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A Review of Partial Shading MPPT Algorithm on Speed, Accuracy, and Cost Embedded

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ABSTRACT

This paper describes several maximum power point tracking algorithms for partial shading conditions that have detrimental effects on photovoltaic systems. The method used was a literature review of articles from reputable publishers. Fifty-two articles were obtained after meeting the established criteria for selection. The literature review focused on the ability of the maximum power point tracking algorithms to overcome partial shading conditions in terms of tracking speed, tracking accuracy, efficiency and implementation complexity. Some algorithms were recommended to be applied for maximum power point tracking, including the single swam algorithm and the perturb and observe algorithm, the enhanced adaptive step size perturb and observe algorithm, the novel adaptable step incremental conductance algorithm, the improved bat algorithm and fuzzy logic controller algorithm and the particle swarm optimisation with one cycle control algorithm. In terms of implementation complexity, these five algorithms are categorised as medium-complexity algorithms, which can be characterised by low cost, high efficiency and even 100% high tracking speed and accuracy with a minimum number of sensors used.

1. Introduction

The main issue with solar panels or photovoltaic systems is their low efficiency in converting electrical energy, which ranges between 14% and 19% depending on climatic conditions [1]. The characteristics of power and voltage (P–V) and current and voltage (I–V) are nonlinear and highly dependent on environmental factors, such as solar radiation and temperature, the conversion system, control algorithms and load type [2]. Interference in the form of shadows that prevent sunlight from reaching part or all of the surface of the solar panel has previously been discussed in research by experts and specialists in increasing efficiency. Clouds, flocks of birds, buildings and temporary leaves and tree branches can cast shadows. These conditions are referred to as partial shading conditions (PSCs).

Under standard test conditions, the PV system receives normal radiation. However, when PV is installed in the field, it exhibits nonlinear characteristics due to unequal solar radiation reception, particularly when shading occurs. This phenomenon causes fluctuations in the PV's output value, resulting in several local maximum power points (LMPPs) and one global maximum power point (GMPP). In normal radiation conditions, it has only one maximum point, GMPP. The emergence of hotspots is another phenomenon that occurs when PV works when shading occurs even

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under certain conditions, causing PV to burn in some cases [3]. Another effect of PSCs is energy loss, which varies with the amount of PV in the PSCs [4].

In the PV characteristics, a specific point exists, known as the maximum power point (MPP), in which the solar energy extraction efficiency can be maximised if the system operates at this point. As a result, tracking MPP points in different sunlight conditions is critical for the system to work in GMPP areas [5]. An algorithm known as MPP tracking (MPPT) [1], [6] can be used to track MPP points. In general, the MPPT algorithm is divided into two main parts: based on normal (uniform) solar radiation conditions and based on different solar radiation conditions or PSCs (nonuniform) [7].

Several MPPT methods have been developed and presented in the literature, including perturb and observe (P&O), hill climbing, incremental conductance (InC), InC with direct duty cycle, fractional short-circuit current, fractional open-circuit voltage and ripple correlation [8]–[13]. The P&O and InC methods are the most fundamental types of MPPT techniques. They have been widely used and developed given the simple qualities that they possess. Additionally, these methods are cost-effective in terms of their application and their price, despite the fact that they have some drawbacks [14], [15]. The PSCs were the impetus behind the creation of MPPT algorithms, which were designed to improve not only the speed and accuracy of tracking but also the overall effectiveness of systems. They include ant colony optimisation [16]–[19], grey wolf [20]–[24], artificial bee colony (ABC) [25]–[29], genetic algorithms [30]–[32], particle swam optimisation (PSO) [33]–[37], fuzzy logic controllers (FLCs) [38]–[40] and artificial neural networks (ANNs) [41]–[44]. A few things need to be considered in selecting the MPPT method or algorithm that will be used. These things include the tracking speed and accuracy in the tracking process, as well as the efficiency and implementation complexity related to the costs that will be incurred [45]–[47].

A significant problem is how to track GMPPs properly even in extreme weather conditions, under which conventional MPPT methods are ineffective because they may be trapped in LMPPs [48].

