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Comparing MPPT Algorithms for Improved Partial-Shaded PV Power Generations

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A B S T R A C T

Solar energy, accepted as an alternative energy source, is attracting commercial interest and scholars and researchers for improving efficiency and lowering the losses within the system. One of these significant losses is due to partial and complex shading. This study concentrates on reducing losses to enhance the efficiency of solar systems. Maximum Power Point Tracking (MPTT) uses several alternative algorithms for efficient operations. We have selected four algorithms supporting MPPT, namely P&O, PSO, Adaptive cuckoo, and Dragonfly. These algorithms are applied on photovoltaic (PV) systems in four different scenarios: uniform irradiance, partial shading, complex partial shading, and multiple local maximum power points. According to this study, results show that the algorithms' performance vary significantly based on these scenarios. It has been shown that PSO has the longest tracking time compared to other but tracks the maximum power best when exposed to uniform irradiance. In contrast, DFO takes the shortest tracking time and performs best in I-V curves but do not have a maximum power point at the knee. Both adaptive cuckoo and PSO perform well in tracking the global maximum power point, particularly in partial shadings. The study provides insights into the strengths and weaknesses of each algorithm in different scenarios and can guide the selection of an appropriate algorithm for a given PV system.

INTRODUCTION

The use of renewable energy sources to generate electricity has recently expanded worldwide, primarily due to ongoing need to meet the rising demand for electricity and minimize adverse environmental effects [1], [2]. As a result, renewable energy sources, which use natural resources including solar power, wind power, and hydro power, have been crucial in supplementing or replacing conventional electricity generation (namely fossil, nuclear, and natural gas) [3], [4].

Global electricity consumption reached 29 TWh in 2022, a significant portion of the world's total energy consumption [5]. Photovoltaics (PV) provide electricity in a clean and renewable manner, and the PV market has grown remarkably in the past couple of decades. In 2022, newly installed PV cumulatively capacity exceeded 1.289 TWh worldwide [6], [7]. With the fast development of PV technology, the final price of electricity generated by PV has exhibited competitiveness among the other alternative energy sectors. As an example, Abu Dhabi Water and Electric Authority (ADWEA) reported that the price bidding for PV was as low as 2.42 US cents/kWh, even lower than that of fossil energy [6], [7]. Solar cells have been extensively studied in recent years, and several improvements have been introduced to improve their efficiency. However, the output power of PV systems is affected by factors such as shading, temperature, and irradiance, which may cause the system to operate at reduced capacity at local Maximum Power Points (MPPs)[8], [9]. There are numerous reasons related to the inefficiencies of solar systems. The main issues towards the inefficiencies of PV systems are the DC to DC conversion [10], the DC to AC conversion [11], [12], and the partial and complex partial shading [13]–[15].

Complex partial shading is a type of partial shading mostly due to the presence of clouds in the sky, PV installations defects, shades of trees, and factors affecting single PV cells, and finally, the settlement of dust particles and sooth on the panels. Shading is an important factor contributing to the lower efficiency of solar systems, thus rendering their operations incomplete and uneconomical. Many researchers concentrate on eliminating or minimizing energy losses by developing fresh and novel ideas and techniques.

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Nowadays, PV efficiency has become an attractive topic for scholars to find methods concentrating on the electrical components for energy optimization, making design changes in the solar cell structures, and altering arrangements to cope with losses. A recent study shows the usage of gross hopper for optimization of MPPT [8], [16] technique, and the result was quite enjoyable which improves the tracking efficiency to 99.5%, reduces the oscillations by up to 85 %, and yields 14-16% improvement in fast-tracking [17]. Also, the application of a hybrid Perturb-and Observe (P&O) [18] and Particle Swam Optimization (PSO) [19], [20] has been shown to have improved maximum power point tracking [21] significantly. These methods incorporate the search skip judge mechanisms to minimize regions within the PV curve.

PSO also rapidly shows global maximum power point convergence and guarantees tracking under complex partial shading conditions [22]. B. Jainbo. et al. proposed an algorithm with several subsection functions for the solar system under complex partial shading to evaluate the effectiveness of the proposed system. They conducted experiments showing high accuracy in calculating PV and IV characteristics on PV modules. Their results have been shown to operate effectively on arrays in complex partial shading and mismatch conditions [23], [24]. T.R.Wellawatta. et. Al developed a new partial shading determinant algorithm using an adaptive threshold level. Their study shows improved results in comparison with the conventional methods. The conventional methods tend to be insensitive to smoothing operations, while their proposed method shows an improved performance regardless of the partial shading patterns [25], [26].

In this work, we aim to investigate and compare the performance of four MPPT algorithms: Adaptive cuckoo [27], [28], Dragonfly algorithms [29], [30], as well as P&O PSO techniques. They will be applied in four scenarios: uniform irradiance, partial shading, complex partial shading, and multiple local MPPs. This study simulates the PV system under each scenario and compares their performance in tracking time, settling time, and efficiency. This study's results can help identify each algorithm's strengths and weaknesses and provide insight into selecting appropriate ones for a given PV system subjected to different operating conditions.

