds. Social behavior consists of individual actions and influences from other individuals in a group [11]. The MPPT control flowchart using the PSO algorithm is shown in Figure 2.

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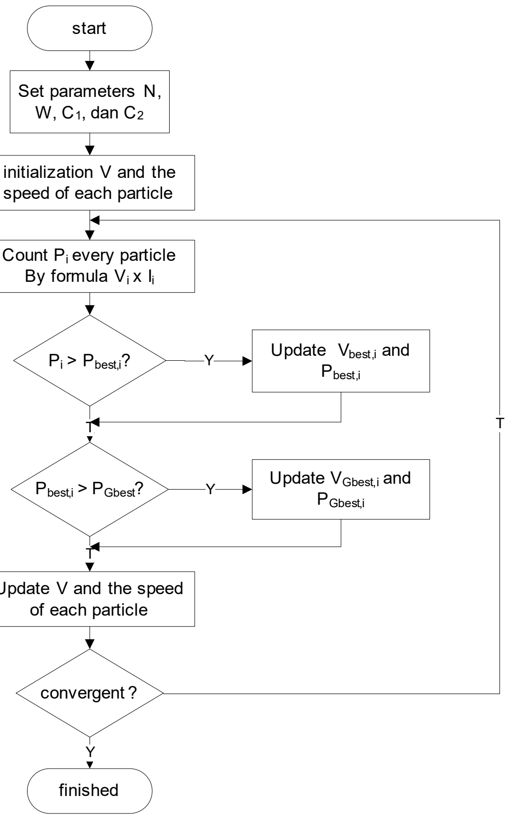


Fig. 2. MPPT flowchart with PSO

TABLE III. PSO PARAMETER SETTING

| Parameter | Value |
|---|---|
| Number of particles (k) | 5 |
| Inertial weight (w) | 0.4 |
| Cognition-only learning factor ($C_1$) | 2.1 |
| Social-only learning factor ($C_1$) | 2.1 |
| Tolerance ($\varepsilon 1$) | 1 |

The steps for the PSO calculation process are as follows.

Step 1 : Determine the number of particles ($O$), inertial weight (W), and learning factor (C1, C2).

Step 2 : Initialize the position and velocity for each particle randomly.

Step 3 : Substitute the initial position into the objective function to evaluate the fitness value for each particle.

Step 4 : Compare the fitness value with the individual best position memory (*P*best) on each particle to get a better position and update the best.

Step 5 : Compare the best fitness value and the best fitness swarm value. If the best fitness value is higher than the fitness best, update best.

Step 6 : Use Equation (3) to update the particle's velocity and Equation (4) to update the particle's position.

Step 7 : Repeat steps 4 through 6 until the global optimal location is reached.

The velocity of the particle is updated by Eq [12].

$$V_i^{j+1} = \mathrm{W} \times V_i^j + C_1 \times rand1\,(\cdot)\mathrm{X}\left(P_{best,i} - P_i^j\right) + C_2 \times rand2(\cdot) \times \left(G_{\text{best}} - P_i^j\right) \quad (3)$$

the position of the particle is updated by Equation

$$P_i^{j+1} = V_i^{j+1} + P_i^j \quad (4)$$

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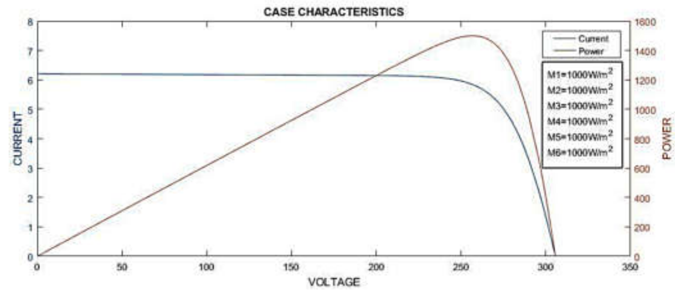
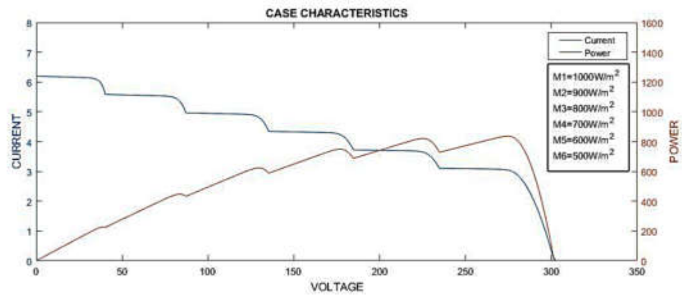
## DISCUSSION

The ACO and PSO algorithms were tested in tracking MPP using 6 PV modules by varying solar irradiation in Matlab Simulink Software. This study, there are 6 test scenarios to determine tracking efficiency and the length of time tracking in the global MPP search. The resulting characteristics of the 6 cases are shown in the figure below.




a)