Utilising an optimisation algorithm (hybrid) is one of the pragmatic approaches that can be considered to track GMPP when PSCs occur [49], [50]. Accordingly, the primary emphasis of this study is placed on the investigation of MPPT optimisation strategies to address the challenges posed by the occurrence of PSCs. Specifically, this study examines tracking speed, precision, efficiency and application complexity. Complexity is proportional to the costs that must be incurred; the more complex the method, the greater the costs that must be incurred, and vice versa. The expected contribution of this study is providing important information about an MPPT method that satisfies the criteria for tracking speed, accuracy, efficiency and cost embedded under PSCs for the next researchers or other relevant parties.

This paper will focus on the tracking speed, accuracy, efficiency and cost embedded in MPPT algorithms, particularly those that are frequently used in research.

2. Methodology

Articles or reading materials that are reviewed in this study are found using several keywords, including MPPT techniques for PV systems, MPPT for partial shading conditions, MPPT for non-uniform irradiance and improved MPPT method. In accordance with the main requirements in selecting MPPT, the articles used in the review contain a discussion of tracking speed, tracking accuracy, efficiency and implementation complexity. A search for the articles is conducted on the websites listed below:

https://ieeexplore.ieee.org
https://www.sciencedirect.com
https://link.springer.com
https://ietresearch.onlinelibrary.wiley.com
https://www.mdpi.com
https://www.tandfonline.com
https://onlinelibrary.wiley.com
https://www.nature.com

https://www.hindawi.com
https://ijpeds.iaescore.com
https://journals.plos.org/plosone/
https://thescipub.com
https://academic.oup.com/ce

The articles are reputable or SCOPUS-indexed publications dated from 2018 to 2022.

After all the articles are obtained, selection or filtering is performed in accordance with the criteria specified in the MPPT algorithm selection. The articles used in the literature review are the result of the selection process. A total of 174 articles are obtained from 13 websites that contain mentions of keywords determined during the initial screening. However, after detailed screening and selection are performed in accordance with the specified conditions, the number of articles that meet the criteria is only 52, as depicted in Figure 1. These articles are the result of the previous selection and will be used as material for the article review.

