Review

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A Comprehensive Review of Maximum Power Tracking Techniques for Photovoltaic Systems

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Review

A Comprehensive Review of Maximum Power Tracking Techniques for Photovoltaic Systems

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Abstract

Various maximum power point tracking (MPPT) techniques have been proposed to optimize the efficiency of solar photovoltaic (PV) systems. These techniques differ in several aspects such as design simplicity, convergence speed, implementation types (analog or digital), decision optimal point accuracy, effectiveness range, hardware costs, and algorithmic modes. Choosing the most suitable MPPT controller is crucial in PV system design as it directly impacts the overall cost of PV solar modules. This paper presents a comprehensive exploration of 65 MPPT techniques for PV solar systems, covering optimization, traditional, intelligent, and hybrid methodologies. A comparative analysis of these techniques, considering cost, tracking speed, and system stability, indicates that hybrid approaches exhibit higher efficiency albeit with increased complexity and cost. Amidst existing PV system review literature, this paper contributes serves as an updated comprehensive reference for researchers involved in MPPT PV solar system design.

Keywords: convergence speed; photovoltaic (PV); renewable energy; system efficiency; maximum power point tracking (MPPT); maximum power point (MPP)

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1. Introduction

Globally, the escalating demand of electricity has spurred researchers to focus on developing clean and highly efficient electrical power sources, considering both production and cost [1,2]. The adverse environmental impacts of fossil fuel-fired power plants emphasize the urgent need to transition towards sustainable and secure renewable energy alternatives [3,4]. Hybrid models of generating electricity generation have emerged as promising solutions, offering enhanced system reliability [5,6]. However, the intermittent nature of renewable energy sources, such as wind and solar, alongside fluctuating weather conditions, poses challenges to consistent stability [7,8]. In addition, solar photovoltaic (PV) modules, reliant on solar panels and integrated systems to harness solar energy, encounter limitations in extracting maximum power [9,10].

To address these challenges, various mechanisms are employed to track the maximum power point (MPP) in PV systems, given the variation in irradiance and temperature [11]. Achieving the MPP, a crucial determinant of the output power (P_{out}) in PV systems, necessitates the continuous tracking of the operating point, a task entrusted to the maximum power point tracking (MPPT) algorithms [12]. MPPT facilitates optimal power extraction from PV systems by dynamically adjusting parameters to match the impedance [13,14].

One of the main difficulties associated with the MPPT algorithms; pertains to voltage monitoring and duty ratio variation when aiming to achieve the PV maximum output power (P_{max}) from the PV system. Figure 1 and Figure 2 illustrate variations in voltage (V), current (I), and power (P) in a conventional solar panel in response to changes in irradiance and temperature [11,15]. As can be seen

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in Figure 1, the temperature variations impact the V_{out} as compared to I_{out}, while Figure 2 demonstrates the influence of irradiance on the I and V of a PV system.

Accordingly, the PV panel's Pout also varies [16]. In addition, the I-V curve is never identical if under full irradiance or at partial sun shading, as Vout and PV power (PPV) change with variations in irradiance and temperature [17,18].

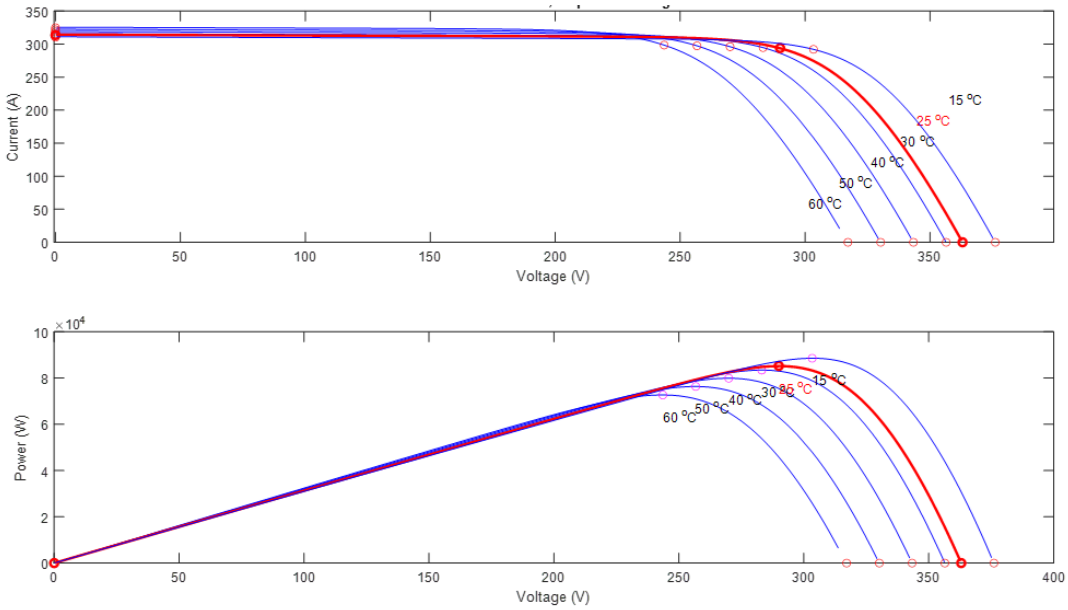

Figure 1. I-V and P-V characteristics at different temperature levels.

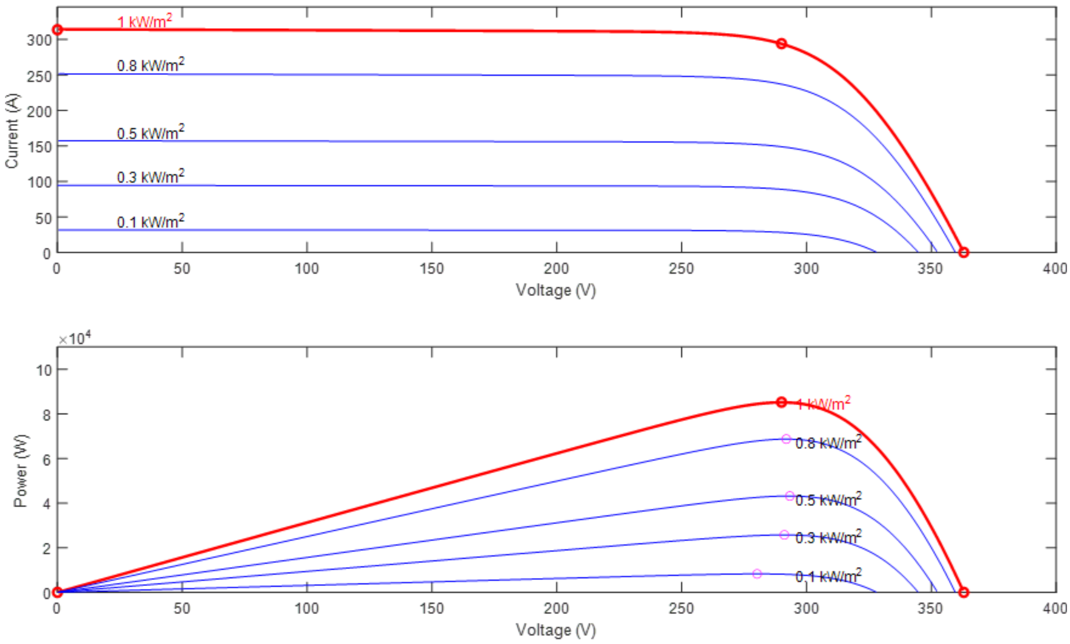

Figure 2. Characteristic curves at different irradiances.

This paper aims to provide a comprehensive review of prevalent MPPT techniques published in the recent literature and currently employed in industry practices [19]. The main contributions of this paper can be summarized as under:

- Classification of MPPT algorithms based on their efficiency, accuracy, cost, convergence speed, and complexity using multi-criteria decision-making algorithm.
- Evaluate the efficiency performance of each MPPT technique.
- Compare PV applications' dependency on the MPPT technique.

- Distinguish MPPT accuracy based on their precision to reach the peak point.
- Illustrate the parameters influencing the MPPT algorithms.

2. Novel Classification of MPPT Methods

In this section, we present a novel way of classifying more than 70 different MPPT methods into a single figure stating the different tracking methods and comparing many criteria such as (1) complexity, (2) convergence speed, (3) accuracy, (4) cost, and (5) efficiency as presented in Figure 3. The letters represent the MPPT method, as an example AZM stands for Azab Method. While the numbers represent the criteria as mentioned above. The number in green circle (1) represents an advantage, such as low cost, high efficiency, etc. The number in red color (1) represents a moderate value, such as medium cost, moderate efficiency. While the number in black circle (1) represents a disadvantage, such as high cost, and low efficiency. By arranging and comparing the five above mentioned criteria of the MPPT algorithms into a single figure, it becomes much easier to select the method that meets specific requirements. As an example, if we want to select an algorithm that has a low cost, high accuracy, and medium efficiency, we look for the numbers that have the following sequence color: 3 4 5. Then, from the figure, we try to find the algorithms that have the closest performance. In this case, it is the AM (Analytic method) algorithm.

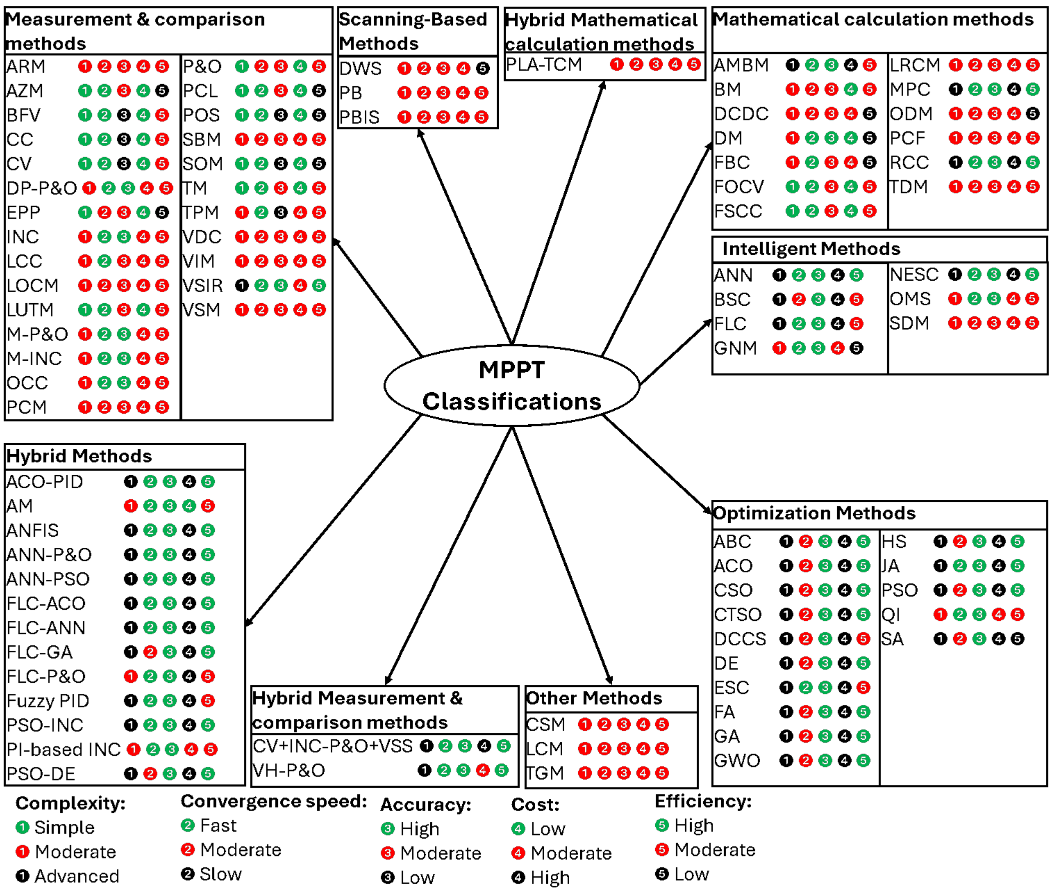

Figure 3. Classification of MPPT Techniques

For an advanced selection of the appropriate MPPT methods for very specific applications with strict requirements and criteria. We propose a novel multi-criteria decision-making optimization algorithm named Rank-Weigh-Rank (RWR) to rank and select the best MPPT method for specific applications considering many criteria and weighting factors. The main goal of the proposed optimization algorithm is to help decision-makers to select the best MPPT method that meets their requirements and specifications. The algorithm is described in Figure 4, in which it is mainly divided into three sections. The first section is to collect MPPT methods data such as the efficiencies, accuracies, convergence

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speed, etc. Then, associate criterion for each required dataset. The second section sorts and ranks the criteria in descending order. In addition, weighting factors are associated with each criterion in order to provide different weights for each criterion depending on its importance in the decision making and selection. The third section is used to calculate the average rank of each attribute (MPPT method). Then, the algorithm sorts all attributes based on their final ranking in order to help the decision-makers to select the best MPPT method that meets their expectations.

