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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 is 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 algorithm to overcome partial shading conditions in terms of tracking speed, tracking accuracy, efficiency, and implementation complexity. As the results, some algorithms are recommended to be applied for Maximum Power Point Tracking including the Single Swam Algorithm and the Perturb And Observer 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 Optimization with One Cycle Control algorithm. In terms of implementation complexity, these five algorithms are categorized as medium-complexity, which can be characterized as low cost, high efficiency, and even 100% with 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]. Where 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, temperature, the conversion system, control algorithms, and the type of load [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).

Standard Test Conditions (STC) the PV system receive normal radiation. However, when PV is installed in the field, it exhibits non-linear characteristics due to unequal solar radiation reception, particularly when shading occurs. This 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. Aside from that, the emergence of hotspots is another phenomenon

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that occurs when PV works when shading occurs even 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, there is a specific point known as the Maximum Power Point (MPP) where the solar energy extraction efficiency can be maximized 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 Maximum Power Point 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 different solar radiation conditions or PSCs (non-uniform) [7].

Several MPPT methods have been developed and presented in various literatures including Perturb and Observer (P&O), Hill Climbing, Incremental Conductance (INC), INC with Direct Duty Cycle, Fractional Short Circuits Current (FOCC), Fractional Open Circuits Voltage (FOCV) and Ripple Correlation (RC) [8]–[13]. The P&O and INC methods are the most fundamental types of MPPT techniques. They have been widely used and developed up until this point due to the simple qualities that they possess. Additionally, these methods are more cost-effective in terms of both their application and their price, despite the fact that they have some drawbacks. [14], [15]. The Partial Shading Conditions (PSCs) were the impetus behind the creation of the MPPT algorithm, which was designed to improve not only the speed and accuracy of tracking but also the overall effectiveness of the system. Some of them include the MPPT Ant Colony Optimization (ACO) method [16]–[19], the Gray Wolf (GW) method [20]–[24], the Artificial Bee Colony (ABC) method [25]–[29], the Genetic Algorithm (GA) method [30]–[32], the Particle Swam Optimization (PSO) method [33]–[37], the Fuzzy Logic Controller (FLC) [38]–[40] and Artificial Neural Network (ANN) [41]–[44]. However, in order to select the MPPT method or algorithm that will be used, there are a few things that need to be taken into consideration. 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 need to be incurred [45]–[47].

A very significant problem is how to properly track GMPP points even in extreme weather conditions where conventional MPPT methods are ineffective as they may be trapped in LMPPs [48].

Utilizing an optimization algorithm (hybrid) is one of the more pragmatic approaches that can be considered to track GMPP when PSCs occur [49], [50]. As a result, the primary emphasis of this paper is placed on the investigation of MPPT optimization strategies for the purpose of addressing the challenges posed by the occurrence of PSCs. Specifically 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. Consequently, the expected contribution of this paper can take the form of important information about the MPPT method that satisfies the criteria for tracking speed, accuracy, efficiency, and cost embedded for PSCs conditions for the next researcher or other relevant parties.

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

2. Methodology

Articles or reading materials that are reviewed in this paper 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 article used as a review contains 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 obtaining all the articles, selection or filtering is performed in accordance with the criteria specified in the MPPT algorithm selection, which discusses tracking speed, tracking accuracy, efficiency, and implementation complexity. The articles used in the literature review are the result of the selection process. There are a total of 174 articles obtained from 13 websites that contain mentions of keywords determined during the initial screening. However, after performing detailed screening and selection in accordance with the specified conditions, the number of articles that met the criteria was 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.