METHODS

This study is based on a simulation of photovoltaic energy conversion under four scenarios by applying P&O, PSO, adaptive cuckoo, and dragonfly algorithms. In the first scenario, all PV modules are receiving uniform irradiance. In the second and third scenarios, partial shading of modules are introduced. Finally, the fourth scenario deals with complex shading. Figure 1 shows the designed model in Simulink with the embedded MPPT block. PV array is connected to a DC-to-DC power conversion mechanism called the Switched-Mode Power Supply (SMPS). DC-DC converters have two or more semiconductor elements, such as diodes, transistors, and various energy storage elements. The storage elements can be one or more inductors, capacitors, or combinations. A filter circuit comprising capacitors or a combination of capacitors and inductors is introduced to remove the voltage ripples.

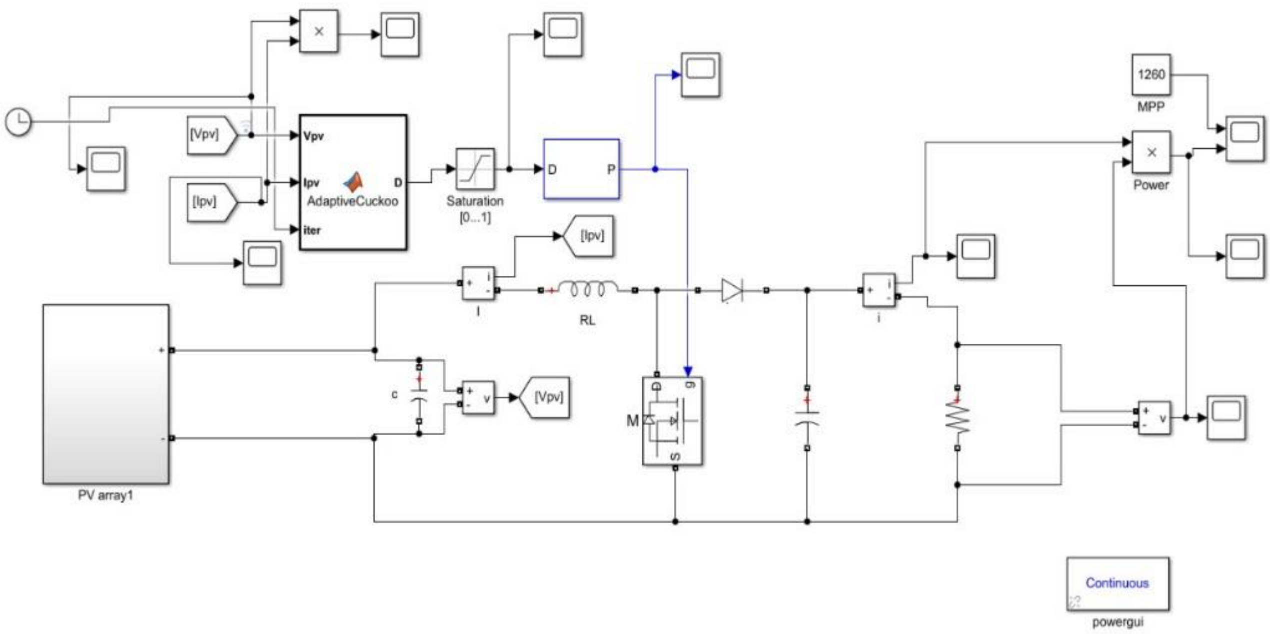

Figure 1. PV system model designed on Simulink.

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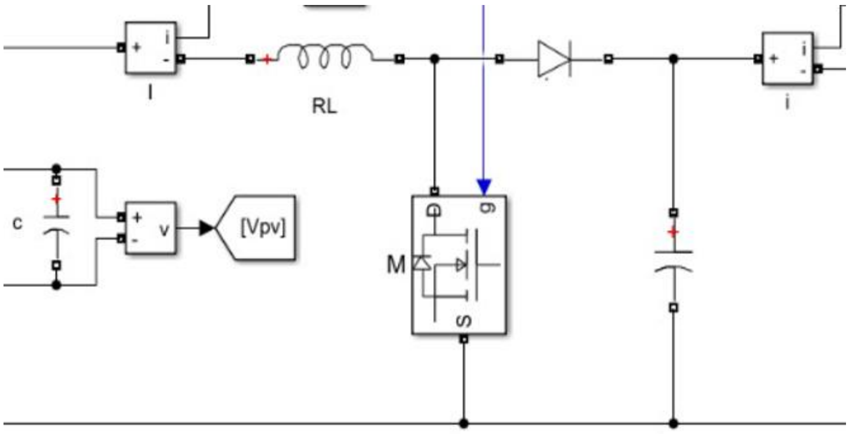

Figure 1. DC to DC convertor

Figure 2 shows a DC-to-DC converter having a PV array as a source of DC voltage input source inductor 'RL' or the boost inductor, a capacitor acting as the filter, a diode, and an ideal switch. The control function is performed by the ideal switch` which works according to the variations in the duty cycle needs of the installed switch. The duty cycle can be calculated with Equation (1) below.

$$V_0 = \frac{V_{in}}{1-D} \quad (1)$$

The arrangement is constructed to simulate scenarios 1, 2, and 3. Each module is subjected to variations in the output following temperature and solar irradiance. During partial shading, the I-V curve of PV modules varies, and multiple local MPPs are generated. The arrangement of PV panels in Simulink can be shown in Figure 3.