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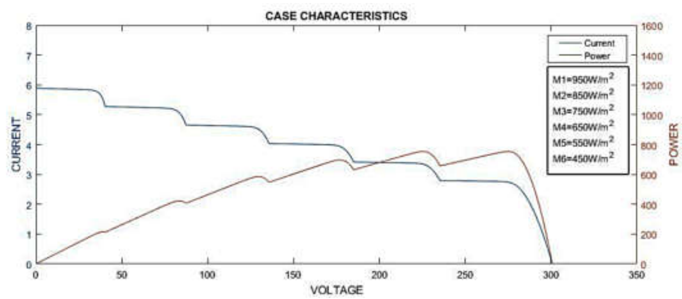
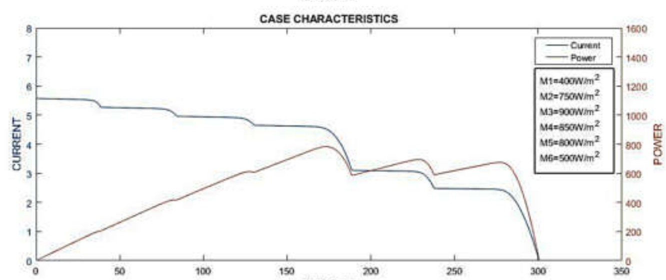



c)

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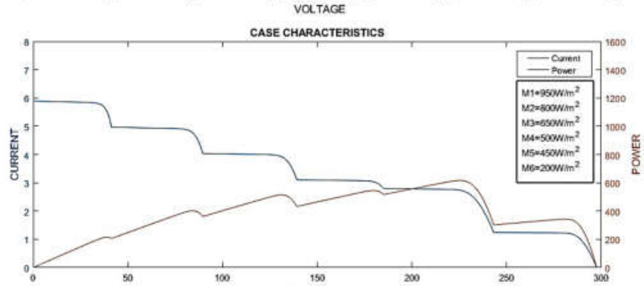


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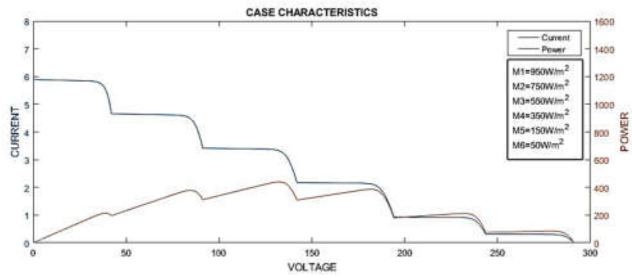
f) 

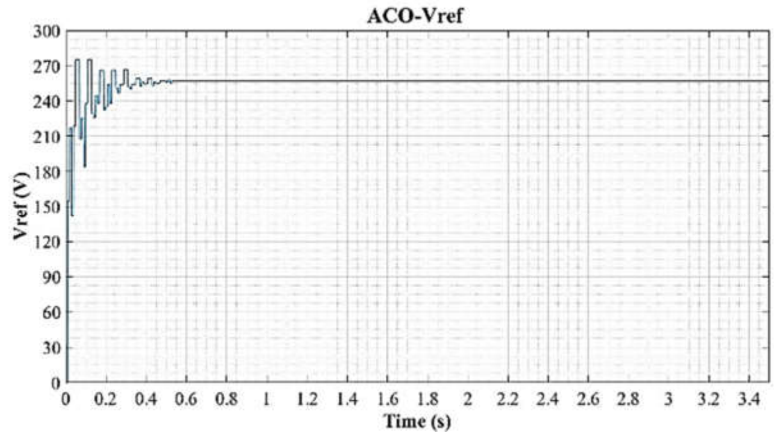

Figure 3. Characteristics I-V and P-V (a) case 1 (b) case 2 (c) case 3 (d) case 4 (e) case 5 and (f) case 6.

MPP tracker of 6 curves generated from various shadow patterns. The ACO and PSO Algorithms track each curve for 10 trials each by taking data on the Ppv, Vref, number of iterations, tracking time, and program execution time for each tracking, then calculating the efficiency of tracking and taking the average, best value. , and worst of all. Vref is a reference voltage sent by MPPT to the comparator so that the PV array works at that voltage point. Ppv is the power generated by the PV array when the voltage is following Vref. The number of iterations and the tracking time indicate the number of times the program iterated and the program time to reach a convergent state. Execution time is the program execution time using MATLAB software. The algorithm's efficiency is the comparison between the tracked power and the actual MPP, while the PV efficiency is the ratio between the PV power generated and the maximum power that PV can produce when fully illuminated.

