

Review

A Comprehensive Review of Recent Maximum Power Point Tracking Techniques for Photovoltaic Systems under Partial Shading

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Abstract: To operate photovoltaic (PV) systems efficiently, the maximum available power should always be extracted. However, due to rapidly varying environmental conditions such as irradiation, temperature, and shading, determining the maximum available power is a time-varying problem. To extract the maximum available power and track the optimal power point under these varying environmental conditions, maximum power point tracking (MPPT) techniques are proposed. The application of MPPT for extracting maximum power plays a crucial role in developing efficient PV systems. These MPPT techniques face several issues and limitations, particularly during partial shading conditions caused by non-uniform environmental conditions. Researchers have been focusing more on mitigating the partial shading condition in PV systems for the last few years due to the need to improve power output and efficiency. This paper provides an overview of MPPTs proposed in the literature for uniform and non-uniform environmental conditions broadly categorized as MPPT-based and circuit-based methods. The MPPT-based methods are classified as conventional, soft computing, and hybrid techniques. A critical analysis of each approach regarding tracking speed, algorithm complexity, and dynamic tracking under partial shading is discussed. The literature shows hybrid strategies provide fast-tracking speed and are efficient with a tracking efficiency of around 99% compared to conventional methods; however, their design and practical implementation are complex. This comprehensive review of MPPT methods aims to provide power utilities and researchers with a reference and guideline to select the best MPPT method for normal operation and partially shaded PV systems based on their effectiveness and economic feasibility.

Keywords: photovoltaic; MPPT; partial shading; global peak; MPPT classification



Citation: Worku, M.Y.; Hassan, M.A.; Maraaba, L.S.; Shafiullah, M.; Elkadeem, M.R.; Hossain, M.I.; Abido, M.A. A Comprehensive Review of Recent Maximum Power Point Tracking Techniques for Photovoltaic Systems under Partial Shading. *Sustainability* **2023**, *15*, 11132. <https://doi.org/10.3390/su151411132>

Academic Editor: Yagang Zhang

Received: 7 June 2023

Revised: 8 July 2023

Accepted: 10 July 2023

Published: 17 July 2023



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1. Introduction

Recently, power generation from renewable sources such as solar and wind is receiving more attention as their operation is pollution free to reduce the environmental impact of fossil fuels [1,2]. Photovoltaic (PV) is the fastest-growing renewable system, and it directly converts solar energy to electrical energy. The power generated from the PV source can also be utilized for chemical energy transformation, such as hydrogen fuel cells [3–5]. The power generated from a PV system varies according to the temperature and irradiation received

at any instant [6–8]. To generate the maximum available power from the PV system under varying irradiation and temperature, maximum power point tracking (MPPT) methods are integrated [9,10].

On the other hand, the optimal tilt and orientation of the PV panels can improve the solar yield, as reported by a study conducted in the United Arab Emirates (UAE) [11]. However, the optimal tilt and orientation are region-dependent and vary considerably. The Kingdom of Saudi Arabia in the Sun Belt region experiences high irradiance levels between 4.479 kWh/m² and 7.004 kWh/m², depending on the geographical location [12]. This available abundance of solar power is being utilized and integrated into the grid by the kingdom. The 300 MW Sakaka PV power plant is the first renewable-based power source covering an area of six square kilometers in Saudi Arabia [13]. Power generation based on PV is growing fast, and different developing countries are generating and integrating this power into their respective grids [14,15].

In the case of uniform irradiance, one maximum power point appears in the PV array characteristics curve that the conventional MPPT techniques can track. However, due to shadows and clouds, PV arrays receive non-uniform irradiation, creating multiple maximum points in the PV array curve. Many modern MPPT techniques are proposed to handle the numerous maximum points since most conventional MPPT methods fail under such circumstances. One of the most crucial factors in choosing a proper MPPT method mainly lies within three specifications. The first factor is performance, which is the tracking speed and accuracy. The second factor is the complexity of the control system, voltage and current sensors, parameter tuning or perturbation, and partial shading detections. The third factor is the cost of the entire MPPT system.

Several MPPT techniques for PV systems have been proposed in the last decade, and the methods developed so far can be broadly classified into MPPT-based and circuit-based methods. The MPPT-based method is classified as conventional, soft computing, and hybrid techniques. Some of the techniques classified under the traditional approach include fractional short circuit (FSC) [16,17], fractional open circuit (FOC) [18], perturb and observe (P&O) [19–24], incremental conductance (IC) [25–32], hill climbing (HC) [33–35], curve fitting (CF) [36], constant voltage (CV) [37,38], and ripple correlation control (RCC) [39]. FSC and FOC methods are less accurate and perform better only in low-power applications. Although the popular MPPT techniques such as P&O, HC and IC can track the maximum power under uniform irradiation, they fail to operate under partial shading properly and have slow tracking speed, poor convergence, and high steady-state oscillations. Hence, conventional methods should work with other methods to track the maximum power under partial shading conditions [40–43].

Since PV systems have nonlinear characteristics, soft computing methods have been proposed by researchers to handle non-linearity and are considered the prime choice for nonlinear optimization. Numerous soft computing techniques for MPPT application are proposed, including fuzzy logic control (FLC) [44–48], artificial neural network (ANN) [49–52], genetic algorithm (GA) [53–56], particle swarm optimization (PSO) [57–60], nonlinear control [61], chaotic approach (CA) [62], differential evolution (DE) [63–65], simulated annealing (SA) [66], grey wolf optimization (GWO) [42,67–69], cuckoo search [70–72], bat search algorithm, bee colony search algorithm [73,74], ant colony optimization [75–78], firefly algorithm [79], and random search methods [80]. PSO is the most popular and widely used optimization technique to track the maximum power in PV systems. Although FLC and ANN effectively track the maximum power, they require large memory and data for training and implementation. They also need detailed knowledge of the system while implementing the algorithm.