As shown in Figure 4, a twelve PV panel arrangement was arranged in Simulink to extend the investigations. The arrangements are constructed for the simulation of scenario 4. Each module is subjective to vary output according to temperature and solar irradiance. During partial shading I-V curve of PV modules varies and multiple local MPPs are generated.

The properties of the scenarios and their irradiance levels can be shown in Table 1 below.

Table 1. The scenarios and set irradiance levels.

Scenario	Settled irradiance(W/m2)	Maximum power(W)
Scenario 1: Uniform Irradiance	PV1 PV2 PV3 PV4 900 900 900 900	1250
Scenario 2: Partial Shading	PV1 PV2 PV3 PV4 800 1000 500 900	800
Scenario 3: Partial Shading	PV1 PV2 PV3 PV4 750 600 850 900	810

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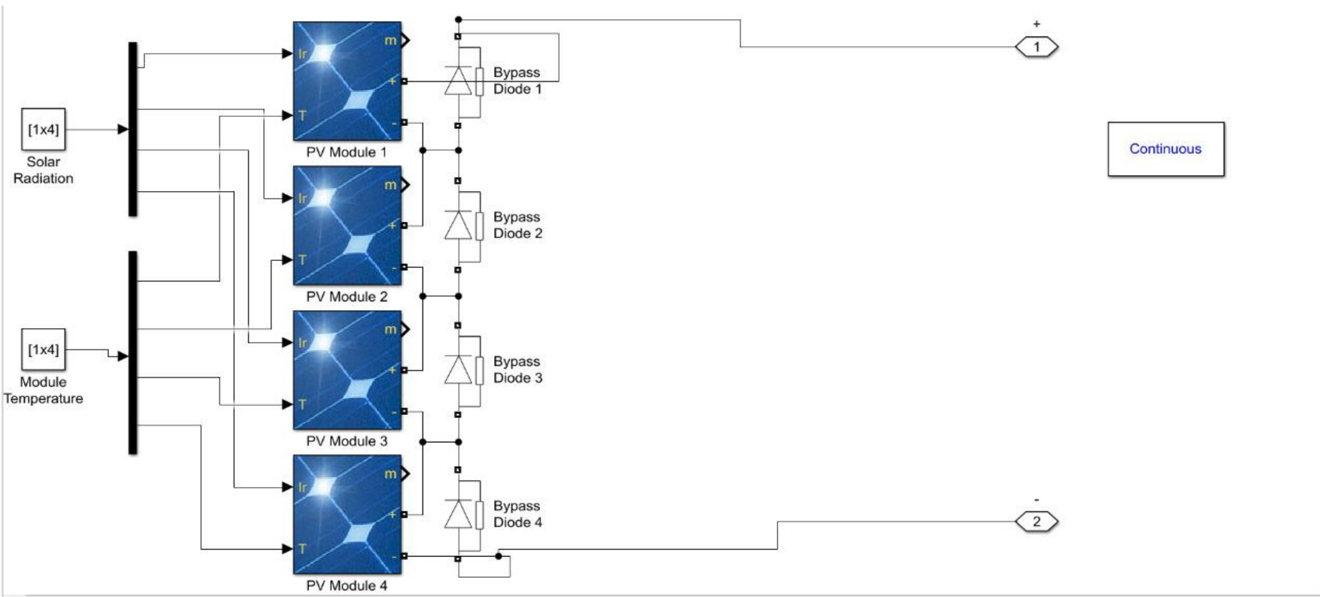

Figure 2. Arrangement of PV panels for scenario 1, 2 and 3.