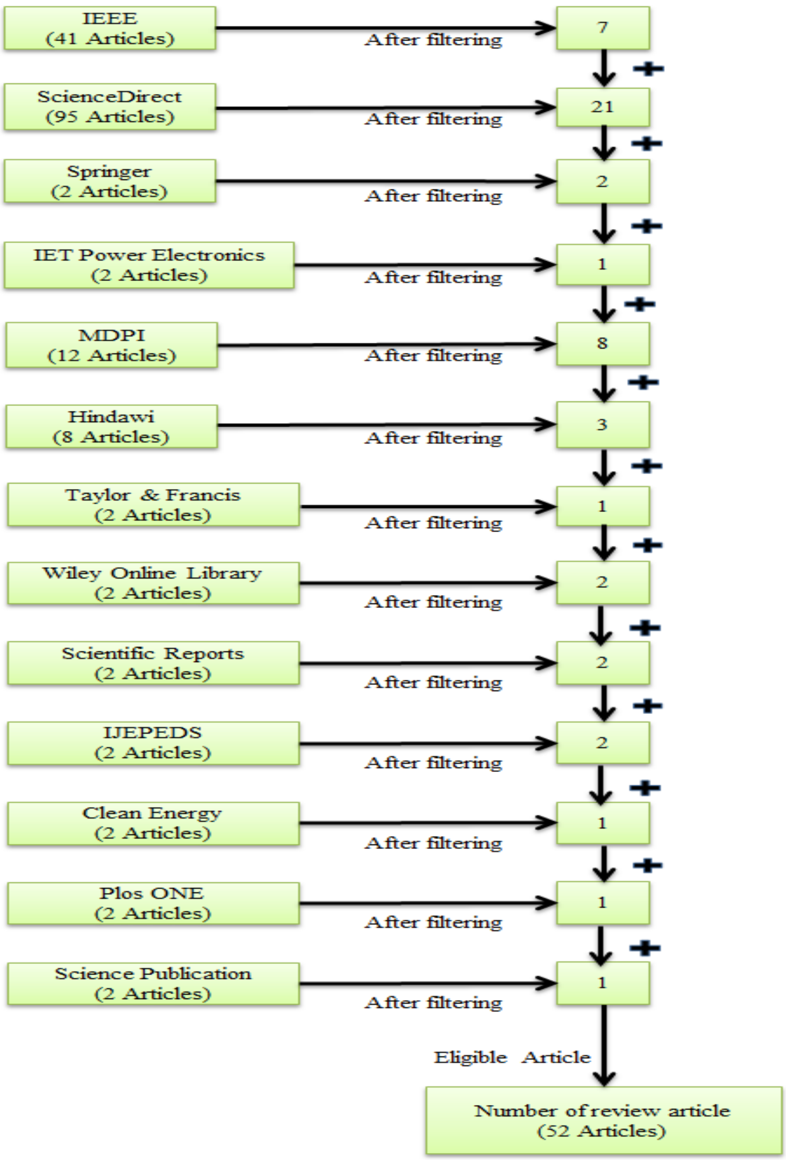

Figure 1. Number of articles used in the literature review process

3. Results and discussion

The purpose of the MPPT algorithm is to increase the efficiency of converting solar energy into electrical energy. When selecting and designing the MPPT algorithm, several factors must be considered, including tracking speed, accuracy, implementation efficiency, and implementation complexity. 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 partial shading (PSCs). Due to 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 point is unsuccessful. Utilizing an optimization algorithm also known as the Hybrid Optimization MPPT method is one solution. The results of the study of the hybrid optimization MPPT algorithm under partial shading conditions are displayed in tables 1 through 6.

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

Table 1: The comparison of the performance of the MPPT Perturbe and Observer (P&O) algorithm and its combination under PSCs conditions

No	MPPT techniques	Appilcation	Sensor parameter	Tracking speed	Tracking accuracy	Efficiency %	Complexity
1	Pertube 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 Observer (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 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 since 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%. Meanwhile, 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. Meanwhile, the Modified Drift Free P&O MPPT and P&O Algorithm Based on Trapezoidal Rule algorithms have low implementation complexity.

Table 2: The comparison of the performance of the MPPT Incremental Conductance (InC) algorithm and its combination under PSCs conditions

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 Optimization Algorithm (GOA) [68]	Stand alone	V_{PV} and I_{PV}	Fast	High	93.70	High
9	Incremental Conductance (InC) and Dragonfly Optimization (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%, while the MPPT InC-GOA algorithm has the lowest, at 93.70%. Meanwhile, 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 the GWO-FLC algorithms, has the highest efficiency of 99.99% but the slowest tracking speed when compared to other algorithms. Some FLC hybrid algorithms, such as the combination of the 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: The comparison of the performance of the MPPT Fuzzy Logic Controller (FLC) algorithm and its combination under PSCs conditions

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	Improve 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 Optimization (GWO) and Fuzzy Logic Controller (FLC) [73]	Stang 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]	Stang 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 Pertube and Observer (P&O) [77]	Grid Connected	V_{PV} and I_{PV}	Fast	High	98.50	Medium
9	Hybrid Fuzzy Logic Controller and Pertube and Observer (P&O) [78]	Stang alone	V_{OC}, I_{SC}, $I_{PV,}$ and V_{PV}	Fast	High	99.90	Medium
10	Gray Wolf Optimization (GWO) and Fuzzy Logic Controller (FLC) [79]	Grid Connected	V_{PV} and I_{PV}	Medium	High	99.99	High
11	Grasshopper Optimized Fuzzy Logic Control (GO-FLC) [1]	Stang alone	V_{PV} and I_{PV}	Fast	High	99.79	Low

In addition, there is 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 PSO-FLC, are the most accurate based on 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, while the PSO-SSO algorithm is the least expensive.

Table 4: The comparison of the performance of the MPPT Particle Swarm Optimization (PSO) algorithm and its combination under PSCs conditions

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

Table 5: The comparison of the performance of the MPPT Artificial Neural Network (ANN) algorithm and its combination under PSCs conditions

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 Pertube and Observer (P&O) [92]	Stand alone	V_{PV} and I_{PV}	Fast	High	98.93	High

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

Table 6: The comparison of the performance of the MPPT Adaptive Neuro Fuzzy Inference System (ANFIS) algorithm and its combination under PSCs conditions

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 Optimization (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 based on 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 Perturb and Observe (P&O) and Modified P&O algorithms have the highest efficiency (100%) with the lowest implementation complexity, good tracking speed and accuracy, and can be implemented for both stand-alone and grid-connected applications.
b. In terms of efficiency, the InC-FLC algorithm also has the highest efficiency (100%) but requires more funding due to its high complexity and more sensors used. Therefore, the algorithms Modified Incremental Conductance, InC-DFO, and NAS-InC are recommended. Even though the algorithm's efficiency is lower than InC-FLC, it is superior to InC-FLC in terms of tracking speed and accuracy while 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 also better performance with high tracking speed and accuracy
g. Out of all the different algorithms that have been investigated, the author suggests 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 categorized as having a medium level of implementation complexity.This means that they are all low-cost, highly efficient, and can even reach 100% tracking speed and accuracy with the fewest number of sensors.

4. Conclusions

Researchers have developed a variety of 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 conditions. 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, there are five algorithms that are recommended due to their effectiveness of up to 100% including The NAS-InC, LF-PSO, PSO-FLC, ANN-MP&O, and ANFIS algorithms. These algorithms are acknowledged to have the best performance to the other algorithm in terms of tracking speed. Meanwhile, in terms of precision, the SMC-PSO, PSO-FLC, and ANFIS algorithms are superior. Modified Drift Free P&O, P&O Based 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.

But 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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