TABLE IV. ACO TRACKING RESULTS TO FIND MPP IN CASE 1.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 1499,6364 | 257,2156 | 9 | 0,538 | 99,9946 | 99,9946 |
| 2 | 1499,6688 | 257,0316 | 7 | 0,411 | 99,9967 | 99,9967 |
| 3 | 1499,4549 | 256,3183 | 9 | 0,535 | 99,9825 | 99,9825 |
| 4 | 1499,6641 | 257,015 | 8 | 0,476 | 99,9964 | 99,9964 |
| 5 | 1498,7027 | 254,7623 | 8 | 0,479 | 99,9323 | 99,9323 |
| 6 | 1499,6236 | 256,8747 | 9 | 0,539 | 99,9937 | 99,9937 |
| 7 | 1499,3767 | 256,0743 | 9 | 0,539 | 99,9772 | 99,9772 |
| 8 | 1499,4902 | 256,4313 | 8 | 0,479 | 99,9848 | 99,9848 |
| 9 | 1499,6919 | 257,1401 | 9 | 0,539 | 99,9983 | 99,9983 |
| 10 | 1499,6688 | 257,0316 | 7 | 0,419 | 99,9967 | 99,9967 |
| Average | 1499,4978 | 256,5894 | 8 | 0,495 | 99,9853 | 99,9853 |
| Best | 1499,6919 | 257,1401 | 9 | 0,539 | 99,9983 | 99,9983 |
| Worst | 1498,7027 | 254,7623 | 8 | 0,479 | 99,9323 | 99,9323 |

From Table 4, it can be concluded that the results of ACO tracking to find MPP in the first case are excellent. From 10 attempts, ACO managed to track MPP in the first case without any failure in tracking it. So the chance of success of the ACO algorithm in tracking the first case MPP is 99%. The ACO's best tracking results to find MPP in the first case.

a) 

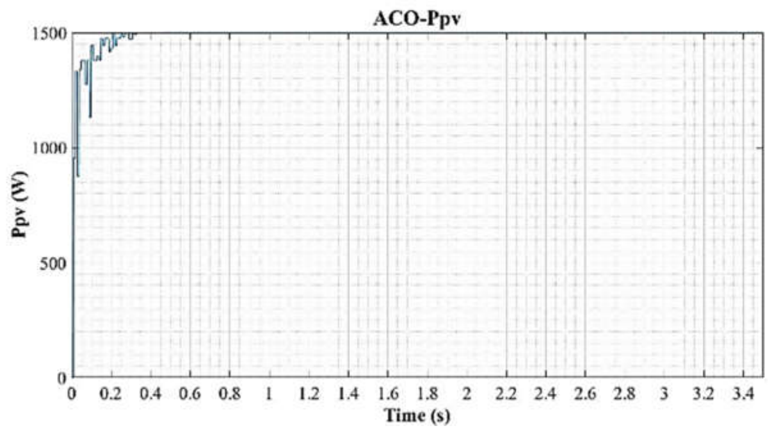

b) 


Figure 4. (a) change in Vref (b) change in Ppv in the best tracking of the first case ACO algorithm.

In Figure 4 it can be seen that the best efficiency is at a voltage of 257 V with a power of 1499.6919W and an algorithm efficiency of 99.9983%. The number of iterations for tracking with the best efficiency is 9 iterations with a tracking time of 0.539 seconds.

TABLE V. ACO TRACKING RESULTS TO FIND MPP IN CASE 2.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 836,3826 | 274,094 | 22 | 1,319 | 99,9984 | 55,7693 |
| 2 | 836,1941 | 273,835 | 19 | 1,139 | 99,9759 | 55,7567 |
| 3 | 836,3548 | 274,055 | 28 | 1,679 | 99,9951 | 55,7674 |
| 4 | 836,3548 | 274,055 | 28 | 1,679 | 99,9951 | 55,7674 |
| 5 | 836,2783 | 273,950 | 67 | 4,019 | 99,9859 | 55,7623 |
| 6 | 836,3905 | 274,314 | 10 | 0,599 | 99,9993 | 55,7698 |
| 7 | 836,3874 | 274,100 | 42 | 2,519 | 99,9990 | 55,7696 |
| 8 | 835,9143 | 273,453 | 12 | 0,719 | 99,9424 | 55,7380 |
| 9 | 836,3826 | 274,094 | 22 | 1,319 | 99,9984 | 55,7693 |
| 10 | 836,3954 | 274,123 | 49 | 2,939 | 99,9999 | 55,7701 |
| Average | 836,3034 | 274,007 | 29 | 1,793 | 99,9889 | 55,7640 |
| Best | 836,3954 | 274,123 | 49 | 2,939 | 99,9999 | 55,7702 |
| Worst | 835,9143 | 273,453 | 12 | 0,719 | 99,9425 | 55,7381 |

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From 5 it can be concluded that the results of ACO tracking to find MPP in the second case are very good. Out of 10 attempts, ACO managed to track MPP in the second case without any failure in tracking it. So the chance of success of the ACO algorithm in tracking MPP in the second case is 99%.