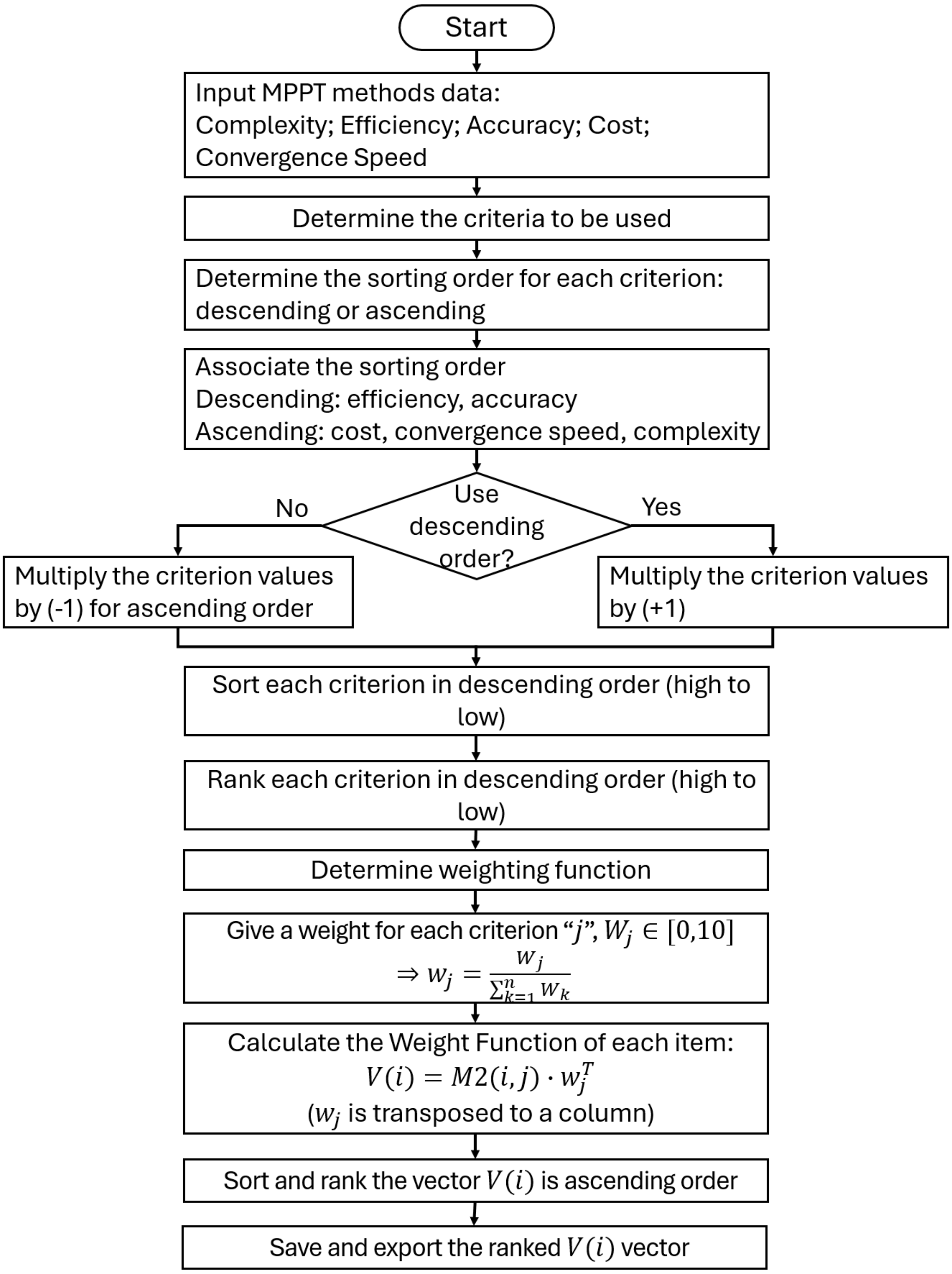

Figure 4. Proposed multi-criteria decision-making optimization algorithm for ranking, sorting and selecting the best MPPT methods for specific applications

For the purpose of visualizing the importance of the proposed optimization algorithm for selecting the best MPPT methods, two examples will be presented considering different weighting factors for the attributes. For simplicity, 20 different MPPT methods are chosen and compared, which are: ARM,

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AZM, BFV, DP-P&O, EPP, INC, LOCM, LUTM, ACO-PID, AM, ANFIS, ANN-P&O, FLC-GA, FLC-P&O, Fuzzy PID, PSO-INC, PI-based INC, CSM, ANN, and PCL.

For the first example, we are more interested in having a high convergence speed, high accuracy, low cost and high efficiency. By supplying our preferences to the algorithm, the AM method is considered as the best option among all other methods as presented in Figure 5.

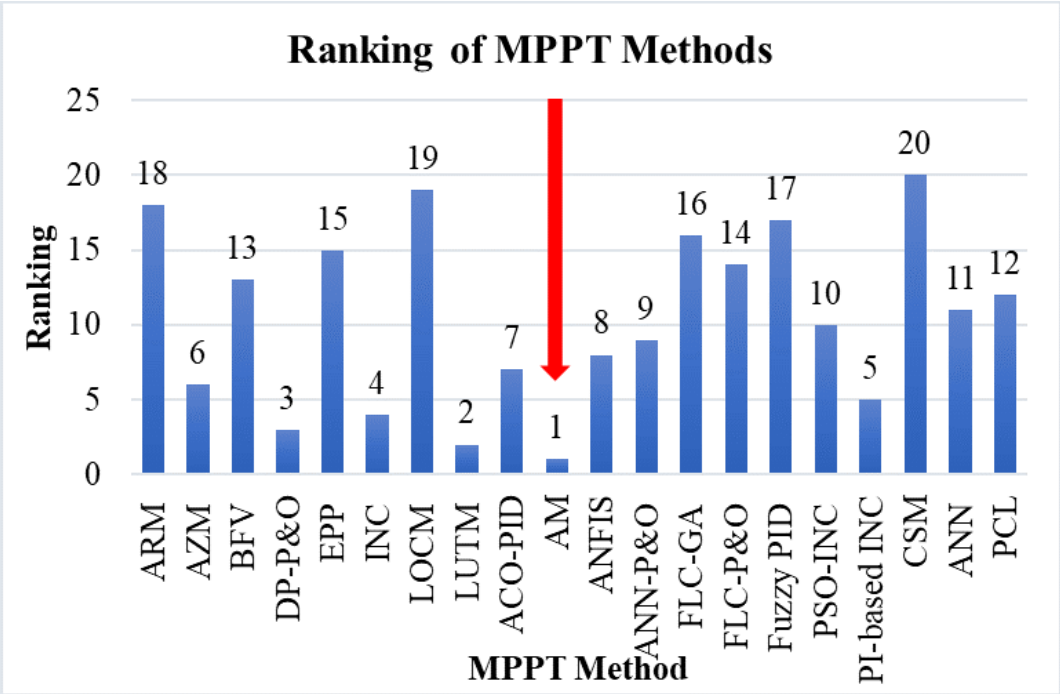

Figure 5. Selection of the best MPPT method considering weighting factors of example 1

For the second example, we are more interested in having a high efficiency and low cost MPPT method, with less consideration to other factors. By supplying our preferences to the algorithm, the LUTM method is considered as the best option among all other methods as presented in Figure 6.

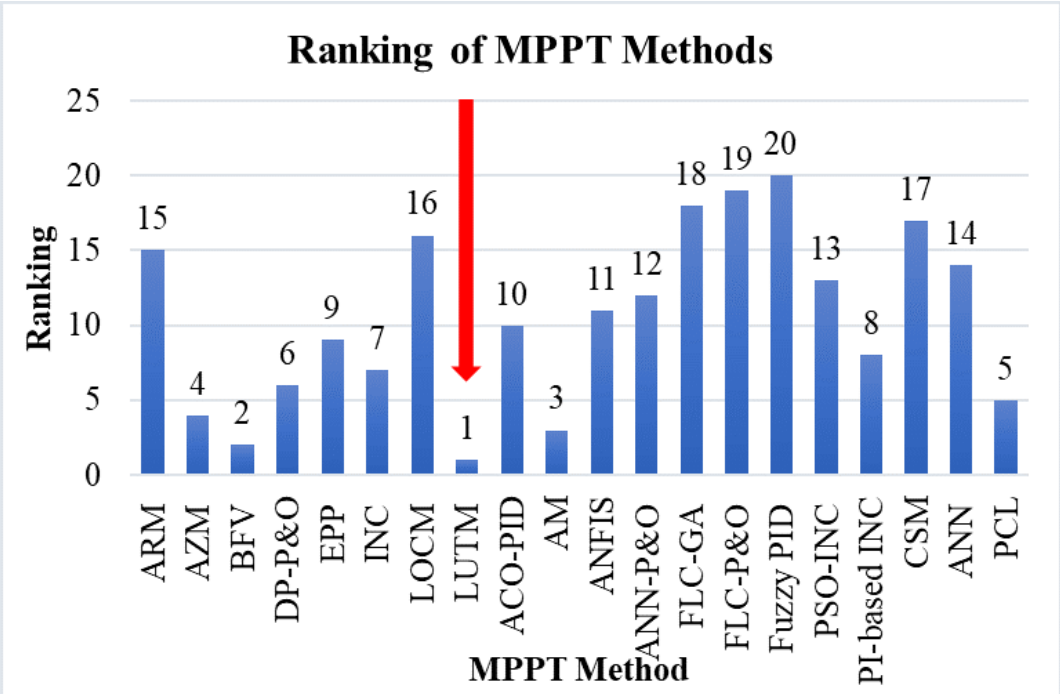

Figure 6. Selection of the best MPPT method considering weighting factors of example 2

3. Scanning-Based MPPT Algorithms

An essential component of the scanning-based method is the utilization of iterative decremented step-size scanning-based MPPT algorithms [20].The variability in partial shading circumstances presents a major issue in photovoltaic structures. The power curves of these structures do not only feature a global maximum power point but also several local maximum power points [21–25].

Furthermore, these curves are subject to alterations based on climates environment, which have a direct influence on the partial shading settings [26–29]. To address this challenge, three iterative scanning-based MPPT algorithms have been introduced: decremented window scanning, peak bracketing (PB) method, and PB with initial scanning [30–33].

3.1. Decremented Window Scanning (DWS)

DWS is an algorithm employed to track the global MPP of a PV system by progressively decreasing the scanning domain range in each iteration. The duty cycle percentage of the pulse signal for the DC/DC converter is used as the unit for the scanning domain, while the converter's output power is measured in Watts as the co-domain unit [30]. By dividing the scanning domain into ND number of scan points, an equivalent number of domain segments is established [34]. A segmented domain with the MPP within its range is then chosen as the new decremented scanning domain. Through a process of iteratively identifying and decreasing segmented scanning domains, the optimal perturbing duty cycle, which leads to the global peak power point, is ultimately determined [35–37].

3.2. Peak Bracketing (PB)

The PB algorithm employs a bisection method to trace the global maximum power point. This is achieved when the peak power point is being bracketed with three duty cycle points denoted as follow: a left duty cycle point, a right duty cycle point, and a center duty cycle point [30,38]. Through iterative reduction of the searching domain, the algorithm identifies the ultimate perturbing duty cycle point that corresponds to the global MPP [33,39,40].

3.3. Peak Bracketing with Initial Scanning (PBIS)

The PBIS is developed as a combination of the DWS and PB algorithms, which is specifically designed to decrease the cycling periods associated with locating the global maximum power point (GMPP). The initial step involves the implementation of the DWS algorithm to identify a segmental reductional window scanning. Subsequently, the PB algorithm is applied to identify the optimal perturbing duty cycle point (D), which ultimately leads to the discovery of the GMPP [30,32,41].

4. MPPT Intelligent Control Techniques

4.1. Neural Network

Deep learning suites are rooted in a specific branch of machine learning called neural networks, which are also referred to as artificial neural networks (ANNs) or in many literatures is being known as simulated neural networks (SNNs). These networks are designed to mimic the structuring and functioning of the human brain, replicating the intricate communication patterns observed in real neurons. In general, the neural network consists of different sets of layers. Three layers are commonly used as shown in Figure 7; input, output, and hidden layers. At each layer the nodes number can vary where it's user dependent. Input variables are selected for photovoltaic system parameters such as irradiance, temperature I_{SC}, V_{OC} or any combination of those [42–45]. Whereas an output selection may be selected such as, duty cycle. As per hidden layer this can be related to the distance of an operating point is getting towards the MPP and how effective is a neural network trained. Note that all links are using a weight. As an example, nodes i and j link has W_{ij}link as shown in [46]. The term W_{ij} is determined to be as accurate as possible using a training process, to precisely detect the MPP.