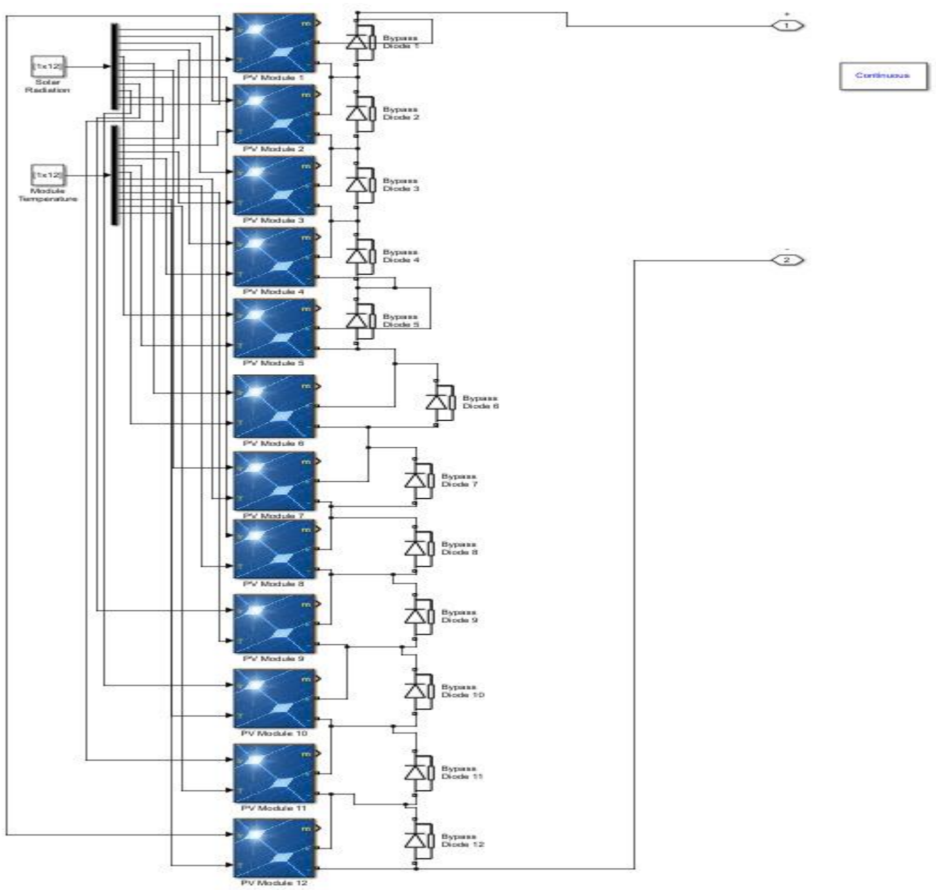

Figure 3. PV panel arrangement for scenario 4

RESULTS AND DISCUSSION

There are four scenarios in this research, such as scenario 1, 2, 3 and 4. In scenario 1, analysis of P&O, PSO, Dragonfly and Adaptive cuckoo can be shown in Figure 5 below.

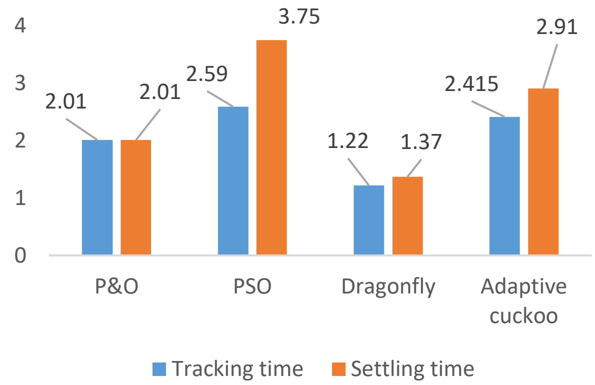

Figure 4. Analysis of P&O, PSO, Dragonfly and Adaptive cuckoo

In Scenario 1, all four PV panels receive uniform irradiance (900 W/m2). The results are depicted in Figure 6 below.

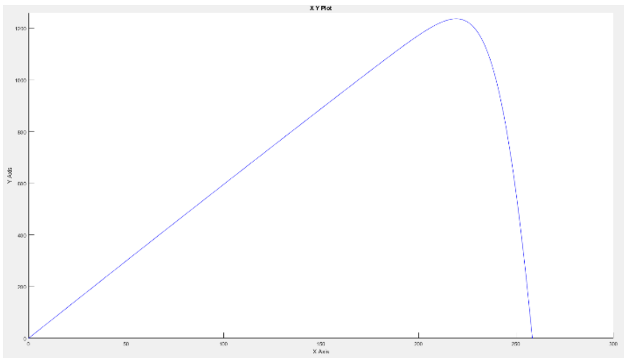

Figure 6. I-V curve in scenario 1

Under uniform irradiance, I-V curve is a standard knee curve having maximum power point achieved at the knee of curve shown in Figure 7 below. Figure 7 is the current vs time analysis of the algorithms.

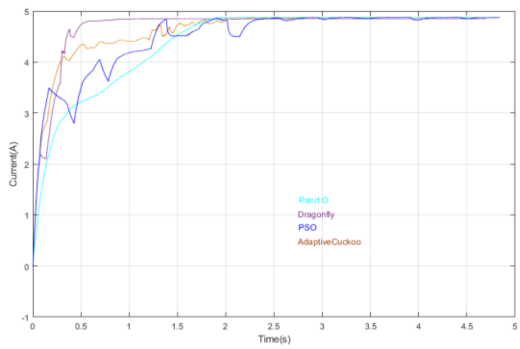

Figure 7. Current vs time analysis of algorithms

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For the Figure 8, it can be seen other graphic. It is the voltage vs time analysis graphic. It can be shown below.