TABLE VI. ACO TRACKING RESULTS TO FIND MPP IN CASE 3.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 784,1572 | 173,0022 | 21 | 1,259 | 99,9925 | 52,2869 |
| 2 | 784,2052 | 173,2264 | 19 | 1,139 | 99,9986 | 52,2901 |
| 3 | 784,2108 | 173,2881 | 12 | 0,719 | 99,9993 | 52,2905 |
| 4 | 695,3778 | 228,6084 | 41 | 2,459 | 88,6717 | 46,3672 |
| 5 | 784,2023 | 173,2023 | 15 | 0,899 | 99,9982 | 52,2899 |
| 6 | 784,211 | 173,2541 | 12 | 0,719 | 99,9993 | 52,2905 |
| 7 | 784,2134 | 173,266 | 25 | 1,499 | 99,9996 | 52,2907 |
| 8 | 695,375 | 228,6124 | 39 | 2,339 | 88,6713 | 46,3670 |
| 9 | 784,2052 | 173,2988 | 25 | 1,499 | 99,9986 | 52,2901 |
| 10 | 784,1874 | 173,1417 | 12 | 0,719 | 99,9963 | 52,2889 |
| Average | 766,4345 | - | 22 | 1,325 | 97,7325 | 51,1052 |
| Best | 784,2134 | 173,266 | 25 | 1,499 | 99,9996 | 52,2907 |
| Worst | 695,375 | 228,6124 | 39 | 2,339 | 88,6713 | 46,3670 |

From table 6, it can be concluded that the results of ACO tracking to find MPP in the third case. From 10 attempts, the ACO algorithm, 8 times succeeded in tracking MPP and 2 times failed to track it. So the chance of success of the ACO algorithm in tracking MPP in the third case is 80%. The ACO algorithm failed to track MPP 2 times because it was stuck at the 5th local peak with a voltage of 228. Where in this third case there are 6 peaks, from the characteristic curve in the 3rd case, the global peak is at the 4th peak and the others are local peaks.

TABLE VII. ACO TRACKING RESULTS TO FIND MPP IN CASE 4.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 753,8942 | 225,6806 | 69 | 4,139 | 99,9985 | 50,2690 |
| 2 | 696,9241 | 176,9121 | 33 | 1,979 | 92,4419 | 46,4703 |
| 3 | 753,9032 | 225,6505 | 43 | 2,579 | 99,9997 | 50,2696 |
| 4 | 753,8281 | 225,371 | 14 | 0,839 | 99,9898 | 50,2646 |
| 5 | 753,9047 | 225,6446 | 13 | 0,779 | 99,9999 | 50,2697 |
| 6 | 753,8529 | 225,4586 | 18 | 1,079 | 99,9930 | 50,2663 |
| 7 | 753,9004 | 225,656 | 79 | 4,739 | 99,9993 | 50,2694 |
| 8 | 753,8934 | 225,604 | 21 | 1,259 | 99,9984 | 50,2690 |
| 9 | 753,892 | 225,6871 | 18 | 1,029 | 99,9982 | 50,2689 |
| 10 | 753,8092 | 225,3045 | 11 | 0,659 | 99,9872 | 50,2634 |
| Average | 748,1802 | - | 31 | 1,908 | 99,2406 | 49,8880 |
| Best | 753,9047 | 225,6446 | 13 | 0,779 | 99,9999 | 50,2697 |
| Worst | 696,9241 | 176,9121 | 33 | 1,979 | 92,4419 | 46,4703 |

From table 7 it can be concluded that the results of ACO tracking to find MPP in case four. From 10 attempts, the ACO algorithm, 9 times succeeded in tracking MPP and 1 time failed to track it. So the chance of success of the ACO algorithm in tracking MPP in the fourth case is 90%. The ACO algorithm failed to track MPP once because it was stuck at the 4th local peak with a voltage of 176V. Where in this fourth case there are 6 peaks, from the characteristic curve in the 4th case, the global peak is at the 5th peak and the others are local peaks.

TABLE VIII. ACO TRACKING RESULTS TO FIND MPP IN CASE 5.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 616,5503 | 225,3001 | 12 | 0,719 | 99,9996 | 41,1110 |
| 2 | 616,5525 | 225,247 | 21 | 1,259 | 99,9999 | 41,1112 |
| 3 | 616,5464 | 225,3828 | 15 | 0,899 | 99,9989 | 41,1108 |
| 4 | 616,5526 | 225,2507 | 18 | 1,079 | 99,9999 | 41,1112 |
| 5 | 616,5518 | 225,2683 | 26 | 1,559 | 99,9998 | 41,1111 |
| 6 | 616,5521 | 225,2418 | 60 | 3,599 | 99,9999 | 41,1112 |
| 7 | 616,5483 | 225,3428 | 15 | 0,899 | 99,9993 | 41,1109 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| 8 | 616,5435 | 225,158 | 13 | 0,779 | 99,9985 | 41,1106 |
| 9 | 616,5488 | 225,3318 | 47 | 2,819 | 99,9993 | 41,1109 |
| 10 | 616,5519 | 225,2388 | 20 | 1,199 | 99,9998 | 41,1111 |
| Average | 616,5498 | - | 24 | 1,481 | 99,9995 | 41,1110 |
| Best | 616,5526 | 225,2507 | 18 | 1,079 | 99,9999 | 41,1112 |
| Worst | 616,5435 | 225,158 | 13 | 0,779 | 99,9985 | 41,1106 |

From table 8, it can be concluded that the results of ACO tracking to find MPP in the fifth case are very good. From 10 attempts, ACO managed to track MPP in the fifth case without any failure in tracking it. So the chance of success of the ACO algorithm in tracking MPP in the fifth case is 99%.