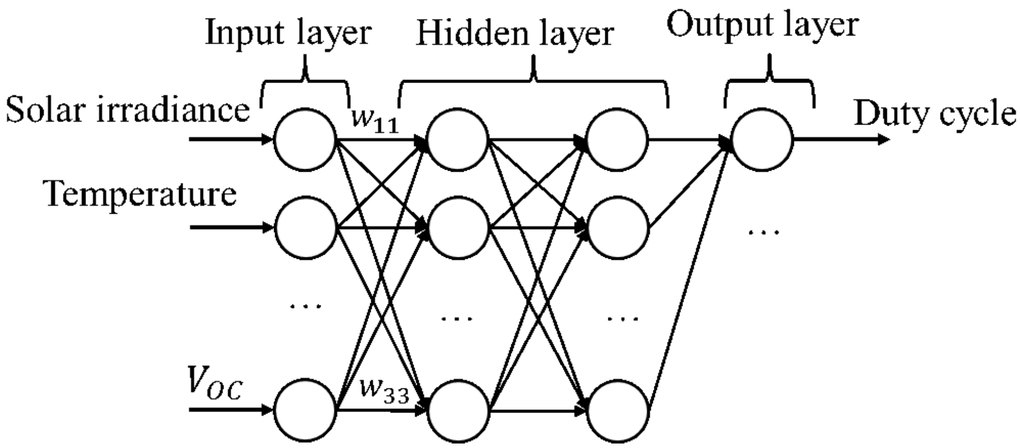

Figure 7. The structure of an Artificial Neural Network for MPPT

4.2. Fuzzy Logic Controller (FLC)

FLC is well applied in PV systems especially in dealing with imprecise inputs. Further, it does not need to be based on a precise model of the model or an exact mathematical model which is able to cope with non-linearity systems issues [47–49]. It can also obtain MPPT under varying climatic and environmental conditions. It entails four different sections; fuzzification, inference engine, rule-base and defuzzification. Where a numerical value at the input is transformed to linguistic variable constructed using Membership Functions (MF) [49], as shown in Figure 8. Where five membership functions are used, FLC in an MPPT scenario has two inputs and an output. There are two input variables denoted as the error (E) and change of error (E), at sampling time k. Following equations show these inputs [50–53].

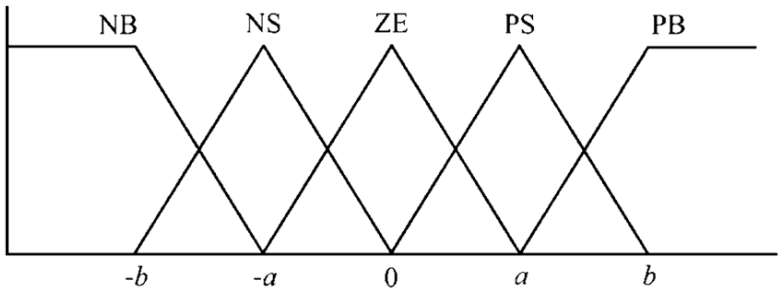

Figure 8. MF in a fuzzy logic [50,51].

$$E(K) = \frac{P_{PH}(K) - P_{PH}(K-1)}{V(K) - V(K-1)} \quad (1)$$

$$\Delta E(K) = E(K) - E(K-1) \quad (2)$$

From Eq. (1) we can conclude whether the operation point at a k instant is either at the right or left of the MPP of a PV curve k is situated at either the right or left sides of MPP on P-V curve. Equation's 2 input articulates the direction's move for P-V curve's operating point [54,55].

4.3. Artificial Neural Network (ANN) Based on the Technique of Perturb & observe (P&O)-MPPT

The role of the ANN is to predict the power value in the subsequent cycle. There is an observed difference between ANN output value and the power measured [56–59]. Thus this is applicable in changing step-value of the next cycle by applying Eq. (3);

$$\Delta V_{i+1} = k\frac{\Delta P_r}{\Delta V_i} f(I_r/I_p) \quad (3)$$

where; ΔV_{i+1} is the perturbation step at ith cycle, k is a constant, is the reel power, is a function of inputoutput characteristic, is the reel current, and is the predicted value.

4.4. Gauss-Newton Method

Gauss-Newton method is a fast mechanism as compared to P&O. It applies the 1st and 2nd derivatives of parameter value changes in an attempt to approximate the distance and direction of a program shall go through to approach enhanced point. Calculation of operating point in tracking MPP, is shown in Eq. (4) [60–68].

$$V_{K+1} = V_K - \frac{\frac{dp}{dv}\big|_{V=V_K}}{\frac{d^2p}{dv^2}\big|_{V=V_K}} \tag{4}$$

where dp/dv is the power derivation.

4.5. Steepest-Descent Method

The steepest-descent method is used to search for the closest local MPP under the condition where a function's gradient is calculated. MPPT tracking is shown by Eq. (5).

$$V_{K+1} = V_K - \frac{\frac{dp}{dv}\big|_{V=V_K}}{K_\epsilon} \tag{5}$$

Knowing that K_ϵ value will determine the steepness of each step which is taking gradient direction. Power derivation computed as follows;

$$\frac{dP}{dV} = F(V, P) \tag{6}$$

$$F(V_K, P_K) = \frac{P_{K+1} - P_{K-1}}{2\Delta V} + O(\Delta V^3) \tag{7}$$

where $O(\Delta V^3)$ is the local truncation error which is considered for center differentiation, that designates 2nd order accuracy. Controllers required to search for a point where $F(V, P)$ is equal to zero in an MPPT context [69–72].

4.6. Newton-Like Extremum Seeking Control Method

To ensure the practicality of a MPPT control system, it is often necessary to have control over the convergence of the controller. This requirement can be met by employing the Newton-based extremum seeking approach. When equipped with knowledge of the power map, the Newton optimization algorithm can be utilized to successfully identify the maximum power point. It utilizes panel characteristic's gradient and Hessian in estimating the operating point's optimal value, and requiring from the side of Hessian approximation of the P-V characteristic as shown in Figure 9 [73–76].

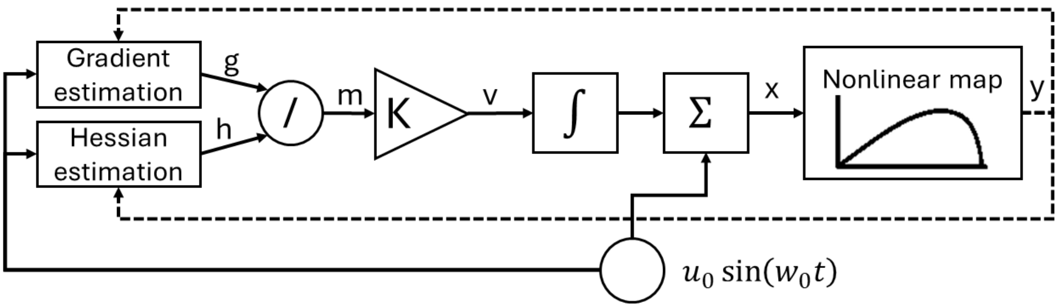

Figure 9. Block diagram representing Newton-Like extremum seeking control method.

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4.7. On-Line MPP Search Algorithm

On-line MPP search algorithm works on finding a reference value of maximum power, where a comparison with the current power is achieved as shown in Figure 10. This mechanism results in having a difference; named the maximum power error. Error shall stand around zero in-order of reaching MPP. When a referenced value for MPP changes because of changes in temperature or irradiance levels this method works on adjusting the voltage's array and search for another new MPP. When the power/current at load is lesser of that for MPP power this method cannot execute searching and regulate the MPP. More loads in this case are needed to be and get connected for increasing (Ipv) to allow the system to operate at MPP [78,79].

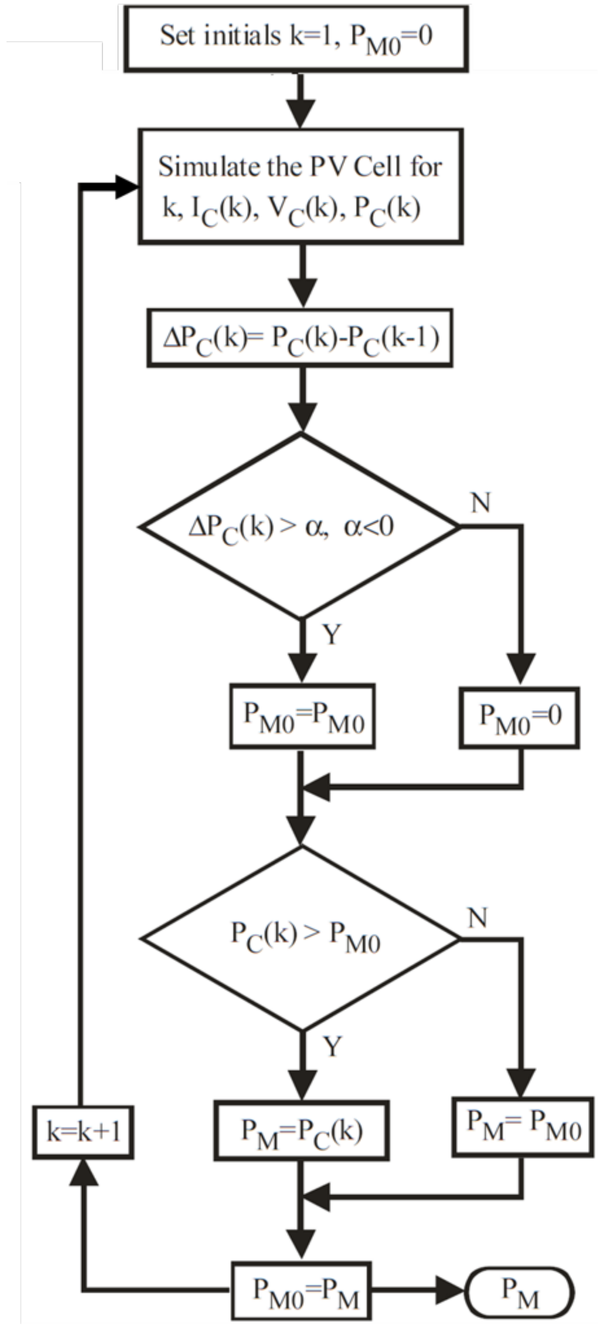

Figure 10. Flowchart of the On-line MPP search algorithm [77]

4.8. Particle Swarm Optimization (PSO) Algorithm

Decentralized schemes are at the core of swarm intelligence, an artificial intelligence technique that explores the study of collective conduct. Among the various paradigms within swarm intelligence,

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PSO has gained significant popularity. By simulating the social behavior observed in bird grouping, PSO has been developed as a worldwide optimization algorithm. This algorithm effectively addresses problems where the best solution is represented by a surface or point at an N dimensioning space.

In this sort of algorithms its primarily usage to increase the performance of MPPT. Every segment seen to be particle; whereas MPP assumed a drive move target. In this scenario a PV module can search for MPP as shown in Figure 11 [80–83].

The PSO algorithm's effectiveness and applications existing in numerous local MPPs. PSO uses a particle with a fitness and cost values assessed to be minimized by the function. Particles hover at the search space through the following of optimum particles. This technique relies on collaboration of multi agents, where they commit themselves in making an exchange of information resulted from their individual search process [49,84–86]. State of the algorithms shown in (8), and (9)

$$V_i^{K+1} = wV_i^k + c_1 r_1 (P_l X_i^{K+1^k} - X_l^k) + c_2 r_2 (P_g^k - X_l^k) \tag{8}$$

$$X_i^{K+1} = X_i^k + X_i^{k+1} \tag{9}$$

where V_i^{K+1} is the velocity of the particle, X_i^{K+1} is the particles' position, P_i^k is the best local position, P_g^k is the best global position, r_1 and r_2 are numbers randomly taken between [0–1], and c_1 and c_2 are learn factors.

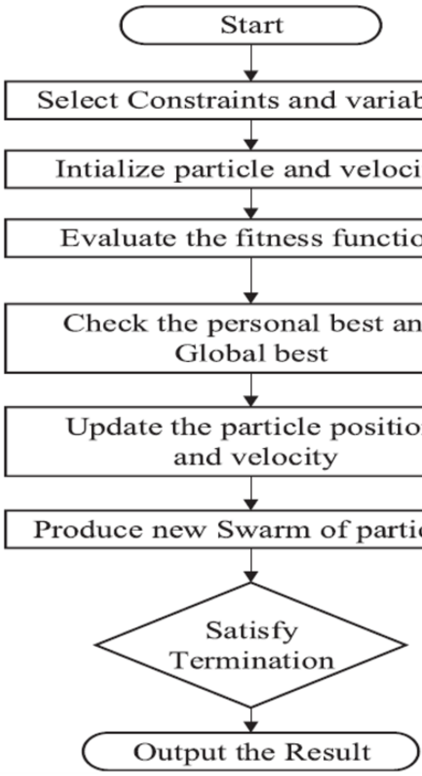

Figure 11. Flowchart of the PSO-based MPPT method [80]

5. Hybrid Intelligent Control Algorithms

5.1. Adaptive Neuro-Fuzzy Inference System (ANFIS)

The integration of artificial neural networks and fuzzy logic in a hybrid system has proven to be advantageous in various modeling and forecasting issues. This approach has found particular application in predicting the maximum power point (MPP) based on the exposure of Solar's data and neighboring temperature [87–89]. This method offers several benefits, including rapid response,

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non-invasive sampling, reduction of total harmonic distortion, improved utilization of photovoltaic system, and straightforward training of the ANFIS algorithm [90,91].