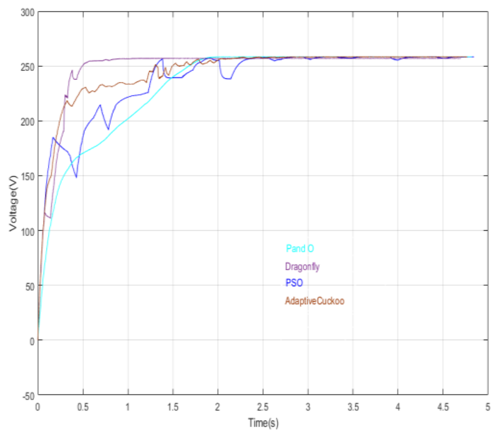

Figure 8. Voltage vs time analysis

From these figures, oscillations of voltages and currents take place in 5 sec intervals. Comparison of the results for the power generation shows: the maximum power tracked are 1251W, 1256W, 1245 W and 1254W for P&O, PSO, dragonfly and adaptive cuckoo respectively. The expected maximum power is 1260 watts. The highest maximum power of 1256 W was tracked by the PSO. The performance of algorithms can be ranked as: PSO > Adaptive cuckoo > P&O > Dragonfly.

The tracking time is measured from initialization point to the time it takes to seek maximum power point, as shown in Figure 9.

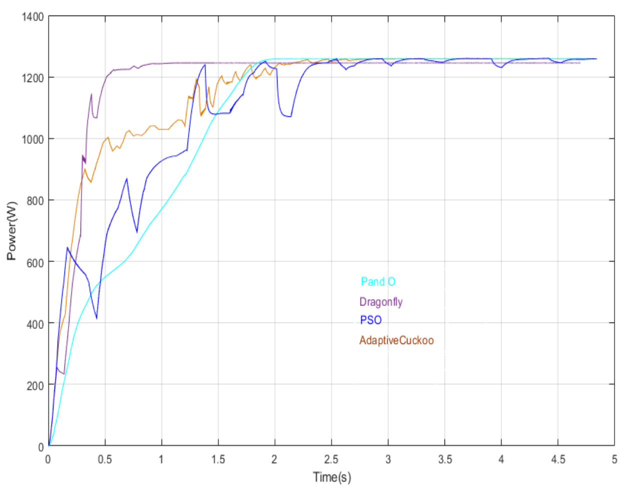

Figure 9. Power vs. time analysis

Figure 9 shows the tracking times are 2.01 s, 2.59 s, 1.22 s and 2.415 s for P&O, PSO, Dragonfly, and Adaptive cuckoo respectively. As can be seen, the DFO takes the least tracking time to reach the maximum power point, while the particle swarm optimization takes the longest time, 2.59 seconds. By the same token PSO tracks the maximum power, best of them all. Although the PSO explores as data set randomly in the initial stages, it results in precise maxima. Under the uniform irradiance conditions, the system shows only one maximum power point. It also requires less exploration time.

Settling time can be defined as the time from initialization point to reach the maximum power point value without any oscillations. The settling times of 2.01 s, 3.75 s, 1.37 s and 2.91 s are computed for P&O, PSO, Dragonfly and Adaptive cuckoo algorithms respectively. The perturb and observe did not take extra time to settle once the maximum power point is located.

For the duty cycle, it can be compared between the variation of duty cycle and the number of samples. It can be shown in Figure 10 below.

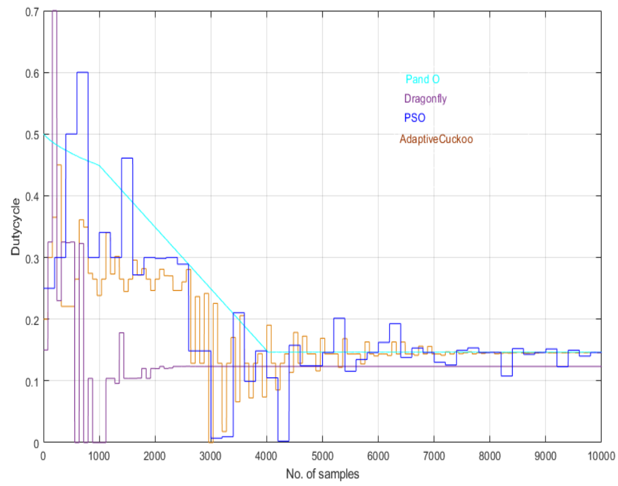

Figure 10. Variation of duty cycle w.r.t number of samples

Duty cycle is a ratio between high samples and total number of cycles. The accuracy of duty cycle increases as the number of samples increases. DFO shows an arbitrary oscillation, while PSO and adaptive cuckoo both tend follow a very predictive path.

In Scenario 2, PV panels are subjected to partial shading. Figure 11 shows the comparative analysis of the algorithms. The solar irradiance of PV1, PV2, PV3 and PV4 panels are set to 800, 1000, 500, and 900W/m2, respectively.