TABLE IX. ACO TRACKING RESULTS TO FIND MPP IN CASE 6.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 439,5947 | 132,3447 | 36 | 2,159 | 99,9999 | 29,3118 |
| 2 | 439,5947 | 132,3298 | 58 | 3,479 | 99,9999 | 29,3118 |
| 3 | 439,5947 | 132,3251 | 37 | 2,219 | 99,9999 | 29,3118 |
| 4 | 439,5947 | 132,3121 | 46 | 2,759 | 99,9999 | 29,3118 |
| 5 | 439,5947 | 132,3921 | 25 | 1,499 | 99,9999 | 29,3118 |
| 6 | 439,5785 | 132,1573 | 11 | 0,659 | 99,9963 | 29,3107 |
| 7 | 439,5947 | 132,2917 | 22 | 1,319 | 99,9999 | 29,3118 |
| 8 | 439,5947 | 132,3165 | 44 | 2,639 | 99,9999 | 29,3118 |
| 9 | 439,5948 | 132,3387 | 76 | 4,559 | 99,9999 | 29,3118 |
| 10 | 439,5947 | 132,3902 | 18 | 1,079 | 99,9999 | 29,3118 |
| Average | 439,5930 | - | 37 | 2,237 | 99,9995 | 29,3117 |
| Best | 439,5948 | 132,3387 | 76 | 4,559 | 99,9999 | 29,3118 |
| Worst | 439,5785 | 132,1573 | 11 | 0,659 | 99,9963 | 29,3107 |

From table 9, it can be concluded that the results of the ACO tracking to find MPP in the sixth case are very good. From 10 attempts, ACO managed to track MPP in the sixth case without any failure in tracking it. So the chance of success of the ACO algorithm in tracking MPP in the sixth case is 99%.

TABLE X. PSO TRACKING RESULTS TO FIND MPP IN CASE 1.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 1499,6801 | 257,071 | 11 | 0,659 | 99,9975 | 99,9975 |
| 2 | 1499,6915 | 257,112 | 14 | 0,839 | 99,9982 | 99,9982 |
| 3 | 1499,6811 | 257,155 | 12 | 0,719 | 99,9975 | 99,9975 |
| 4 | 1499,6964 | 257,129 | 15 | 0,899 | 99,9986 | 99,9986 |
| 5 | 1499,6103 | 256,829 | 10 | 0,599 | 99,9928 | 99,9928 |
| 6 | 1499,6872 | 257,097 | 12 | 0,719 | 99,9979 | 99,9979 |
| 7 | 1499,6945 | 257,123 | 13 | 0,779 | 99,9984 | 99,9984 |
| 8 | 1499,6090 | 256,825 | 11 | 0,659 | 99,9927 | 99,9927 |
| 9 | 1499,6953 | 257,135 | 14 | 0,839 | 99,9985 | 99,9985 |
| 10 | 1499,6549 | 256,983 | 7 | 0,419 | 99,9958 | 99,9958 |
| Average | 1499,6700 | - | 12 | 0,713 | 99,9968 | 99,9968 |
| Best | 1499,6964 | 257,129 | 12 | 0,899 | 99,9986 | 99,9986 |
| Worst | 1499,6090 | 256,825 | 11 | 0,659 | 99,9927 | 99,9927 |

From table 10, it can be concluded that the results of the PSO tracking to find MPP in the first case obtained good results. From 10 attempts, PSO succeeded in tracking MPP in the first case, there were no failures in tracking it, so the probability of success of the PSO algorithm in tracking MPP in the first case is 99%. PSO's best tracking results to look for MPP in the first case.