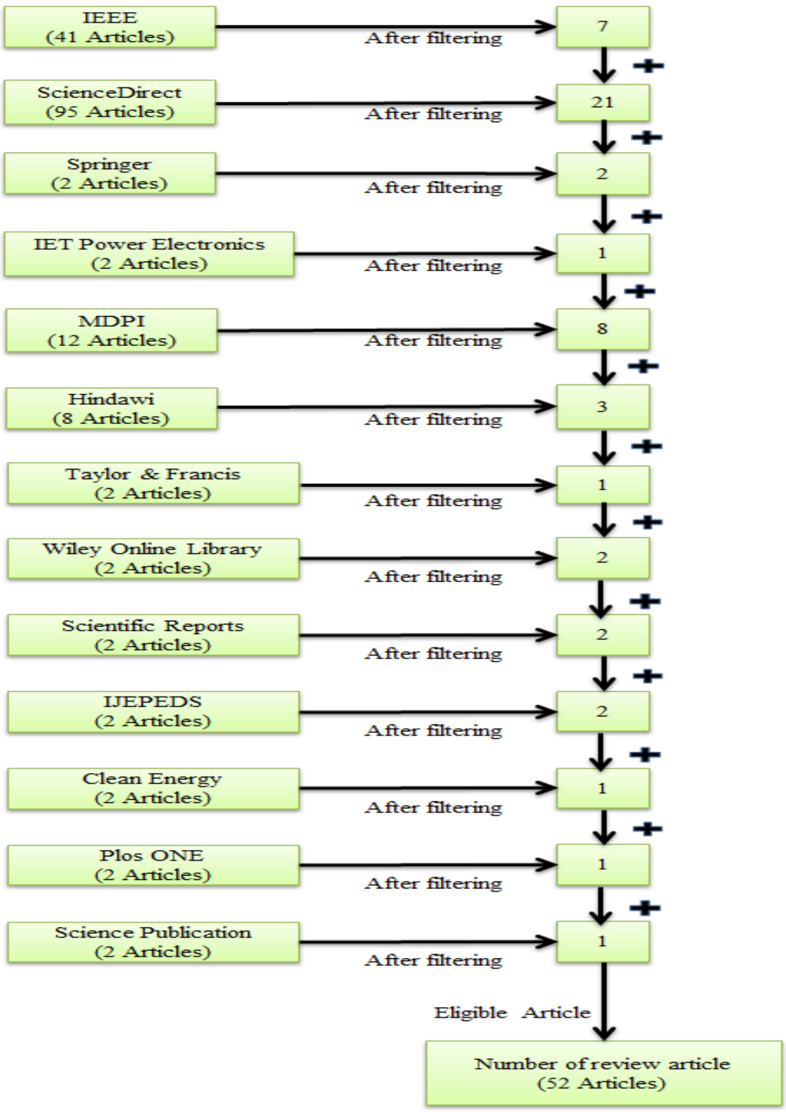

Figure 1. Number of articles used in the literature review process

3. Results and discussion

The purpose of MPPT algorithms is to increase the efficiency of converting solar energy into electrical energy. When selecting and designing an MPPT algorithm, several factors, including tracking speed, accuracy, implementation efficiency and implementation complexity, must be considered. The MPPT implementation will incur expenses proportional to its degree of difficulty. The problem is how to design MPPT algorithms that are appropriate for a wide variety of environmental conditions, particularly those that involve PSCs. As a result of their confinement in the LMPP region, a number of existing MPPT methods are unable to function effectively under these conditions. Consequently, the attempt to locate the GMPP is unsuccessful. Utilising an optimisation algorithm also known as the hybrid optimisation MPPT method is one solution. The results of the study of the hybrid optimisation MPPT algorithm under PSCs are displayed in Tables 1–6.

The paper review can be roughly divided into several sections, including discussions of P&O, InC, FLC, PSO, ANN and ANFIS hybrid algorithms.

Table 1: Comparison of the performance of the MPPT perturb and observe (P&O) algorithm and its combination under PSCs

No	MPPT techniques	Application	Sensor parameter	Tracking speed	Tracking accuracy	Efficiency %	Complexity
1	Perturb and Observation (P&O) and Fractional Characteristic Curve [51]	Stand alone	V_{PV}, I_{PV} and T_{PV}	Fast	Very High	99.46	High
2	Single Swam Algorithm (SSA) and Perturb and Observe (P&O) [52]	Charging battery	$I_{baterei}$	Fast	High	99.90	Medium
3	Salp Swarm Algorithm (SSA) with Perturb and Observation (P&O) [53]	Stand alone	V_{PV} and I_{PV}	Fast	High	98.65	Medium
4	Modified Drift-free P&O MPPT [54]	Stand alone	V_{PV} and I_{PV}	Fast	High	99.80	Low
5	Perturb and Observe Algorithm Based on the Trapezoidal Rule [55]	Grid connected	V_{PV} and I_{PV}	Fast	High	99.76	Low
6	Enhanced Adaptive Step Size Perturb and Observe(P&O) [56]	Stand alone	V_{PV} and I_{PV}	Fast	High	100	Medium
7	Enhanced Adaptive Perturb and Observe (EA-P&O) [57]	Stand alone	V_{PV} and I_{PV}	Fast	High	99	Medium
8	Enhanced P&O Checking Algorithm [58]	Stand alone	V_{PV} and I_{PV}	Fast	High	99.86	Medium
9	Artificial Bee Colony Integrated Perturb & Observe (ABC-P&O) [28][59]	Stand alone and grid connected	V_{PV} and I_{PV}	Fast	High	99.93	Highly complex
10	Modified P&O [60]	Grid connected	V_{PV}, I_{PV} and G	Fast	High	100	Medium

The MPPT hybrid P&O algorithm has the best tracking speed because it combines the ABC and P&O algorithms. The modified P&O algorithm and the adaptive step size P&O algorithm have the highest efficiency, which is 100%. The FCC-P&O algorithm combination provides the best accuracy tracking. In terms of implementation complexity and funding, the ABC-P&O algorithm combination is the most complex and the most expensive. The modified drift-free P&O MPPT and the P&O algorithm based on the trapezoidal rule have low implementation complexity.