The neuro-fuzzy method plays a crucial role in the development of fuzzy expert scheme. However, it is essential to carefully select the rules, the total number, type sort, and other various parameters of the membership functions in the fuzzy system to achieve optimal performance [92,93]. Trial and error are often employed to fine-tune these settings and attain the minimal desired level of performance. This highlights the significance of configuring the fuzzy systems appropriately. ANFIS, as a Sugeno network embedded within adaptive systems, simplifies learning and training processes [94,95]. This framework enhances the systematic nature of models and leverages expert knowledge, thereby enabling non-experts to utilize the system effectively [96,97].

5.2. Hybrid Genetic Algorithmic

Among the various evolutionary algorithms, genetic algorithms hold a prominent position in research applications. This algorithm is highly effective in exploring complex solution spaces to identify optimal or near-optimal solutions. Genetic algorithms are commonly utilized in optimizing fuzzy controllers or neural networks for the management control of the Maximum Power Point (MPP) [98–103]. The fundamental concept guiding genetic algorithms is to replicate the principles of evolution theory, leading to the determination of an optimal parameter set through the application of the "survival of the fittest" principle [104–107].

5.3. Fuzzy-PID

The PID controller, an acronym for proportional integral differential controller, is a conventional controller widely employed in various control applications [108,109]. Its output is determined by three constants: one for the proportional term, one for the integral term, and one for the differential term. To tune the PID controller and determine the appropriate proportional, integral, and differential gains, several methods exist. Among these methods, the Ziegler-Nichols tuning formula is the most commonly used [110–112]. In control systems, there are directions addressed that involve the utilization of fuzzy logic and the PID block. One to entails employing the FL block as a tuning mechanism for the PID controller [110,113,114]. This allows for the online tuning of the PID controller using the fuzzy block. Additionally, a novel adaptive fuzzy PID controller has been introduced for maximum power point tracking. Through this method, the fuzzy block is utilized to fine-tune the PID controller. Numerous studies have conducted a comparative analysis between the fuzzy tuned PID controller versus other traditional PID control schemes. These studies have demonstrated the algorithm's exceptional tracking capabilities, highlighting the advantages of the fuzzy tuned PID controller [115–118].

5.4. Ant Colony Optimization

The Ant colony optimization (ACO) algorithm is a probabilistic method utilized for determining the optimal path as shown in Figure 12. In the context of MPPT, the Ant colony is employed in two distinct manners: initially as a direct controller aimed at identifying the optimal power point rather than the optimum path and secondly can be utilized as an optimization tool for Fuzzy controllers or PI controllers [119–123].

During the search mechanism of MPP the path seeking information is performed by using pheromone density as a first practice and an idea function, and sort out the ultimate answer in accordance with the density of pheromone.

A disperse field establishes ant colony whereas the PV output curve of a system in practice is a succeeding curve. In continuous field we use this technique and present Gaussian mutation for optimizing the algorithm and thus, realizing MPP tracking, through a combination of practical situation PV electrical production [124,125].

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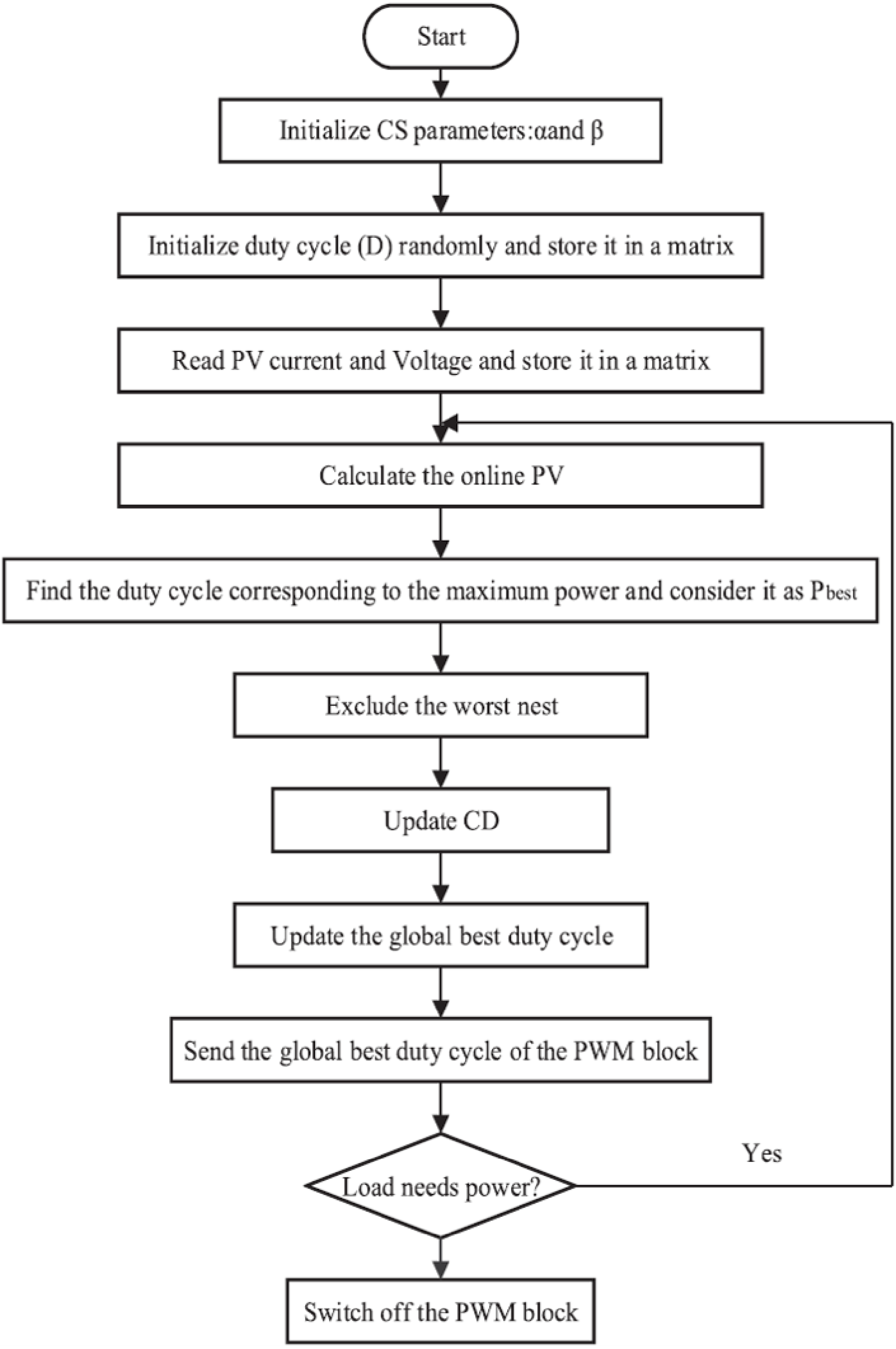

Figure 12. Flowchart of the ACO-based MPPT method

5.5. Fuzzy-Neural Network

In lieu of utilizing ANFIS controllers, there exists an alternative hybrid technique that combines neural network and fuzzy control. Such hybridization methods are consistently referenced in literature using two distinct structures [99, 126-128]. The initial method involves employing the neural network to estimate a specific variable for the fuzzy logic controller. Conversely, the second method entails utilizing the fuzzy logic in conjunction with the Hopfield neural network to govern the maximum power point [42,129,130].

5.6. Analytic Method

The field of MPPT for PV modules heavily relies on analytical methods. These methods often encompass a combination of theoretical control, mathematical modeling, and optimization methods. By employing these approaches, an algorithm can be derived to effectively determine the optimal operating point, thereby hitting the maximum power output. This method depends on experimental/observation results where it provides an analytical clarification to photovoltaic MPP problems. It's based on real analysis theorem (mean value theorem). The precise manifestation neighborhood's point of MPP is acquired and demonstrated being within a small radius ball which also handle MPP [131,132].

5.7. PI Based Incremental Conductance (INC)

Implementing PI controller through an INC is beneficial in minimizing the difference between true conductance and INC. A compensator updates the systems' requirement. An advantage at the steady state a PI minimize ripple oscillations [133–135].

5.8. PSO-INC Structure

The performance of the INC algorithm in tracking the MPP efficiently under varying environmental conditions is enhanced by optimizing the parameters of the INC, such as the step size or perturbation value, using the PSO algorithm. This hybrid structure, which utilizes PSO to dynamically fine-tune the parameters of the INC algorithm, aims to enhance the overall efficiency and adaptability of MPPT in PV systems.

The PSO technique is employed to improve the associated parameters of the INC algorithm, including the perturbation step size/value utilized for effectively tracking the MPP. Through an iterative process, PSO systematically explores the parameter space to identify the most suitable values that enhance the performance of the INC algorithm in accurately tracking the MPP, even when faced with varying environmental circumstances [136–138].

6. Measurement MPPT Methods and Comparison

6.1. Perturb & Observe (P&O)

To start with one of the simplest and easy to implement algorithms along with a low cost is the P&O algorithm which is also called in many literatures "hill-climbing". In addition to the above features, P&O is popular due to its simplest structure along with the minimal required parameters that need to be addressed for being measured. Those measured values are related to a PV set of arrays and are; the V and I.

Figure 13 addresses a flowchart of P&O algorithm operation [8,139]. In this method, the voltage of the module is perturbed periodically in accordance with the requirement of driving the operating point through a set of fixed step size perturbation and the Pout of the module is compared with the Pout from the previous perturbation cycle. In this algorithm, a slight step size but fixed perturbation applied to system and being introduced. That perturbation would cause the solar power to vary based on the variation of perturbation step size applied [8,140]. When an increase in power is observed that would be due to the effects of the perturbation. Since perturbation led to an increment in power then; next perturbation will continue through the similar direction. The main goal is reaching MPP and thus that would be achieved when the MPP power is zero and during the next available instant the power decreases and after that the perturbation will start to go in the other reversed direction as Figure 14 shows.

Note that the P&O keeps perturbing in an effort for arriving towards MPP by decreasing and increasing perturbation steps [139]. This algorithm has the disadvantage of the oscillation that takes

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place around the MPP as well as it has a slower response time due to the dynamic changes that may occur to the climatic parameters; the temperature and irradiance [141].

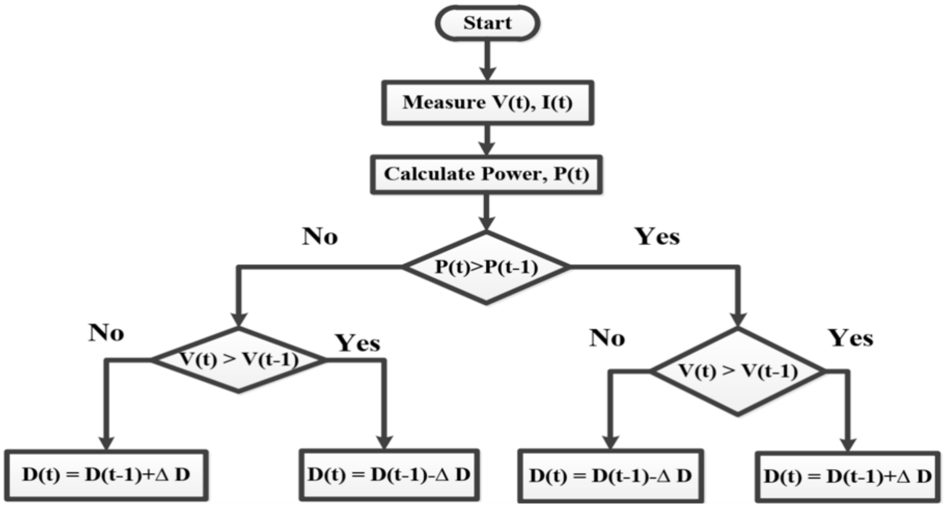

Figure 13. P&O MPPT algorithm

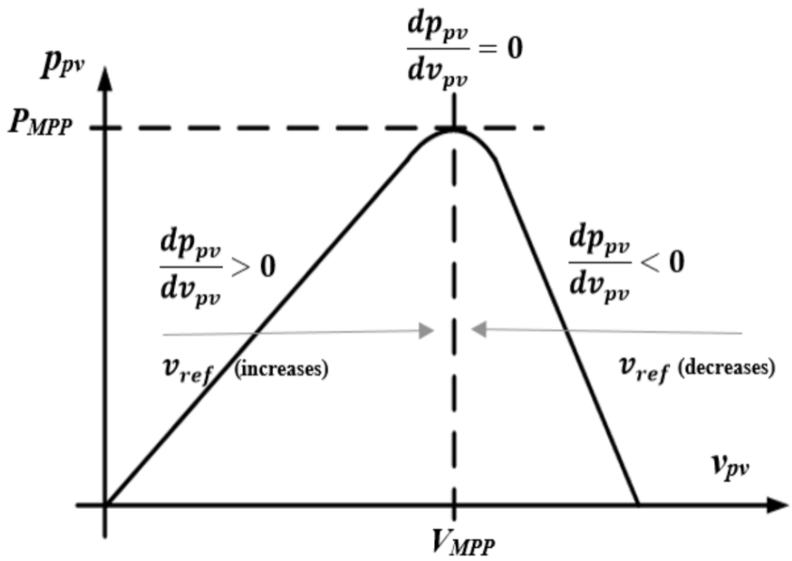

Figure 14. P&O algorithm principle [140].