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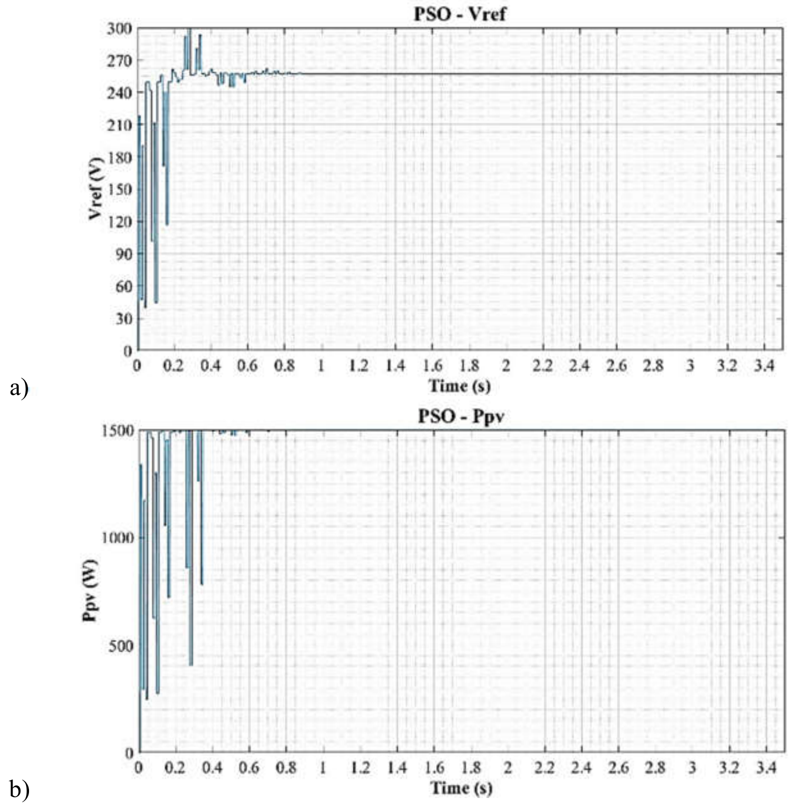


Fig. 5 (a) change in Vref (b) change in Ppv in the best tracking of the first case PSO algorithm.

Figure 5 shows that the tracking with the best efficiency is at a voltage of 257 V with a power of 1499.6964 W and an algorithm efficiency of 99.9986%. The number of iterations for tracking with the best efficiency is 12 iterations with a tracking time of 0.899 seconds.

TABLE XI. PSO TRACKING RESULTS TO FIND MPP IN CASE 2.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 836,3909 | 274,2996 | 11 | 0,659 | 99,9994 | 55,7698 |
| 2 | 821,4761 | 225,4092 | 16 | 0,959 | 98,2162 | 54,7753 |
| 3 | 836,3921 | 274,2581 | 11 | 0,719 | 99,9995 | 55,7699 |
| 4 | 836,3951 | 274,1403 | 12 | 0,719 | 99,9999 | 55,7701 |
| 5 | 836,3941 | 274,1779 | 13 | 0,779 | 99,9998 | 55,7700 |
| 6 | 836,3909 | 274,3012 | 14 | 0,839 | 99,9994 | 55,7698 |
| 7 | 821,4737 | 225,4177 | 11 | 0,659 | 98,2159 | 54,7752 |
| 8 | 836,3951 | 274,1403 | 12 | 0,719 | 99,9999 | 55,7701 |
| 9 | 836,3954 | 274,1207 | 15 | 0,899 | 99,9999 | 55,7701 |
| 10 | 821,4737 | 225,4177 | 11 | 0,659 | 98,2159 | 54,7752 |
| Average | 831,9177 | 259,5683 | 12 | 0,761 | 99,4646 | 55,4716 |
| Best | 836,3954 | 274,1207 | 15 | 0,899 | 99,9999 | 55,7701 |
| Worst | 821,4737 | 225,4177 | 11 | 0,659 | 98,2159 | 54,7752 |

From table 11, it can be concluded that the results of the PSO tracking to find MPP in the second case obtained good results. From 10 attempts, PSO succeeded in tracking MPP in the second case, succeeded 7 times and failed 3 times in tracking it, so that the probability of success of the PSO algorithm in tracking MPP in the second case is 70%. The PSO algorithm failed to track MPP 3 times because it was stuck at the 5th local peak in experiments 2,7 and 10 with a voltage of 225V. Where in this second case there are 6 peaks, from the characteristic curve in the 2nd case, the global peak is at the 6th peak and the others are local peaks.

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TABLE XII. PSO TRACKING RESULTS TO FIND MPP IN CASE 3.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 784,2039 | 173,2202 | 12 | 0,719 | 99,9985 | 52,2901 |
| 2 | 784,2051 | 173,299 | 12 | 0,719 | 99,9986 | 52,2902 |
| 3 | 784,1883 | 173,1459 | 11 | 0,659 | 99,9965 | 52,2891 |
| 4 | 784,208 | 173,2395 | 13 | 0,779 | 99,999 | 52,2904 |
| 5 | 784,2089 | 173,2916 | 13 | 0,779 | 99,9991 | 52,2904 |
| 6 | 784,2145 | 173,2709 | 10 | 0,599 | 99,9998 | 52,2908 |
| 7 | 784,2061 | 173,2307 | 10 | 0,779 | 99,9987 | 52,2902 |
| 8 | 784,2134 | 173,2656 | 13 | 0,779 | 99,9997 | 52,2907 |
| 9 | 695,3571 | 228,5417 | 11 | 0,659 | 88,6691 | 46,3659 |
| 10 | 784,2081 | 173,2401 | 10 | 0,599 | 99,999 | 52,2904 |
| Average | 775,3213 | - | 11 | 0,707 | 98,8658 | 51,6978 |
| Best | 784,2145 | 173,2709 | 10 | 0,599 | 99,9998 | 52,2908 |
| Worst | 695,3571 | 228,5417 | 11 | 0,659 | 88,6691 | 46,3659 |