Table 2: Comparison of the performance of the MPPT incremental conductance (InC) algorithm and its combination under PSCs

No	MPPT Techniques	Application	Sensor Parameter	Tracking Speed	Tracking Accuracy	Efficiency %	Complexity
1	Incremental Conductance (InC) and Fuzzy Logic Controller (FLC) [61]	Grid Connected	V_{PV}, I_{PV}, I_{SC} and V_{OC}	Fast	High	100	High
2	Incremental Conductance (InC) and Fuzzy Logic Controller (FLC) [62]	Grid Connected	V_{PV}, I_{PV} and V_{out_conv}	Fast	High	99.07	High
3	Modified Incremental Conductance [63]	Stand alone	V_{PV} and I_{PV}	Fast	High	95.28	Medium
4	Modified Incremental Conductance [64]	Stand alone	V_{PV} and I_{PV}	Fast	High	98.8	Medium
5	Modified Incremental Conductance [65]	Stand alone	V_{PV} and I_{PV}	Fast	High	99.78	Medium
6	Modified Incremental Conductance [66]	Stand alone	V_{PV} and I_{PV}	Faster	High	95.28	Medium
7	Self-Predictive Incremental Conductance Algorithm [67]	Stand alone	V_{PV} and I_{PV}	Fast	High	98.81	Medium
8	Incremental Conductance (InC) and Grasshopper Optimisation Algorithm (GOA) [68]	Stand alone	V_{PV} and I_{PV}	Fast	High	93.70	High
9	Incremental Conductance (InC) and Dragonfly Optimisation (DFO) [69]	Stand alone	V_{PV} and I_{PV}	Fast	High	99.98	Medium
10	Novel Adaptable Step Incremental Conductance (NAS-InC) [70]	Stand alone	V_{PV} and I_{PV}	Fastest	High	99.42	Medium

The InC-FLC algorithm has the highest efficiency value of 100%, whereas the MPPT InC-GOA algorithm has the lowest at 93.70%. The NAS-InC algorithm is the fastest in terms of tracking speed. The MPPT InC-FLC algorithm is more difficult to implement and has more measuring parameters than other InC hybrid algorithms. As a result, the costs associated with implementing the MPPT algorithm will be higher. The MPPT hybrid InC algorithm has the same accuracy value across all literature reviews.

The hybrid FLC MPPT algorithm, which combines GWO and FLC algorithms, has the highest efficiency of 99.99% but the slowest tracking speed compared with other algorithms. Some FLC hybrid algorithms, such as SCC-FLC, IBA-FLC and hybrid FLC algorithms, have high accuracy values. When it comes to the costs of implementing the MPPT algorithm, the GWO-FLC, hybrid FLC and GO-FLC algorithms are the most affordable. The MPPT SCC-FLC and hybrid FLC algorithms are two combinations of algorithms that use only one sensor from the MPPT hybrid FLC algorithm. Except for the combination of the MPPT GWO-FLC algorithm, all of the FLC algorithms discussed have the same tracking speed.

Table 3: Comparison of the performance of the MPPT fuzzy logic controller (FLC) algorithm and its combination under PSCs

No	MPPT Techniques	Application	Sensor Parameter	Tracking Speed	Tracking Accuracy	Efficiency %	Complexity
1	Short-circuit current (SCC) and Fuzzy logic controller (FLC) [71]	Charging battery	I_{VP}	Fast	Very High	98.6	High
2	Improved Bat Algorithm and Fuzzy Logic Controller (IBA-FLC) [72]	Grid Connected	V_{PV} and I_{PV}	Fast	Very High	99.00	Medium
3	Grey Wolf Optimisation (GWO) and Fuzzy Logic Controller (FLC) [73]	Stand alone	V_{PV}, I_{PV} and P_{PV}	Fast	High	99.97	Low
4	Modifier Krill Herd (MKH) and Fuzzy Logic Controller (FLC) [74]	Grid Connected	V_{PV} and I_{PV}	Fast	High	99.32	High
5	Adaptive Neuro Fuzzy Inference System (ANFIS) [75]	Grid Connected	V_{PV} and I_{PV}	Fast	Medium	99.56	Medium
6	Adaptive Calculation Block and Fuzzy Logic Controller [76]	Stand alone	T, G V_{PV}	Fast	High	99.9	Medium
7	Hybrid Fuzzy Logic Controller (Approximation and Accurate Adjustment) [71]	Battery charger	I_{PV}	Fast	Very high	98.6	Low
8	Hybrid Fuzzy Logic Controller and Perturb and Observe (P&O) [77]	Grid Connected	V_{PV} and I_{PV}	Fast	High	98.50	Medium
9	Hybrid Fuzzy Logic Controller and Perturb and Observe (P&O) [78]	Stand alone	V_{OC}, I_{SC}, I_{PV} and V_{PV}	Fast	High	99.90	Medium
10	Grey Wolf Optimisation (GWO) and Fuzzy Logic Controller (FLC) [79]	Grid Connected	V_{PV} and I_{PV}	Medium	High	99.99	High
11	Grasshopper Optimised Fuzzy Logic Control (GO-FLC) [1]	Stand alone	V_{PV} and I_{PV}	Fast	High	99.79	Low