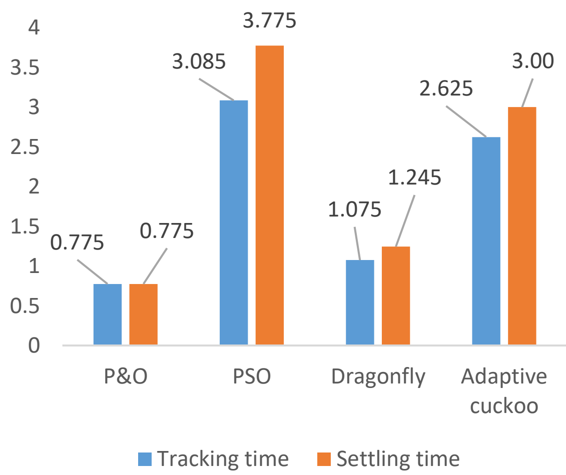

Figure 11. Comparative analysis of P&O, PSO, Dragonfly and Adaptive cuckoo

Under partial shading conditions, I-V curve is illustrated in Figure 12

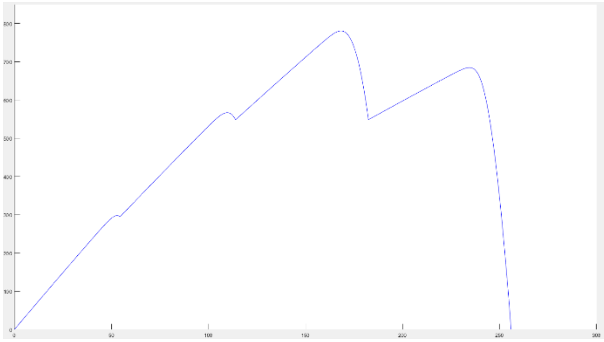

Figure 12. I-V curve

In this scenario, multiple local MPPs occur. The Global maximum power point is where maximum power is observed, as shown in Figure 12. Comparing the power performance in under partial shading, maximum power tracked is 572W, 793.4W, 781.4W and 793.7W for P&O, PSO, Dragonfly and Adaptive cuckoo respectively. Adaptive cuckoo tracked maximum power of 793.7W. Sequentially comparing, power performance of each algorithm can be put as Adaptive cuckoo > PSO > Dragonfly > P&O.

During PSO, it talked about maximum current and voltage oscillation. For maximum oscillation of current, it can be shown in Figure 13 below.

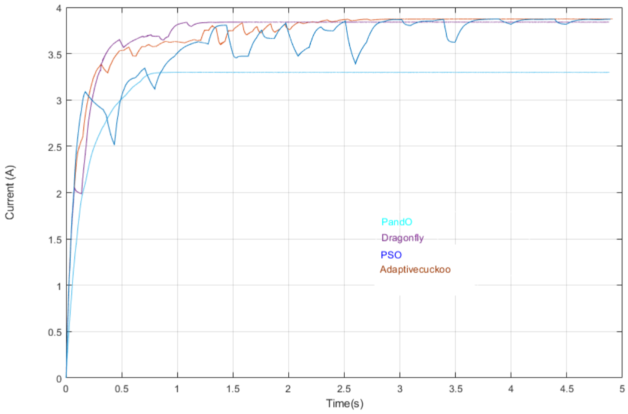

Figure 13. Current vs time analysis

For maximum oscillation of voltage, can be shown in Figure 14 below.

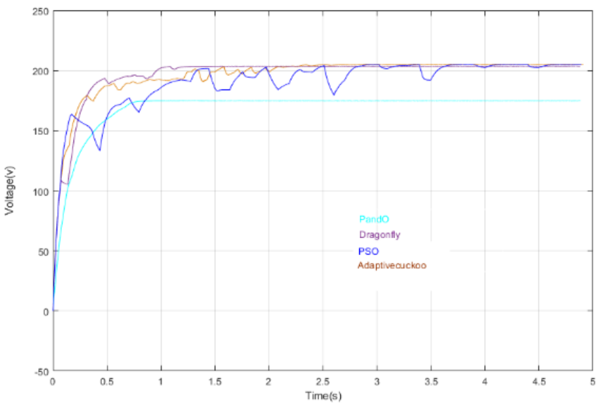

Figure 14. Voltage vs time analysis

From the figures above, A reasonable explanation for a high oscillation during tracking interval of PSO is random dataset at the initialization. Tracking time are 0.775 s, 3.085 s. 1.075 s and 2.625 s are measured for P&O, PSO, Dragonfly and Adaptive cuckoo, respectively. P&O tracking time is the least and it also tracked minimum power. It is the predictive result as it is easy for Perturb and Observe algorithm to get confused between global and local MPPs under partial and complex-partial shading condition. Adaptive cuckoo and PSO both performed well in tracking GMPP. Particle swarm optimization takes the longest time for tracking, GMPP. Settling time for P&O, PSO, Dragonfly and Adaptive cuckoo are observed as 0.775, 3.775, 1.245 and 3 s. Since there are no oscillations in Perturb and the observation method and perturbation can continue in one direction at a single interval, it takes no extra time to settle, as shown in Figure 15.