6.2. Incremental Conductance Algorithm

Incremental Conductance (INC) MPPT algorithm is used in PV, due to its simplicity and easiness of implementation and has the benefit of providing a satisfactory performance at instances of decreased irradiance levels and when it's getting affected by dynamic changes due to climatic conditions. INC uses the current/voltage sensors during the detection of I and V generated by the photovoltaic array [142–145].

INC operates in the following method; the PV voltage (V_{pV}) adjustment is performed in accordance with the array voltage of PV around MPP. INC concept of operation is shown in the flowchart of illustrate in Figure 15 [146–148].

6.3. Short Circuit Current Method

In many literatures, short circuit current method is well known to be called constant current method. The short circuit current (I_{sc}) has a linear relationship with maximum power point current (I_{MPP}) and this is illustrated in (10) [150].

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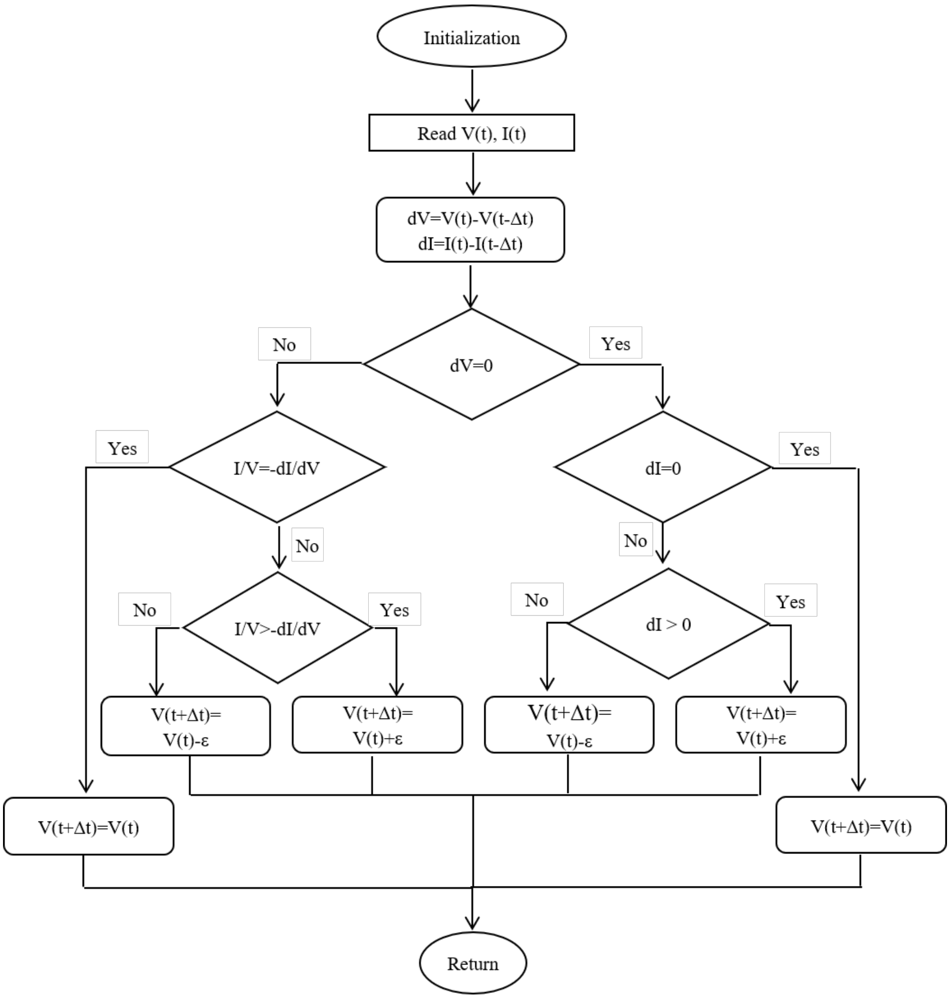

Figure 15. INC Flowchart [148].

$$I_{\text{MPP}} = I_{\text{sc}} \left[1 - e^{\frac{(V_{\text{MPP}} - V_{\text{OC}})}{A}} \right] \tag{10}$$

Figure 16 shows at various climatic conditions (irradiance/temperature) that linear relationship between both the I_{MPP} and I_{sc} [150]. I_{MPP} to relationship does not change significantly under irradiance and temperature variations. It does not change even when the temperature changes. The Short Circuit Current (I_{sc}) technique is a very basic MPPT method. It makes a comparison between the photovoltaic current I_{Pv} and a reference constant current referred to I_{MPP}. To suppress the error in the steady state, the error signal is utilized in a basic controller along an integral action [149,151].

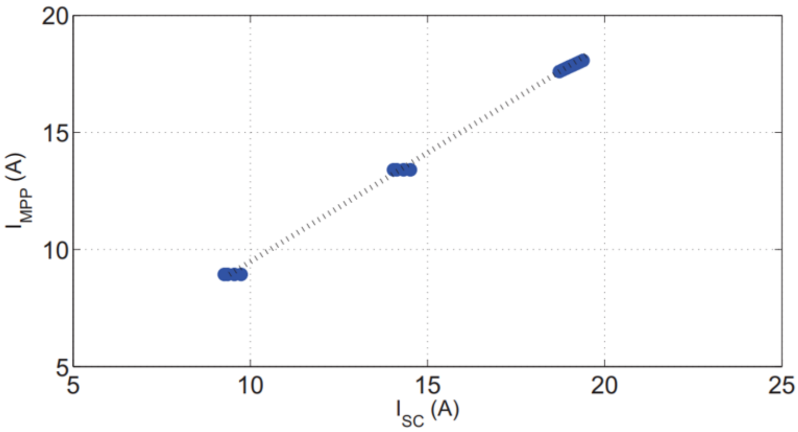

Figure 16. Relationship between IMPP and ISC [149].

6.4. Open Circuit Voltage Method

Open circuit voltage method refers to another naming convention as constant voltage method. PV solar voltage has a proportional relationship with open circuit voltage (V_{OC}). At the MPP it is considered as a reference voltage for various levels of irradiation and temperature. The employed voltage can be attuned over the measurement of a battery V_{OC}. To obtain the MPP we can apply the following equation [152,153];

$$V_{Max} = M_V \times V_{OC} \tag{11}$$

However, the value of constant Mv is challenging in determining it where according to the literature it can range between 0.71 to 0.8 based on photovoltaic array features. An estimated value for this technique is recommended to be 0.76 [152–155].

6.5. Parasitic Capacitances (C_p)

Parasitic capacitances algorithm is close in operation to the INC algorithm excepting parasitic effects of capacitance (C_p). At the terminals C_p setup is added in parallel of preceding models where it's included in diode equation observation. Observed current (I_{ob}) is stated in the following equations [156,157];

$$I_{obs} = I - I_{PC} \tag{12}$$

$$I_{obs} = I_{PH} - I_S\left[\exp\left(\frac{q(V + R_S I)}{AV_{Th}}\right) - 1\right] - \frac{(V + R_S I)}{R_{SH}} - C_p\frac{dV}{dt} \tag{13}$$

$$I_{obs} = F(V) - C_p\frac{dV}{dt} \tag{14}$$

where $C_p(dv/dt)$ is the current in C_p. MPP exists at the point where $dP/dV = 0$. The result of those equations when multiplied by the voltage's panel (V) we can deduce the power's array along with the ability to apply a differentiation of the result. The following is applied for the power's array [157].

$$\frac{dF(V)}{dV} + F(V)V = \frac{dI_{obs}}{dV} + I_{obs}V + C_p\left(\dot{V}V + \ddot{V}\dot{V}\right) = 0 \tag{15}$$

There are three parameters to address;1) parasitic capacities, 2) observed instantaneous conductance, and 3) incremental conductance. Knowing that the 1st and 2nd derivations of the voltage's array would consider ripple effects. The drawback in this algorithm is related to parasitic capacitance where it is at the minimal in each module, thus affect increasing effective capacitance accounted at MPPT [156,158].

6.6. Temperature Method

Temperature method allows avoiding changes that may take place at MPP due to temperature changes. This is implemented through a low cost temperature sensor that varies the MPP algorithm function, and upholding the appropriate MPP track [159]. A major drawback for this technique is the irregularity formation of PV distribution of array's temperature. such sensors may not be accurately calibrated due to its quality that may generate false and inaccurate PV's temperature measurements. The following equation is used to direct the temperature method [159–161].

$$V_{\mathrm{MPP}}(t) = V_{\mathrm{MPP}}(T_{\mathrm{ref}}) + TK_{VOC}(T - T_{\mathrm{ref}}) \tag{16}$$

where V_{MPP} is the voltage of maximum power point, T is the temperature of surface panel, T_{KVOC} is the temperature coefficient's of V_{MPP}, and T_{ref} is the temperature of standard test condition.

6.7. System Oscillation Method

To identify the maximum power point (MPP) a perturbation-based maximum power point tracker incorporates the use of system oscillation. Rather than relying on an explicit perturbation source, the controller of the tracker is specifically engineered to induce self-oscillation within the entire system. As a result, the main switch's duty cycle at a power conversion stage is modulated with a tiny variation in the amplitude in defined frequency about the desired steady-state value. This method relies on using a Cuk converter in the middle between solar panel and load. It depends on calculating the MPP on the switching frequency along with a portion of sinusoidal signal variation [162,163].

6.8. Constant Voltage Method

The constant voltage method assumes a fixed voltage value for the Maximum Power Point, which aligns with the voltage observed under the manufacturing Standard Test Conditions. This fixed voltage value typically varies between 72 to 80 percent of V_{OC} as shown in Figure 17. Subsequently, V_{ref} is utilized to modulate MPPT converter's duty cycle through a feedback control loop. In general, constant voltage depends on using voltage sensor. DC-DC converter's duty cycle is modified to maintain an output voltage (at PV). Relies on the characteristic of temperature. The algorithm has the benefit of using sole sensor, easy to implement and its advantage in tracking [161, 164-167].

6.9. Method of Look-Up Table

The process of locating the maximum power point (MPP) in this method necessitates having previous acquaintance of the PV panel material, technical data, and panel characteristics under different normal circumstances. This information is stored for future reference. The controller, taking into account the measured temperature and insolation values, compares them with the data stored in the look-up table to determine a new voltage for individual cycle. The look-up table is generated based on the specifications provided by the manufacturer or through experimental examinations conducted on the PV panel under numerous climatic situations. An offline considered method used mainly in MPP tracking. Information about technical specs, characteristics of panels for various climatic conditions, are required. PV generator's measured voltage and current will be compared to the ones available in controlling system (stored there), that are corresponding to MPP [168,169]. A drawback of this algorithm is the necessity to implement a large memory capacities to save data in them [169].

6.10. Array Reconfiguration Method

The main purpose of PV array reconfiguration strategies is to enhance the power output when there are non-perfections in irradiance parameter. The primary goal of this method is to regulate the currents flowing through various electrical lines. This MPPT technique is used in partially shading. Where the solar units arranged in a set of series/parallel combinations allowing MPP meeting the requirements of the load. The disadvantage is consumption of time required to track MPP. There are 3 ways of arrangements; series, parallel, and parallel-series arrangements[170–173].