A hybrid PSO MPPT algorithm that can achieve an efficiency up to 100%, which is a combination of the MPPT PSO-FLC algorithm and the PSO-OCC algorithm. Two MPPT algorithm combinations, SMC-PSO and PSOFLC, are the most accurate on the basis of the accuracy perspective. In terms of tracking speed, the LF-PSO and PSO-FLC algorithms are the fastest. When it comes to implementation costs, the combined PSO-FLC algorithm and ABF-PSO algorithm are the most expensive, whereas the PSO-SSO algorithm is the least expensive.

Table 4: Comparison of the performance of the MPPT particle swarm optimisation (PSO) algorithm and its combination under PSCs

No	MPPT Techniques	Application	Sensor Parameter	Tracking Speed	Tracking Accuracy	Efficiency %	Complexity
1	Levy Flight (LF) and Particle Swarm Optimisation (PSO) [80]	Stand alone	V_{PV} and I_{PV}	Fastest	High	99.50	Medium
2	Tunicate Swarm Algorithm (TSA) and Particle Swarm Optimisation (PSO) [81]	Stand alone	V_{PV} and I_{PV}	Fast	High	97.64	Medium
3	Sliding Mode Controller (SMC) and Particle Swam Optimisation (PSO) [82]	Stand alone	V_{PV} and I_{PV}	Fast	Highest	96.40	Medium
4	Particle Swarm Optimisation (PSO) and Fuzzy Logic Controller (FLC) [83]	Grid Connected	V_{PV} and I_{PV}	Fastest	Highest	100	High
5	Particle Swarm Optimisation (PSO) and Salp Swarm Optimisation (SSO) [84]	Charging battery	V_{PV} and I_{PV}	Fast	High	99.52	Low
6	Grey Wolf Optimisation and Particle Swarm Optimisation (GWO–PSO) [85]	Stand alone	V_{PV} and I_{PV}	Fast	High	99.97	Medium
7	Hybrid Series Salp Particle Swarm Optimisation (SSPSO) [86]	Charging battery	V_{PV} and I_{PV}	Fast	Highly	99.99	Medium
8	Adaptive Butterfly Practical Swarm Optimisation (ABF-PSO) and Perturb and Observe (P&O) [87]	Stand alone	V_{PV} and I_{PV}	faster	High	99.43	High
9	Particle Swarm Optimisation with One Cycle Control (PSO-OCC) [45]	Stand alone	V_{PV} and I_{PV}	Fast	High	100	Medium

Table 5: Comparison of the performance of the MPPT artificial neural network (ANN) algorithm and its combination under PSCs

No	MPPT Techniques	Application	Sensor Parameter	Tracking Speed	Tracking Accuracy	Efficiency %	Complexity
1	Artificial Neural Network (ANN) with Modified Perturb and Observation (MP&O) [88]	Stand alone	V_{PV}, I_{PV} and V_{out_conv}	Fastest	High	99.87	Low
2	Artificial Neural Network (ANN) with PI Controller [89]	Stand alone	Ir, T, I_{PV} and V_{PV}	Fast	High	99.56	Medium
3	Artificial Neural Network (ANN) Plus Proportional Integral (PI) Controller [90]	Stand alone	V_{PV}, I_{PV}, T and G	Fast	High	94.50	High
4	Hybrid SFL–PS Algorithm-based Neural Network with Perturb and Observe (HSFL–PS–ANN–P&O) [91]	Grid Connected	V_{PV}, I_{PV}, T and G	Fast	High	99.26	High
5	Artificial Neural Network (ANN) and Perturb and Observe (P&O) [92]	Stand alone	V_{PV} and I_{PV}	Fast	High	98.93	High

In comparison with the other possible combinations of ANN algorithms, the MPPT algorithm combined with ANN-P&O has the fastest tracking speed. This combination of algorithms incurs low cost in terms of the cost required for accurate implementation and performs more effectively. The use of the ANFIS algorithm obtains an efficiency value of up to 99.88% by employing a measuring sensor with fewer parameters than others. The ANFIS algorithm also has the highest speed and the best accuracy.