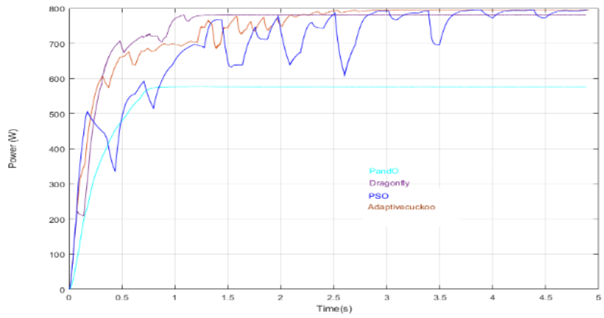

Figure 15. Power vs time analysis

Successful tracking of global MPP in Adaptive Cuckoo, dragonfly, and PSO is due to their design for multiple optimal point locating and their nature of using multi-agents for locating global maxima. The efficiency of each technique remained at 71.5 %, 99.17 %, 97.67 % and 99.21 % for P&O, PSO, Dragonfly and Adaptive Cuckoo, respectively.

In Scenario 3, another case of partial shading is simulated. Four panels, PV1, PV2, PV3 and PV4, are receiving solar irradiance of 750, 600, 850, and 900W/m2, respectively. Figure 16 shows the comparative analysis of the algorithms.

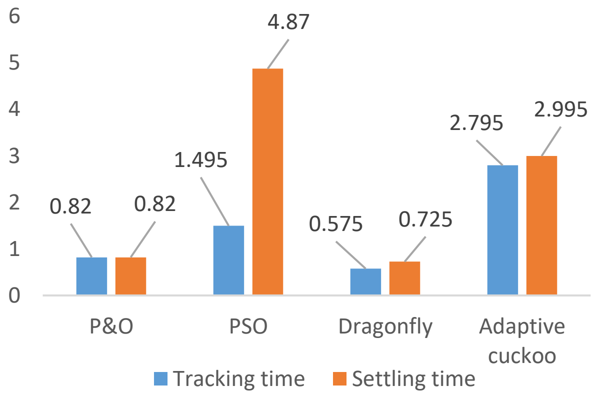

Figure 16. Comparative analysis of P&O, PSO, Dragonfly and Adaptive cuckoo

For the IV curve of this scenario, it can be shown in Figure 17 below.

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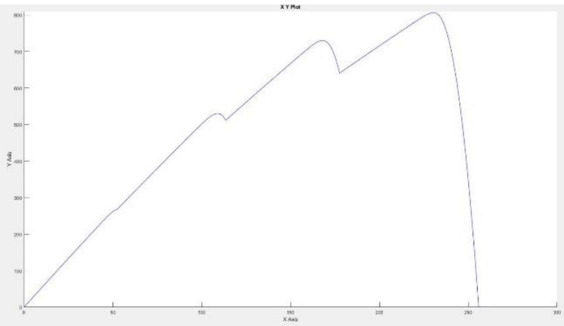

Figure 17. I-V curve

Under no shading conditions, the I-V curve resembles the standard I-V curves as in Figure 17. It has a global maximum power point value at knee of I-V curve. However, due to partial shading, there are three local maximum power points. Power tracked by P&O, PSO, Dragonfly and Adaptive cuckoo is 534 W, 733.9 W, 697.8 W and 738.6 W for P&O respectively, are shown in Figure 16. Adaptive cuckoo tracked maximum power of 738.6W. The efficiencies achieved by each algorithm is 65.97 %, 90.60 %, 86.14 % and 91.18 % for P&O, PSO, Dragonfly and Adaptive Cuckoo respectively.

The tracking times of 0.82 s, 1.495 s. 0.575 s and 2.795 s are measured for P&O, PSO, Dragonfly and Adaptive cuckoo respectively. DFO took least tracking time. Also, high oscillations are observed during tracking interval of PSO due to random datasets. DFO performed the best in tacking global maximum power thus resembling the standard I-V curve. The settling time for P&O, PSO, Dragonfly and Adaptive cuckoo are 0.82, 4.87, 0.725 and 2.995 s.

In this scenario, local MPP and global MPP are located close to each other. PSO persisted in further oscillations near MPPs settling 4.87 s thus being the latest. It is noted that the accuracy of duty cycle increases when the number of samples increases. In this scenario the adaptive cuckoo performed best.

For Scenario 4, a complex partial shading of twelve panels is taken in scenario 4. There are twelve panels PV1, PV2, PV3, PV4, PV5, PV6, PV7, PV8, PV9, PV10, PV11, and PV12, receiving solar irradiance of 400, 200, 600, 300, 1000, 400, 200, 300, 1000, 800, 740 and 1000 W/m2 respectively. Comparative analysis of P&O, PSO, Dragonfly and Adaptive cuckoo in scenario 4 are illustrated in Figure 18.