From table 12, it can be concluded that the results of the PSO tracking to find MPP in the third case obtained good results. From 10 attempts, PSO succeeded in tracking MPP in the third case, succeeded 9 times and failed 1 time in tracking it, so that the probability of success of the PSO algorithm in tracking MPP in the third case is 90%. The PSO algorithm failed to track MPP once because it was stuck at the 5th local peak with a voltage of 228. Where in this third case there are 6 peaks, from the characteristic curve in the 3rd case, the global peak is at the 4th peak and the others are local peaks.

TABLE XIII. PSO TRACKING RESULTS TO FIND IN CASE 4.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 753,8856 | 225,5757 | 14 | 0,839 | 99,9974 | 50,2685 |
| 2 | 753,8971 | 225,6713 | 11 | 0,659 | 99,999 | 50,2693 |
| 3 | 753,8673 | 225,7484 | 11 | 0,659 | 99,995 | 50,2673 |
| 4 | 753,9028 | 225,592 | 9 | 0,539 | 99,9997 | 50,2696 |
| 5 | 753,8964 | 225,6146 | 12 | 0,719 | 99,9989 | 50,2692 |
| 6 | 753,8964 | 225,6146 | 13 | 0,779 | 99,9989 | 50,2692 |
| 7 | 696,9245 | 176,9162 | 13 | 0,779 | 92,442 | 46,4704 |
| 8 | 753,9038 | 225,649 | 13 | 0,779 | 99,9998 | 50,2697 |
| 9 | 753,9763 | 225,5422 | 12 | 0,719 | 999.999 | 50,2745 |
| 10 | 695,6341 | 250 | 5 | 0,299 | 92,2708 | 46,3843 |
| Average | 742,3784 | - | 11 | 0,677 | 99,9999 | 49,5012 |
| Best | 753,9763 | 225,5422 | 12 | 0,719 | 99,9999 | 50,2745 |
| Worst | 695,6341 | 250 | 5 | 0,299 | 92,2708 | 46,3843 |

From table 13, it can be concluded that the results of the PSO tracking to find MPP in the fourth case obtained good results. From 10 attempts, PSO managed to track MPP in the fourth case, succeeded 9 times and failed 1 time in tracking it, so that the probability of the PSO algorithm being successful in tracking MPP in the fourth case is 90%. The PSO algorithm failed to track MPP 2 times because it was stuck at the 4th local peak in experiment 7 with a voltage of 176V and the 10th experiment stuck at the 6th local peak with a voltage of 250V. Where in this second case there are 6 peaks, from the characteristic curve in the 4th case, the global peak is at the 5th peak and the others are local peaks.

TABLE XIV. PSO TRACKING RESULTS TO FIND MPP IN CASE 5.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 616,5113 | 225,5519 | 12 | 0,719 | 99,9933 | 41,1085 |
| 2 | 545,1524 | 179,6603 | 11 | 0,659 | 88,4194 | 36,3503 |
| 3 | 616,5522 | 225,2429 | 13 | 0,779 | 99,9999 | 41,1112 |
| 4 | 545,1389 | 179,6273 | 14 | 0,839 | 88,4173 | 36,3494 |
| 5 | 616,5509 | 225,2262 | 13 | 0,779 | 99,9997 | 41,1111 |
| 6 | 616,5525 | 225,2513 | 11 | 0,659 | 99,9999 | 41,1112 |
| 7 | 616,552 | 225,2407 | 14 | 0,839 | 99,9999 | 41,1112 |
| 8 | 545,1288 | 178,6025 | 11 | 0,659 | 88,4156 | 36,3488 |
| 9 | 545,1389 | 179,6273 | 14 | 0,837 | 88,4173 | 36,3494 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| 10 | 616,5133 | 225,5466 | 11 | 0,659 | 99,9936 | 41,1086 |
| Average | 595,1204 | - | 12 | 0,743 | 95,3655 | 39,2059 |
| Best | 616,5525 | 225,2513 | 11 | 0,659 | 99,9999 | 41,1112 |
| Worst | 545,1288 | 178,6025 | 11 | 0,659 | 88,4156 | 36,3488 |

From table 14, it can be concluded that the results of the PSO tracking to find MPP in the fifth case obtained poor results. From 10 attempts, PSO succeeded in tracking MPP in the fifth case, succeeded 7 times and failed 4 times in tracking it, so that the probability of the PSO algorithm being successful in tracking MPP in the fifth case is 60%. The PSO algorithm failed to track MPP 4 times because it was stuck at the 4th local peak with a voltage of 179V. Where in this fifth case there are 6 peaks, from the characteristic curve in the 5th case, the global peak is at the 5th peak and the others are local peaks.