Table 6: Comparison of the performance of the MPPT adaptive neuro fuzzy inference system (ANFIS) algorithm and its combination under PSCs

No	MPPT Techniques	Application	Sensor Parameter	Tracking Speed	Tracking Accuracy	Efficiency %	Complexity
1	Adaptive Neuro Fuzzy Inference System (ANFIS) and Artificial Bee Colony (ABC) [93]	Grid connected	V_{PV}, I_{PV}, V_G and I_G	Fast	High	98.39	High
2	Adaptive Neuro Fuzzy Inference System (ANFIS) and Particle Swarm Optimisation (PSO) [94]	Grid connected	V_{PV} and I_{PV}	Fast	High	98.35	High
3	Hybrid Crow-Pattern Search Approach-based ANFIS [95]	Grid connected	V_{PV}, I_{PV}, T and G	Fast	High	99	High
4	Adaptive Neural-Fuzzy Inference System (ANFIS) [96]	Stand alone	V_{PV}, I_{PV}, T and G	Fastest	Highest	99.30	High
5	Adaptive NeuroFuzzy Inference System (ANFIS)-based MPPT controller [97]	Stand alone	T and G	Fast	High	99.88	Medium
6	Adaptive Neuro Fuzzy Inference System ANFIS [75]	Grid connected	V_{PV} and I_{PV}	Fast	Medium	99.56	Medium

The following MPPT algorithm methods can be recommended on the basis of the criteria for selecting a superior MPPT method: high tracking speed and precision, high efficiency and low cost.

a. The MPPT enhanced adaptive step size P&O and modified P&O algorithms have the highest efficiency (100%) with the lowest implementation complexity and good tracking speed and accuracy and can be implemented for stand-alone and grid-connected applications.
b. In terms of efficiency, the InC-FLC algorithm has the highest efficiency (100%) but requires more funding because of its high complexity and more sensors used. Therefore, the algorithms modified INC, InC-DFO and NAS-InC are recommended. Although their efficiency is lower than that of InC-FLC, they are superior to InC-FLC in terms of tracking speed and accuracy whilst requiring less funding.
c. The hybrid fuzzy logic controller (approximation and accurate adjustment) algorithm and the GO-FLC algorithm are less expensive, have higher efficiency and use fewer sensors.
d. PSO-FLC, PSO-OCC, LF-PSO and SSPSO algorithms are the most recommended combination of PSO algorithms. In addition to a high efficiency value, each of them has excellent tracking speed and accuracy, as well as lower costs.
e. The ANN-MP&O algorithm also has a lower cost with better tracking speed.
f. In terms of cost, the ANFIS algorithm has better performance with high tracking speed and accuracy.
g. Out of all the different algorithms that have been investigated, the authors suggest using the MPPT SSA and P&O, enhanced adaptive step size P&O, NAS-InC, IBA-FLC and PSO-OCC. All of these algorithms can be categorised as having a medium

level of implementation complexity. That is, they are all low-cost and highly efficient and can even reach 100% tracking speed and accuracy with the fewest number of sensors.

4. Conclusions

Researchers have developed various MPPT algorithms and methods to obtain high efficiency values, allowing them to convert as much solar energy as possible into electrical energy. The conducted literature review presents various MPPT algorithms and methods that are designed and applied to stand-alone and grid-connected photovoltaic systems to reduce the effects of PSCs. The review results provide detailed comparisons of tracking speed, accuracy, efficiency and implementation complexity, allowing for an analysis of the costs that will be incurred.

According to the studies and discussions conducted, five algorithms are recommended in consideration of their effectiveness of up to 100%: the NAS-InC, LF-PSO, PSO-FLC, ANN-MP&O and ANFIS algorithms. These algorithms are acknowledged to have the best performance over the other algorithm in terms of tracking speed. In terms of precision, the SMC-PSO, PSO-FLC and ANFIS algorithms are superior. Modified drift-free P&O, P&O based on the trapezoidal rule, GWO-FLC, hybrid FLC (approximation and accurate adjustment), GO-FLC, PSO-SSO and ANN-MP&O have lower financing than the other algorithms.

Overall, the researchers recommend the MPPT SSA and P&O, enhanced adaptive step size P&O, NAS-InC, IBA-FLC and PSO-OCC algorithms.

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