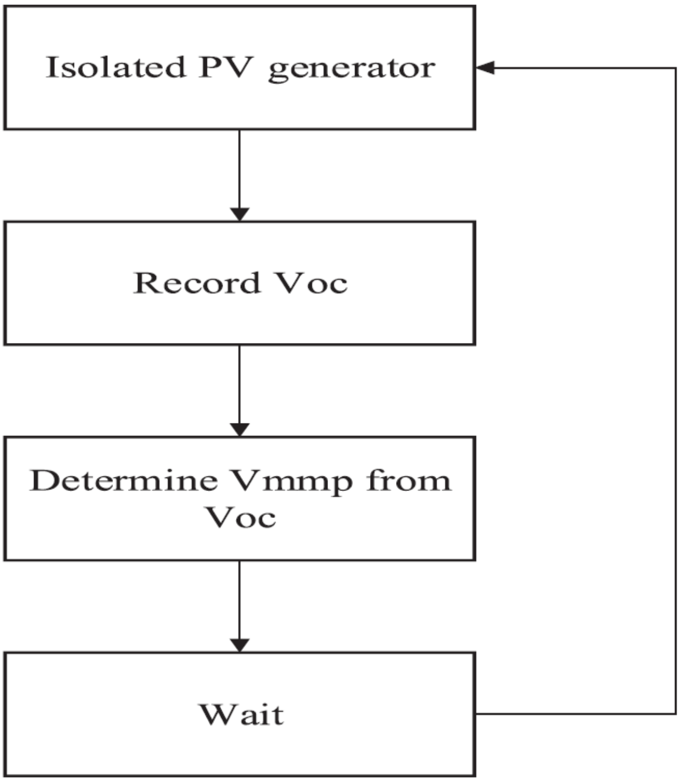

Figure 17. Flowchart of the Constant Vlotage MPPT method [80]

6.11. State-Based MPPT Method

In the realm of photovoltaic (PV) systems, State-based MPPT is utilized to optimize the output power by continuous adjustment of the operating point in solar panels and that would depend on the systems 'current state. This approach takes into consideration a range of environment parameters and electrical status to find out the maximum power point (MPP) and guarantees that the module functions at or close to this point. State space represents a model in this method. The literature shows that it is reliable and non-sensitive to fluctuations in the parameters of a system and MPP can be attained regardless of PV partial shading [86, 174-176].

6.12. One-Cycle Control (OCC) Method

The OCC method involves a non-linear control theory specifically designed for the regulation of switching converters through the utilization of a solitary switching cycle. By employing this controller, it becomes possible to achieve instantaneous dynamic control over the average value of the switching variables subsequent to a transient event. This technique boasts numerous benefits, such as its minimal complexity and cost-effective implementation, its ability to effectively reject disturbances, its robustness, its capacity for maintaining stability, and its swift dynamic response. It is a type of inverter in which the output current can be regulated by a PV voltage to obtain P_{max}. The topology of OCC contains of the following functions: It adjusts Pout based on irradiance, and it outputs an AC current into the grid. Advantages of OCC include: power factor at the highest level, easy to implement circuit, and cost efficient [177–180].

6.13. Best Fixed Voltage (BFV) Algorithm

The BFV algorithm searches for stats data regarding sun light and temperature over a period of time and finds BFV conforming to MPP. Applying controller can set the operating point to BFV or can set the output voltage towards load voltage [181,182]. Further to explain the algorithm in more details, over the span of a period of time, comprehensive statistical data is gathered to analyze the irradiance and temperature levels. This data is crucial in identifying the Best Fit Voltage (BFV) that serves as a representer of the Maximum Power Point (MPP). Subsequently, the controller adjusts either the operating point of the PV module to align with the BFV or sets the Vout to match the nominal load voltage. As a result, the operation is never precisely at the MPP, necessitating the collection of diverse data for different geographical regions. Simplicity and ease of implementation are the main benefits of this algorithm. However, the its efficiency is limited and needs an analysis of mathematical statistics in locating BFV to increase the PV array power [181–183].

6.14. Three-Point Method

Three-point method is used to suppress oscillation problem in P&O algorithm where it applies a comparison of compares only two points only; (current and perturbation point). In this three-point method it periodically perturb the PV voltage and compare output power. So, the method works on avoiding moving rapidly an operating point during varying irradiance. Those points are; (A) is the present operating point, and (B) perturbation starting at points "A" and "C", perturbation through the opposite direction from "A" , shown in Figure 18 [184,185].

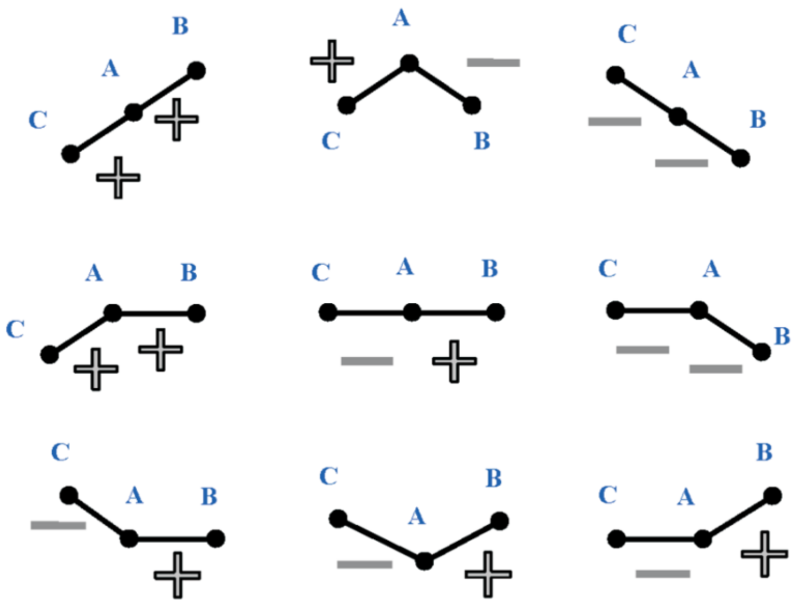

Figure 18. Three perturbation points of possible states [186].

6.15. The Method of PV Output Senseless (POS)

The primary benefit of employing Pv output senseless (POS) approach lies in the fact that the sole significant factor to be considered is the current that flows into the load. When dealing with a large photovoltaic (PV) generation system, it can be operated with a significantly higher level of safety compared to a conventional system. Here we have only the flowing current in load that require a specific consideration. Here we have only the flowing current in load that is considered. The source and load power are proportional in PV system. When the current increased at load power is increased, and thus the current at load is proportional to power at source which is the solar cell output power. Power in this method is controlled by PWM. Incrementing duty ratio leads to increase current output at the converter [187,188].

6.16. Variable Inductor MPPT Method

Variable inductor MPPT method introduces a novel MPPT topology controller for the applications of solar power, incorporating adjustable inductance against characteristics of current. It has been demonstrated that, under steady process, the pinpointed output inductor exhibits a characteristic where the inductance decreases as the current increases, corresponding to the upsurge in solar radiation incident. This technique demonstrates variable inductor slope airgap, which gradually saturating with cumulative raise in current, in meeting this requirement. This design offers the advantage of dropping the overall size of the inductor by almost 60% and expanding the range of operation of the entire tracker, enabling the retrieval of solar energy even under the lowest irradiance. It introduces variable inductance to boosting the operatable range tracking method to extract P_{max} even at lower irradiance. This technique is recommended when we have low irradiance [181,189].

6.17. Variable Step-Size Incremental Resistance (INR) Method

Variable step-size algorithm is proposed to overcome the issue of fixed step size for dynamic environmental condition. An advantage of this algorithm is to switch the points and values of threshold function, as shown below [83,128,190];

$$C = P_n \times \left| \frac{dP}{dI} \right| \tag{17}$$

where; n is assumed an index. Here we assume that the curves 'power slope is zero on MPP, positive when it is at the left, and eventually negative when is moving to the right of MPP. Tracking MPP is done through a comparison of instantaneous resistance (V/I) along with incremental resistance$(\Delta V/\Delta I)$.

6.18. DP-P&O MPPT

DP-P&O MPPT applies additional power measuring in the center of sampling MPPT period where no perturbation occurs, as shown below [191]. Figure 19 shows that P_x and P_{k+1} when they have a change in their power this is reflecting only the power changes due to weather conditions and changes. Differentiation between P_x and P_k holds a power change initiated an MPPT perturbation and irradiance variation. dP is computed [192–194];

$$dP = dP_1 - dP_2 = (P_x - P_k) - (P_{k+1} - P_x) \tag{18}$$

$$dP = 2P_x - P_{k+1} - P_k \tag{19}$$

A resultant (dP), is the result of modifying the MPPT algorithm

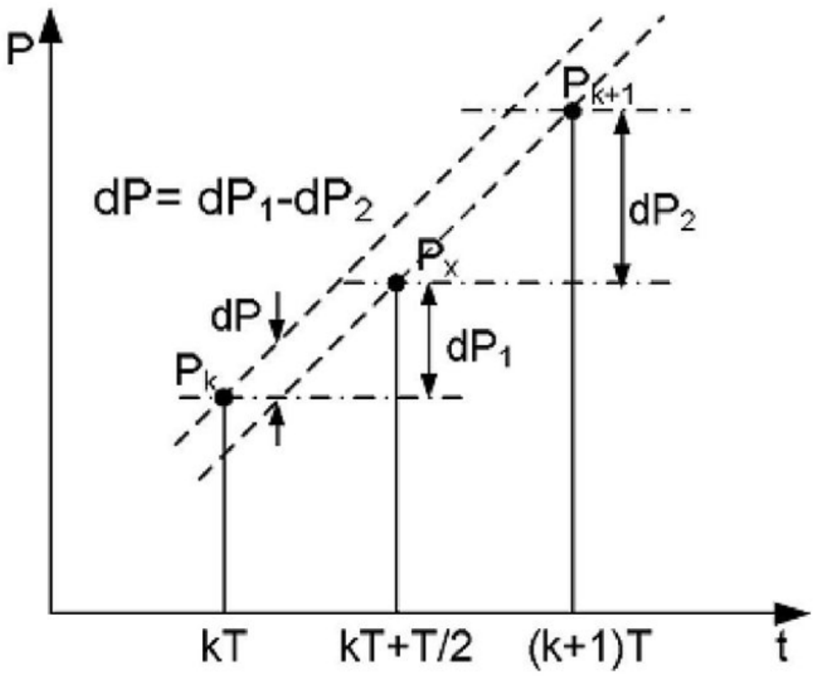

Figure 19. Power Measurement between sampling of two MPPT [194].

6.19. Pilot Cell

In pilot cell scheme, it is utilized to operate the pilot cells at their MPP. This method removes any photovoltaic power losses at pilot cell or else MPP measurements. Yet, there is still the issue of a missing constant value (K). However, pilot cell parameters requisite to be precisely matched to the parameters the arrays represented by the pilot cell, thus increasing the system's energy cost. In this method MPPT can function a PV system at MPP without PV power losses in the pilot cell measurements. Nevertheless, there is still an issue of missing the value of "K" constant. The pilot cell parameters must be calibrated accordingly in an accurate manner, where each pilot cell calibration, will push for an increasing system's energy cost [152,195–197].

6.20. Modified Perturb and Observe

Modified perturb and observe method works well in non-dynamic changing environment. However, it has some problems in detecting the MPP at rapid climatic atmosphere. Where the effects come from an inaccurate tracking of MPP. Moving over those issues, a Modified P&O (M-P&O) used to segregate the variations caused by the process of perturbation from the variations caused by irradiance or changes in weather. Since the estimation procedure terminates tracking MPP by holding PV voltage constant, modified P&O method tracking speed is around 50% of the conventional method [198–204].

6.21. Estimate Perturb and Perturb (EPP)

In EPP approach, an extended P&O method is utilized. This method involves the integration of one estimate mode and two perturb modes. The perturb process is employed to search through the issue of high nonlinear PV specifications, while the estimate process is designed to compensating for any variations in irradiance during the perturb process. Despite its complexity, this technique exhibits a superior tracking speed that is both faster and more precise than the conventional P&O method. It improves speed while maintaining the key characteristics of M-P&O algorithm. Compared to M-P&O algorithm, this method depends on using a single estimation mode for every 2 perturb approaches significantly raising track speed of MPPT with no reduction in the accuracy of tracking. Compared to M-P&O, EPP is faster by 1.5 in tracking speed time but almost has the same time delay among estimation and perturb processes [205–208].

6.22. CVT + INC-CON (P&O) + VSS Method

According to the CVT + INC-CON (P&O) + VSS method, it showed many improvements in harvesting an excellent tracking performance; however, the initial process to start is complex. Its control algorithm is straightforward. All it has to do is to check if V_{out} is larger than the voltage instruction of PV arrangement. However, the change of voltage is only in one direction. Thus this causes power increasing in one direction and a suppression of oscillation [209,210].

6.23. VH-P&O MPPT Algorithm

VH-P&O MPPT algorithm is a mechanism that halts conventional perturbation during any change in irradiance but before going beyond MPP voltage and holding V_{ref} to $V_{capacitor}$ of PV, where it is a fundamental tracking factor. Once irradiation change is stopped and MPP reached, step size tracking must be gradually reduced to zero. If there is any change of PV power, then the step size tracking is resettled to the original value to maintain a fast tracking. This technique will drive a photovoltaic response to irradiance change leads to a straight-lined tracking performance and is completed with suppression of oscillation at MPP [211–215].