TABLE XV. PSO TRACKING RESULTS TO FIND MPP IN CASE 6.

| Test | Ppv (W) | Vref (V) | Iteration | Convergent time (s) | Algorithm Efficiency (%) | PV.Efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 439,5917 | 132,455 | 12 | 0,719 | 99,9994 | 29,3116 |
| 2 | 439,5947 | 132,383 | 11 | 0,659 | 99,9999 | 29,3118 |
| 3 | 439,5947 | 132,379 | 13 | 0,779 | 99,9999 | 29,3118 |
| 4 | 439,5947 | 132,333 | 12 | 0,719 | 99,9999 | 29,3118 |
| 5 | 378,8598 | 84,7934 | 20 | 1,299 | 86,1839 | 25,2621 |
| 6 | 439,5946 | 132,314 | 11 | 0,659 | 99,9999 | 29,3118 |
| 7 | 378,8598 | 84,7934 | 25 | 1,499 | 86,1839 | 25,2621 |
| 8 | 439,5947 | 132,362 | 11 | 0,659 | 99,9999 | 29,3118 |
| 9 | 439,5928 | 132,449 | 11 | 0,659 | 99,9996 | 29,3117 |
| 10 | 439,5947 | 132,359 | 12 | 0,719 | 99,9999 | 29,3118 |
| Average | 433,5207 | - | 13 | 0,809 | 97,2366 | 28,9068 |
| Best | 439,5947 | 132,383 | 11 | 0,659 | 99,9999 | 29,3118 |
| Worst | 378,8598 | 84,7934 | 25 | 1,499 | 86,1839 | 25,2621 |

From table 15, it can be concluded that the results of the PSO tracking to find MPP in the sixth case obtained good results. From 10 attempts, PSO succeeded in tracking MPP in the sixth case, succeeded 9 times and failed 2 times in tracking it, so that the probability of the PSO algorithm being successful in tracking MPP in the sixth case is 80%. The PSO algorithm failed to track MPP 2 times because it was stuck at the 2nd local peak with a voltage of 84V. Where in the sixth case there are 6 peaks, from the characteristic curve in the 6th case the global peak is at the 3rd peak and the others are local peaks.

TABLE XVI. PERCENTAGE OF THE ALGORITHM'S AVERAGE EFFICIENCY ADVANTAGE

| Scenario | Tracking Time(s) | | Percentage of Excellence |
|---|---|---|---|
| | ACO | PSO | ACO |
| Case 1 | 99,9853 | 99,9968 | -0,01 |
| Case 2 | 99,9889 | 99,4646 | 0,52 |
| Case 3 | 97,7325 | 98,8658 | -1,13 |
| Case 4 | 99,2406 | 99,9999 | -0,76 |
| Case 5 | 99,9995 | 97,6809 | 2,32 |
| Case 6 | 99,9995 | 98,6182 | 1,38 |
| Average Percentage | | | 0,39 |

From the 6 case scenarios, the efficiency of the ACO algorithm is 0.39% superior to the PSO algorithm. The PSO algorithm has a worse average efficiency because it is often trapped in the local maximum. The ACO algorithm is more suitable for tracking many peaks because getting caught in local maximums is not easy. The number of coefficients that control the tracking causes the ACO algorithm to be 0.78 s slower in tracking time compared to the PSO algorithm.

TABLE XVII. PERTAGE OF LEAD TIME TRACKING

| Scenario | Tracking Time(s) | | Percentage of Excellence | |
|---|---|---|---|---|
| | ACO | PSO | ACO-PSO | PSO-ACO |
| Case 1 | 0,495 | 0,713 | 0,22 | -0,22 |
| Case 2 | 1,793 | 0,749 | -1,04 | 1,04 |
| Case 3 | 1,325 | 0,707 | -0,62 | 0,62 |
| Case 4 | 1,908 | 0,677 | -1,23 | 1,23 |
| Case 5 | 1,481 | 0,743 | -0,74 | 0,74 |
| Case 6 | 2,237 | 0,809 | -1,43 | 1,43 |

| | | |
|---|---|---|
| Average Percentage | -0,81 | 0,81 |

## CONCLUSION

Based on the study results, the average efficiency of the ACO algorithm was 99.4910% in 6 cases and 10 trials in each case. Tracking time is 0.81 s slower than PSO. The average efficiency of the PSO algorithm was 99.1043% in 6 cases and 10 trials in each case. Tracking time is 0.81 s faster than ACO. It can be concluded that the ACO algorithm has an overall average efficiency that is 0.39% superior to PSO, but has a tracking time of 0.81 s longer than the PSO algorithm.

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