The maximum power tracked are 453 W, 1080 W, 1082 W and 899.1 W by P&O, PSO, Dragonfly and Adaptive cuckoo respectively. DFO tracked maximum power of 1082W. Tracking times are 0.565, 3.0. 0.945 and 1.655 s are for P&O, PSO, Dragonfly and Adaptive cuckoo, respectively. P&O took the least time but was unable to track Maximum power point. Settling times for P&O, PSO, Dragonfly and Adaptive cuckoo are observed as 0.565, 4.91, 0.945 and 3.52 s.

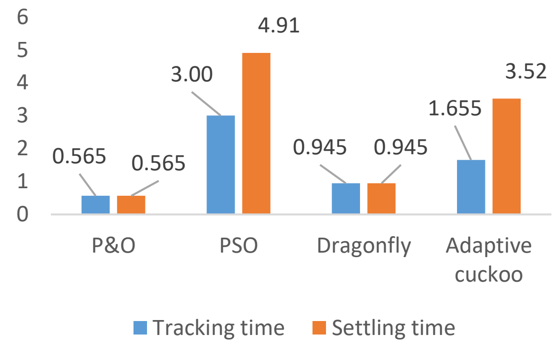

Figure18. Comparative analysis of P&O, PSO, Dragonfly and Adaptive cuckoo

Table 1. Comparison of results of considered techniques

Technique	Scenarios	Tracking time	Settling time	Maximum power(W)	Power Tracked(W)	Efficiency%	MPP located
P&O	scenario 1	2.01	2.01	1260	1251	99.36	YES
	scenario 2	0.775	0.775	800	572	71.5	NO
	scenario 3	0.82	0.82	810	534.4	65.97	NO
	scenario 4	0.565	0.565	1140	453	39.73	NO
PSO	scenario 1	2.59	3.75	1260	1256	99.68	YES
	scenario 2	3.085	3.775	800	793.4	99.17	YES
	scenario 3	1.495	4.87	810	733.9	90.60	YES
	scenario 4	3.00	4.91	1140	1080	94.73	YES
Dragonfly	scenario 1	1.22	1.37	1260	1245	98.8	YES
	scenario 2	1.075	1.245	800	781.4	97.67	YES
	scenario 3	0.575	0.725	810	697.8	86.14	YES
	scenario 4	0.945	0.945	1140	1082	94.9	YES
Adaptive cuckoo	scenario 1	2.415	2.91	1260	1254	99.52	YES
	scenario 2	2.625	3.00	800	793.7	99.21	YES
	scenario 3	2.795	2.995	810	738.6	91.18	YES
	scenario 4	1.655	3.52	1140	899.1	78.86	YES

In this scenario, the DFO tracking favors partial shading condition and performs best, and Table 2 compares the overall result.

The comparative research shows that the suggested DFO technique is the most effective at achieving a global peak quickly and with a greater output power. Of all the MPPT approaches discussed above, the DFO technique delivers the fastest response time, resilience, dependability, and efficiency. Additionally, our investigations show the following: Regarding effectiveness, the PsO algorithm achieved the highest efficiency of approximately 96,04%, while DFO achieved an efficiency of approximately 94,37%. Similar to how relatively little output power is obtained in the P&O algorithm. As a result, the efficiency finally drops to 41%.

The algorithms investigated in this study show that they all have advantages and disadvantages. To the authors' knowledge, the previous studies have not comprehensively explored the characteristics of all four MPPT algorithms comparatively under partial shading conditions.

Conventional techniques like Perturb and Observe (P&O) have shown better performance under uniform irradiance conditions, while adaptive techniques like cuckoo algorithms have been observed to perform better under partial shading. This is inline with previous study reported by Muyassar, et al. [9]

The Dragonfly algorithm has demonstrated good performance with minimum tracking time and the ability to locate the global maximum point without oscillations. This is inline with previous study reported by Lodhi, et al.[29]

The suggested Dragonfly Optimization (DFO) technique in this study has shown to be the most effective at achieving a global peak quickly and with a greater output power. This is inline with previous study reported by Meraihi, et al. [30]

Comparison of this work with the previous studies indicates that there has not been a comprehensive attempt made to determine characteristic of all four algorithms used in this study under partial shading conditions. However, individual studies have been reported as discussed in detail in the introduction section. For example, gross hopper optimization improved the tracking efficiency to 99.5% and reduces the oscillations by up to 85 %, thus yielding 14-16% improvement in fast tracking [17]. Their study shows improved results in comparison with the conventional methods.

CONCLUSIONS

This study aims to enhance the efficiency of PV power generation under complex shading conditions. A comparison-based study is conducted with uniform irradiance distribution, partial shaded, and complex partial shaded cases. All techniques can locate the global maximum point for partial shading. The conventional techniques, such as the P&O, perform better in uniform irradiance conditions. However, partial shading adaptive techniques like cuckoo algorithms are observed to perform better. The dragonfly technique showed a good performance displaying minimum tracking time and locating the global maximum point without oscillations. Perturb and observe required minimum time and computational power under uniform irradiance since there was only one maximum power point. DFO shows an arbitrary oscillation, while PSO and adaptive cuckoo both follow expected predictive paths.

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