6.24. Variable DC-Link Voltage

The design of a PV system can be limited by the impact of input voltage and current on the connection structure of PV cells. This limitation results in a reduced MPPT ranging during certain environmental conditions. However, in the case of a restricted PV connectivity structure, this algorithm aims to expand the MPPT range and reduce the increase in total harmonic distortion (THD). It achieves

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this by selecting the suitable DC-link V_{ref}, which is adjusted by comparing the sorted input voltage [212–219].

6.25. Modified INC Algorithm

Modified INC algorithm concentrates on the current rather than the voltage of PV array. It works based on V_{pv} varies slowly at right MPP side. Voltage variations through two sampling times is neglected. In this theory, the change of power to voltage dP/dV with respect to provides a linear relation related a variation of dP/dV as compared to V. Thus reference current I_{ref} is simple to calculate as of linear variation at dP/dV_{pv}, versus a complex calculation of V_{ref} after considering nonlinear variation of V against dP/dV [220–223].

6.26. Azab Method

Azab method is considered as a P&O but modified algorithm. Azab method tracks MPP power extracted from within PV. However, any reduction in calculated MPP power is continued to the point where the error in both P_{MPP} and P_{ACT} is within the boundaries of the upper and lower limits [224–226].

6.27. Voltage Scanning-Based MPPT Method

The Voltage scanning-based MPPT method employs a three-step process to identify the Global MPP (GMPP) [227,228]. The primary objective is to systematically raise the reference voltage of the system at a predetermined rate, thereby enabling the identification of MPPs and their corresponding voltage values through the resulting power changes. By comparing the MPPs with the previous MPP, the Local MPP (LMPP) is eliminated, and a new GMPP is determined at each MPP. This iterative process persists until all voltage levels have been examined. The value of the voltage on GMPP is established as the reference voltage of the module to optimize power generation by leveraging both the system voltage and the change rate in the module voltage [30,35,227–229].

7. Mathematical Calculation MPPT Methods

7.1. Model-Based MPPT

The model-based MPPT approach is addressed to enhance the PV module tracking transients functioning under fast varying irradiance conditions. As an alternative of relying on heuristic methods search to determine the MPP, these techniques use a PV mathematical model to predict the MPP systematically. The value of irradiance, is necessary for resolving the model, and computed using an inverse PV model, along with the measurement conducted for current and voltage [230–233]. However, the current's inverse PV model can't be found in a closed arrangement, however requiring certain simple interpretations that impact the irradiance accuracy estimate and resulting in imprecise tracking. A novel shunt PV model maybe introduced due to its capability to deliver a closed form inverse to develop an enhanced structure of model based MPPT system. The enhanced precision in the estimation of irradiance leads to superior tracking accurateness and increased energy extracts compared to existing model-based trackers [231,232,234,235].

7.2. Piecewise Linear Approximation with Temperature Compensated Method

Piecewise linear approximation with temperature compensated method rapidly tracks PVs' MPP and solve the issue of temperature drifting. Previously attained results confirm that the MPPT tracking effectiveness can hit up to 90 at various irradiances with less than 1% of tracking efficiency at a range of temperatures ranging between (-5°C to 55°C).

7.3. A What's Termed Fit Line

A what's termed fit line is used to get the MPP characteristics and perfectly operates at high irradiance versus decreased tracking efficiency at low irradiance [149,236,237].

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7.4. Beta Method

Beta method is based on I-V curve of PV system and considered an accurate fast tracking of MPP using intermediate variable (β), equation [47,163,238].

$$\beta = \ln(IV) - C \times V = \ln(I_S \times C) \tag{20}$$

$$C = \frac{qAKT}{N_s} \tag{21}$$

where I_s denotes the reverse saturated current, q is the electronic charge, A is the ideality factor, k is Boltzmann constant, T is the temperature and N_s is the number of cells connected in series. When operating settings change, β stays constant. β calculations can be done at any time through the (I) and (V) of panel and fed to conventional closed loop through constant reference.

7.5. Ripple Correlation Control (RCC)

Due to the ripples involved in a PV system this method reconsiders using ripples to accomplish MPPT. RCC works in the following structure; If (I) or (V) increased; that causes increasing power where operating point location is at the left of MPP ($V < V_{MPP}$ and $I < I_{MPP}$). Either when current/voltage are increasing and power (P) is decreasing, we notice that operating point is located towards right side of MPP ($V > V_{MPP}$ and $I > I_{MPP}$). As per controlling the duty ratio cycle of this method we refer to the following equations [239–243];

$$d(t) = -K_3 \int p \cdot v \, dt \tag{22}$$

$$d(t) = K_3 \int p \cdot i \, dt \tag{23}$$

where K_3 is a positive constant.

7.6. Current Sweep

Current sweep applies a sweep waveform at the current of PV array system where an I-V curve (PV module) attained accordingly within a set of fixed intervals of time[244]. The same computation can be done for so as to assure that sweep looks for and search the highest possible peak when multiple peaks exist. This method likely to be achieved if tracking consumption of power tracking lesser than increased power delivered to the system [181,245,246].

7.7. DC-Link Capacitor Droop Control

DC-link capacitor droop control method operates in cascading fashion within PV system. The duty ratio D;

$$D = 1 - \frac{V}{V_{\text{link}}}. \tag{24}$$

Through this scheme we may be able to increase PV system power [247–249].

7.8. Feedback Control

In the realm of power systems, the expressions dP/dV and dP/dI, pertain to the power derivatives in relation to voltage (V) and current (I) correspondingly. Those derivatives are frequently employed in the examination of the power-voltage (P-V) and power-current (P-I) attributes of electrical classifications. The utilization of feedback control is essential in computing slope dP/dV or dP/dI, in P-V curve and fed to power converter. Slope calculations and signs are for past cycles where duty ratio's incremental or decremental of the power conversion applied in arriving into the ultimate MPP [250,251].

7.9. The Method of Linear Current Control

The main purpose of PV array reconfiguration strategies is to enhance the power output when there is non-perfection in irradiance parameter. The primary goal of this method is to regulate the currents flowing through various electrical lines. Depends on an interpretational graphics of two algebraically equations, where two curves' intersecting points on the phase plane applied [188].

7.10. Linear Reoriented Coordinates Method (LRCM)

LRCM works on solving iteratively the MPP equation and employed in finding symbolic approximation of MPP. It measures (I_{SC}, V_{OC}) and additional parameters of P-V curve, to discover an approach of the maximum error through adopting LRCM to get to estimated MPP [252,253].

Slide mode control method

Voltage derivative slope to current utilized for finding MPP. Mathematical model can be created for many DC-DC converters such as boost, buck, etc. to find the MPP. The parameter u is considered as the converter's switching function, where u is articulated as [254–256];

$$u = \begin{cases} 0 & \text{if } S \geqslant 0, \\ 1 & \text{if } S < 0. \end{cases} \tag{25}$$

If $u = 0$ then we have an open switch and when u = 1 we have a closed switch. S is expressed as;

$$S = \frac{dP}{dV} = I + V\frac{dI}{dV} \tag{26}$$

7.11. Polynomial Curve Fitting (PCF)

PCF is called an offline technique. It is Established on the basis of mathematical equations. It describes the PV module electric characteristics. A 3rd order polynomial function can be applied to get a P-V curve fitting accurately using (27) [257,258].

$$p_{pv} = aV_{PV}^3 + \beta V_{PV}^2 + \gamma V_{PV} + \delta \tag{27}$$

where $\alpha, \beta, \gamma, \delta$ are found through of V_{pv} sampling and power in intervals. MPP is at the ultimate value when $dP/dV = 0$, and computed by;

$$V_{\text{MPP}} = \frac{-\beta \pm \sqrt{\beta^2 - 3\alpha\gamma}}{3\alpha} \tag{28}$$

Curve fitting is easy to use since differentiations calculations are not involved. However, it requires a previous acquainting knowledge of; mathematical equations and coefficients. Further it needs to have a large capacity of memory due to the number of computations which are at a high increasing rate [259].

7.12. Differentiation Method (DM)

Numerical differentiation is the main drive for DM. Here we look for seeking numerical value of the derivation of a function at a specific point [260,261].

7.13. MPP Locus Characterization

MPP locus characterization searches for linear relationship to take place between (I&V) at the MPP (MPP locus). Such relation is demonstrated through a tangent line of MPP locus curve for Ipv current where the minimal irradiance circumstance contents the method's sensitivity [163, 262-264]. This method is represented by Equation (29). At high irradiances this technique provides reliable results, as compared to traditional methods.

$$T_L = (A \cdot V_T I_{\text{MPP}} - N_S R_S) \cdot I_{\text{MPP}} + \{V_{\text{OC}} - A[V_{\text{DO}} + V_T]\} \tag{29}$$

where A is the ideality factor, and V_{Do} is the differential voltage.

8. MPPT Optimization Methods

8.1. IMPP and VMPP Computation Method

The optimization of power output in PV systems is heavily reliant on the implementation of MPPT technology. This essential technology enables solar panels to consistently operate at their MPP despite changes in environmental conditions. By continuously adjusting the operating point of the solar panels, the MPPT controller ensures that the power output is maximized. The computational approach encompasses perturbing the operating point, either by modifying the voltage or current, and then examining the consequent variation in power. Subsequently, the controller adapts the operating point in order to converge to the MPP. Measurement of photovoltaic power relies on irradiance/temperature measured by a systematic photovoltaic. A disadvantage of this method is the need for additional measurements which are sometimes hard to obtain and the need for an exact photovoltaic array model. The advantage of this method is that the MPP is accurately monitored even in varying atmospheric conditions [183, 265-267].

8.2. Numerical Method - Quadratic Interpolation (QI)

The QI method is new where it uses numerical calculation of PV power production system. It creates a parabolic scheme along quadratic interpolation. This is achieved by applying the (V&I) parameters from set of 3 sampling points. The peak of parabolic model is found by calculating the voltage value of MPP [268–271]. Basis function technique used to construct quadratic function;

$$L_2(X) = l_0(X)y_0 + l_1(X)y_1 + l_2(X)y_2 \tag{30}$$

where $L2(X)$ is quadratic interpolation polynomial, $l_o(X)$, $l_1(X)$, and $l_2(X)$ refer to the quadratic interpolation functions. MPP achieved at a zero derivative of Equation (30). This algorithm enhances MPPT accuracy, stability and speed [108,109].

8.3. Extremum Seeking Control Method (ESC)

Nonlinear dynamic system and adaptive feedback optimizations are involved in such method. ESC designed for PV systems during the process of tracking MPP. Some of its advantages are; Maximizing power, dynamic adaptation-based feedback control is important factor used in the optimization problem in sinusoidal perturbation [272–274].

8.4. Dual Carrier Chaos Search Algorithm

The effectiveness of the chaos search algorithm is enhanced by incorporating the dual carrier approach, which effectively addresses the limitations of the conventional chaos search method. As a result, the search efficiency is significantly enhanced. Empirical evaluations demonstrate that the suggested technique enables rapid and precise tracking of the step-response, leading to superior optimization outcomes. A logistic and $y_{n+1} = \mu(\pi y_n)$ mapping is added to generate a carrier in this method and getting it in a step of stochastic searching [275,276]

8.5. Algorithm for Stimulated Annealing (SA)

Stimulated annealing, which involves the establishment of crystals using high-temperature heating and low-temperature cooling, is referred to as stimulated crystal formation. This can be further elucidated for the behavior of semiconductors using solid state device theory [277].

System stability increases before heating. A comparison between energy and cost function of MPPT algorithm can be performed. Where this is reflecting an inverse of P_{out} (panel) that is requires to minimize it. At high temperature the likelihood to find duty cycle matching the garbage P_{out} is higher. However, when the temperature is low, the likelihood of selecting duty cycle matching the higher

P_{out} goes up. When the temperature is low enough, the likelihood of picking duty cycle matching the maximum power is unity [278–281].

9. Comparison of MPPT Techniques

There are many differences between the MPPT techniques, which may assist in selecting a system suitable for specific applications. Multiple parameters involve such as overall implementation, types of sensor, total cost, what sort of applications to be applied, and other factors. The sensors' number counts towards making a decision to select an MPPT algorithm. Thus sensors plays an important role in getting the most precise MPPT where increasing the number of sensors would provide better results [196,282,283]. Sensing voltage is possible to be easy as compared to current. Hitting MPP during a specific time is called convergence speed according to Walker at ref [284]. Convergence of the voltage or current required shall be low in order to get high performance. Power losses obtained by decreasing the period of time taken for reaching MPP. At partial shading conditions power losses reaches 70% when the local maximum tracking is reached as compared to actual MPP [285,286]. Performance cost is an additional factor concerning users where using analog system is cheaper as com-pared to digital system. PV selection depends on the type of applications used. For in-stance, in the case of large-scale space satellite and orbital station applications, the cost and complication of tracking MPP are the least essentials in accordance with (performance/ dependability). MPPT module may come as a direct or indirect depending on the parameters of arrays. In the direct type either V or I of photovoltaic is used. Direct methods do not depend on the previous understanding of the PV array configuration. Therefore, the P-V curve operating point does not depend on whether parameters conditions that may change during a period of time. Indirect methods has parametric database which includes data of various irradiances and temperatures or on the estimation of MPP using a series of functions derived from empirical data [287]. Table I refers to a summary of MPPT algorithm's characteristics are utilized in comparing sets of techniques.

Through the study, we introduced a sample literature of the current MPPT algorithms. Further we made an analysis through a theoretical process previously published work and extracted the important set of parameters as shown in Table 1. Around 65 types of algorithms were gathered, where the variances between those ones shown in Table 2 which extend the findings of Ali et al [183]. From all the available algorithms it was a fact that the most commonly used ones were P&O, "hill-climbing", incremental conductance algorithm. Below as shown in Table 2, is an overview of those known algorithms.

Table 1. Two Examples of Weighting Factor Used to Weight Criteria

	Weighting Factor				
	Complexity	**Convergence Speed**	**Accuracy**	**Cost**	**Efficiency**
Example 1	5	10	10	10	10
Example 2	2	2	1	10	10

*A value =10 means that the criterion is of high importance in the selection
*A value =0 means that the criterion is of low importance in the selection

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Table 2. Parameters definition for the MPPT efficiency performance comparison

Parameter	Description
PV array dependencies	No specific configurations required or a predefined parameters value
MPPT accuracy	When the actual MPPT is compared to an inaccurate one, Pout will decrease with respect to the actual value.
Type of operation	Relies on the circuit category.
Tuning over periodic sets of time	Any oscillation involved in this scenario.
Convergence speed	How fast to converge and reach MPP.
Complexity	Describes the complexity of the module.
Parameters	Relies on variables' factors.

Table 3. Evaluation of MPPT Algorithms (D: Digital, A: Analogue, Ir: Irradiance, T: Temperature, Voltage V, Current I)

Algorithm	PV Array Dependency	MPPT Accuracy	Type (D/A)	Periodic Tuning	Convergence Speed	Complexity	Parameters
P&O/ HCS [288-291]	No	Yes	D and A	No	Different	Simple	V, I
INC Algorithm [157, 266, 290-293]	No	Yes	D	No	Different	Simple	V, I
Fractional Isc [290, 291, 294, 295]	Yes	No	D and A	Yes	Moderate	Moderate	I
Fractional Voc [290, 291, 294, 295]	Yes	No	D and A	Yes	Moderate	Simple	V
Parasitic Capacitances (Cp) [14, 157, 296]	No	Yes	A	No	Fast	Simple	V, I
FLC [183, 290, 291, 297]	Yes	Yes	D	Yes	Fast	High	Diverse
Temperature Methods [163, 183]	Yes	Yes	D	Yes	Moderate	Simple	V, T
Beta Method [183]	Yes	Yes	D	No	Fast	High	V, I
Neural Network [183, 291]	Yes	Yes	D	Yes	Fast	High	Diverse
RCC [183, 290, 298]	No	Yes	A	No	Fast	Simple	V, I
Current Sweep [183]	Yes	Yes	D	Yes	Low	High	V, I
DC Link Capacitor Droop Control [183]	No	No	D and A	No	Medium	Simple	V
dP/dV or dP/dI Feedback Control [183]	No	Yes	D	No	Fast	Moderate	V, I
System Oscillation Method [183]	Yes	No	A	No	N/A	Simple	V
Constant Voltage Tracker [161, 183]	Yes	No	D	Yes	Moderate	Simple	V
Lookup Table Method [161, 183, 289]	Yes	No	D	Yes	Fast	Moderate	V, I
On-line MPP Search Algorithm [183]	No	Yes	D	No	Fast	High	V, I
Array Reconfiguration [183]	Yes	No	D	Yes	Low	High	V, I
Linear Current Control [183]	Yes	No	D	Yes	Fast	Moderate	Ir
IMPP and VMPP Computation	Yes	Yes	D	Yes	N/A	Moderate	Ir, T
State Based MPPT [183]	Yes	Yes	D and A	Yes	Fast	High	V, I
OCC MPPT [183]	Yes	No	D and A	Yes	Fast	Moderate	I
BFV [183]	Yes	No	D and A	Yes	N/A	Low	None
LRCM	Yes	No	D	No	N/A	High	V, I

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Algorithm	PV Array Dependency	MPPT Accuracy	Type (D/A)	Periodic Tuning	Convergence Speed	Complexity	Parameters
Slide Control [161, 183, 289, 295, 297, 299]	No	Yes	D	No	Fast	Moderate	V, I
Three Point Weight Comparison [183]	No	Yes	D	No	Low	Simple	V, I
POS Control [183]	No	Yes	D	No	N/A	Simple	Current
Biological Swarm Chasing MPPT [183]	No	Yes	D	No	Varies	High	V, I, Ir, T
Variable Inductor MPPT [183]	No	Yes	D	No	Different	Moderate	V, I
INR method [183]	No	Yes	D	No	Fast	Moderate	V, I
dP-P&O MPPT [191]	No	Yes	D	No	Fast	Moderate	V, I
Pilot Cell [300]	Yes	No	D and A	Yes	Moderate	Simple	V, I
Modified Perturb and Observe [208]	No	Yes	D	No	Fast	Moderate	V, I
Estimate, Perturb and Perturb EPP [208]	No	Yes	D	No	Fast	Moderate	V, I
Numerical Method - Quadratic Interpolation (QI) [268]	No	Yes	D	No	Fast	Moderate	V, I
MPP Locus Characterization [262, 299]	N/A	Yes	N/A	N/A	Fast	Simple	V, I
CVT + INC-CON (P&O) + VSS Method [209]	Yes	Yes	D and A	No	Fast	Moderate	V
Piecewise Linear Approximation with Temp Compensation [301]	Yes	Yes	D and A	Yes	Fast	Simple	V, I, Ir, T
PSO Algorithm [136, 298]	Yes	Yes	D	Yes	Fast	Moderate	V, I
PSO-INC Structure [136]	No	Yes	D	No	Fast	Simple	V, I
Dual carrier chaos search algorithm [275, 298]	No	Yes	D	No	Fast	Moderate	V, I
Algorithm for Stimulated Annealing (SA)[298, 302]	Yes	Yes	D	No	Fast	High	V, I
Artificil neural network (ANN) based P&O MPPT [57, 291]	No	Yes	D and A	No	Fast	Moderate	V, I
VH-P&O MPTT Algorithm [211]	No	Yes	D	No	Moderate	Moderate	V
Ant Colony Algorithm [303]	No	Yes	D	No	Fast	Moderate	V, I
Variable DC-Link Voltage Algorithm [216]	No	Yes	D	No	Moderate	Moderate	V
ESC Method [304]	No	Yes	D and A	No	Fast	Moderate	V, I
Gauss-Newton Method [69]	No	Yes	D	No	Fast	Simple	V, I
Steepest-Descent Method [69, 305]	No	Yes	D	No	Fast	Moderate	V, I
Analytic Method [305]	Yes	No	D and A	Yes	Moderate	High	V, I
PCF [257]	Yes	No	D	Yes	Low	Simple	V
DM [306]	No	Yes	D	Yes	Fast	High	V, I
IC Based on PI [163, 298]	No	Yes	D	No	Fast	Moderate	V, I
Azab Method [224]	Yes	Yes	D	Yes	Moderate	Simple	N/A
Modified INC Algorithm [191]	No	Yes	D	No	Moderate	High	V, I
Newton-Like Extremum Seeking Control Method [74]	No	Yes	D and A	No	Fast	Hogh	V, I

10. Conclusions

The exploration of numerous MPPT techniques in the context of solar PV systems presented in this paper unveils the diverse methodologies available for enhancing efficiency of solar PV systems. The comparison of MPPT techniques, considering factors such as cost, tracking speed, and system stability, underscores the trade-offs inherent in MPPT controller selection. Our findings underscore that hybrid approaches, while demonstrating higher efficiency, entail increased complexity and higher costs. A notable contribution of this research lies in the synthesis of efficiency performance metrics for MPPT algorithms emphasizing their accuracy in reaching the optimal point. The MPPT algorithms

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have been classified based on their dependencies, highlighting those that prioritize simplicity, and assessed their convergence speed in response to peak point detection in the power curve.

In conclusion, this comprehensive study stands as a decisive reference for the MPPT algorithms crucial to companies engaged in the production of PV systems and power charge controllers. This study also holds significant value for both researchers and practitioners, offering valuable guidance for the judicious selection of MPPT controller algorithms for PV applications.

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Abbreviations

The following abbreviations are used in this manuscript:

ABC	Artificial Bee Colony
ACO	Ant colony optimization
ACO-PID	Ant Colony Optimization (ACO) + Proportional-Integral-Derivative (PID) controller
AM	Analytic method
AMBM	Adaptive Model-Based Methods
ANFIS	Adaptive neuro-fuzzy inference system
ANN	Artificial neural network
ANN-P&O	Artificial Neural Network + Perturb and Observe
ANN-PSO	Artificial Neural Network + Particle Swarm Optimization
ARM	Array Reconfiguration Method
AZM	Azab method
BFV	Best fixed voltage method
BM	Beta Method
BSC	Biological Swarm Chasing method
CC	Constant Current (also known as Short Circuit Current Method)
Cp	Parasitic capacitances
CSM	Current Sweep Method
CSO	Cuckoo Search Optimization
CTSO	Cat Swarm Optimization
CV	Constant Voltage (also known as Open Circuit Voltage method)
CV+INC-P&O+VSS	Constant Voltage Tracking + Incremental Conductance with Perturb and Observe + Variable Step Size
D	Duty cycle point
DCDC	DC-link capacitor droop control
DCCS	Dual carrier chaos search
DE	Differential Evolution
DM	Differentiation method
DP-P&O	Dual Perturb and Observe MPPT method
DWS	Decremented window scanning
EPP	Estimate perturb and perturb
ESC	Extremum seeking control
FA	Firefly Algorithm
FBC	Feedback control
FLC	Fuzzy logic controller
FLC-ACO	Fuzzy Logic Controller + Ant Colony Optimization
FLC-ANN	Fuzzy Logic Controller + Artificial Neural Network
FLC-GA	Fuzzy Logic Controller + Genetic Algorithm
FLC-P&O	Fuzzy Logic Controller + Perturb and Observe
FOCV	Fractional Open Circuit Voltage
FSCC	Fractional Short Circuit Current Fuzzy PID (Fuzzy Logic + Proportional-

	Integral-Derivative)
HS	Harmony Search
GA	Genetic Algorithm
GMPP	Global maximum power point
GNM	Gauss-Newton method
GWO	Grey Wolf Optimization
INC	Incremental conductance
Isc	Short circuit current
IMPP	Maximum power point current
JA	Jaya Algorithm
LCM	Load Current Maximization
LCC	Linear Current Control method
LMPP	Local maximum power point
LOCM	Locus Characterization MPP Method
LRCM	Linear reoriented coordinates method
LUTM	Look-up Table Method
MF	Membership Functions
M-INC	Modified INC method
MPC	Model Predictive Control
M-P&O	Modified Perturb and Observe
MPP	Maximum power point
MPPT	Maximum power point tracking
NESC	Newton-based Extremum Seeking Control Method
OCC	One-cycle Control Method
ODM	One-diode model
OMS	Online MPP Search
P	Power
PB	Peak bracketing method
PBIS	Peak bracketing with initial scanning method
PCL	Pilot Cell method
PCF	Polynomial curve fitting method
PCM	Parasitic Capacitance Method
PI	Proportional Integral
PID	Proportional Integral Differential
PI-based INC	(Proportional-Integral + Incremental Conductance)
PLA-TCM	Piecewise linear approximation with temperature compensated method
P&O	Perturb and Observe
POS	PV Output Senseless Method
PPV	PV power
PSO	Particle swarm optimization
PSO-INC	(Particle Swarm Optimization + Incremental Conductance)
PSO-DE	(Particle Swarm Optimization + Differential Evolution)
PV	Photovoltaic
QI	Quadratic interpolation
RCC	Ripple correlation control
SA	Stimulated annealing
SBM	State-Based MPPT method
SDN	Steepest-descent method
SI	System Identification
SNNs	Simulated neural networks
SOM	System Oscillation Method
TDM	Two-diode model
TGM	Temperature Gradient Method
THD	Total harmonic distortion

TM	Temperature Method
TPM	Three-Point Method
V	Voltage
VDC	Variable DC-link voltage
VSM	Voltage Scanning-Based MPPT method
VH-P&O	Variable Hill-Climbing Perturb and Observe Maximum Power Point Tracking
VIM	Variable Inductor MPPT Method
VSIR	Variable Step-Size Incremental Resistance Method

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