To enhance the performance of MPPT methods under partial shading, researchers combined conventional techniques with soft computing techniques to form hybrid strategies. Some of the developed hybrid techniques include incremental conductance combined with firefly algorithm (IC-FFA) [81], perturb and observe with artificial neural network (P&O-ANN) [82], perturb and observe with fireworks (P&O-FWA) [83], perturb and

observe with grey wolf (P&O-GWO) [84], perturb and observe with genetic algorithm (P&O-GA) [85], perturb and observe with bat search algorithm (P&O-Bat) [86] and perturb and observe with particle swarm optimization (P&O-PSO) [87,88]. Two or more intelligent algorithms such as particle swarm optimization and simulated annealing (PSO-SA) [89], particle swarm optimization and fish swarm [90,91], differential evolution with Jaya algorithm (DE-Jaya) [92], and differential evolution with whale optimization (DE-WO) [93] can also be combined to form hybrid methods.

This paper presents a detailed, organized, and up-to-date review of the different maximum power point tracking (MPPT) algorithms for photovoltaic (PV) systems. The advantages and disadvantages of each method are presented to assist power utilities and power engineers in choosing the proper MPPT method while designing a PV generation system under partial shading conditions. Hybrid MPPT methods based on the combination of soft computing and conventional methods are more efficient than the other methods. However, reducing the complexity of practical implementation is a challenge and a research direction that should be addressed. Moreover, MPPT methods based on optimization face challenges with respect to periodic tuning, accuracy, stability, and the number of send parameters.

The rest of the paper is organized as follows; Section 2 describes the PV configuration, Section 3 presents the details of PV under partial shading, Section 4 describes the dynamic tracking and classification of MPPT methods under partial shading, Section 5 is the discussion, and Section 6 concludes the paper.

2. PV Configuration

The five-parameter electric circuit model of a PV cell is shown in Figure 1 [94–96]. It consists of a light-dependent current source, a p-n junction diode, and two resistances, one in series and the other in parallel.

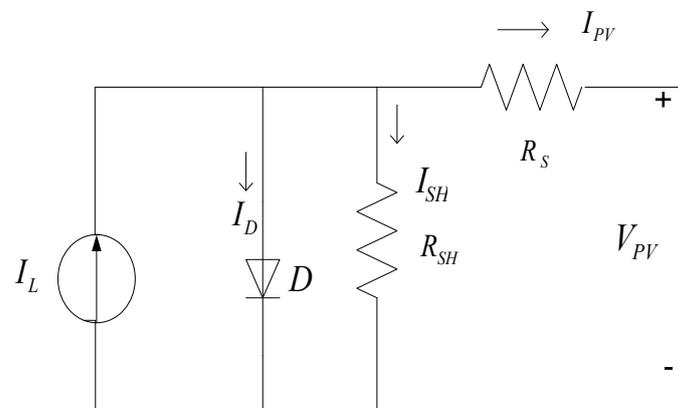


Figure 1. Five-parameter equivalent electric circuit model of a PV cell.

Using simple Kirchoff's current law:

$$I_{PV} = I_L - I_D - I_{SH} \quad (1)$$

where I_D and I_{SH} depict the diode and shunt branch currents, respectively, and are given by:

$$I_D = I_0 \left\{ \exp \left[\frac{V_{PV} + I_{PV} R_S}{a} \right] - 1 \right\} \quad (2)$$

$$I_{SH} = \frac{V_{PV} + I_{PV} R_S}{R_{SH}} \quad (3)$$

Putting these expressions of I_D and I_{SH} into Equation (1) gives the complete I-V characteristics of a PV panel:

$$I_D = I_L - I_0 \left\{ \exp \left[\frac{V_{PV} + I_{PV} R_S}{a} \right] - 1 \right\} - \frac{V_{PV} + I_{PV} R_S}{R_{SH}} \quad (4)$$

where I_{PV} and V_{PV} represent the current and voltage generated from the PV panel. I_L is the light-generated current, I_0 is the diode saturation current, R_S and R_{SH} are the series and parallel resistance, respectively, and factor a is the diode-modified ideality factor, which is given by:

$$a = \frac{N_s n K T}{q} \quad (5)$$

where N_s is the number of cells in the PV panel, n is the ideality factor (it has a value between one and two for the real diode), K is Boltzmann's constant, T is the cell temperature, and q is the electronic charge.

A standard PV cell generates a relatively low voltage (around 0.6 V); hence, PV cells are connected in series and parallel to raise the appropriate voltage level for the required application. PV modules are built using the PV cells' series and parallel connections; a PV array consists of PV modules connected in series or parallel [97]. Equation (4) can be modified to represent the I-V relationship of the series and parallel array and written as:

$$I_{PV} = N_{pp} * I_L - N_{pp} * I_0 \left\{ \exp \left[\frac{V_{PV} + I_{PV} R_S * N}{N_{ss} * a} \right] - 1 \right\} - \left(\frac{V_{PV} + I_{PV} R_S * N}{R_{SH} * N} \right) \quad (6)$$

$$N = \frac{N_{ss}}{N_{pp}} \quad (7)$$

where N_{SS} and N_{PP} represent the number of panels connected in series and parallel, respectively. Figure 2 depicts the current–voltage characteristics of PV panels for different irradiation levels from 200 W/m² to 1000 W/m² and a constant temperature of 25 °C.

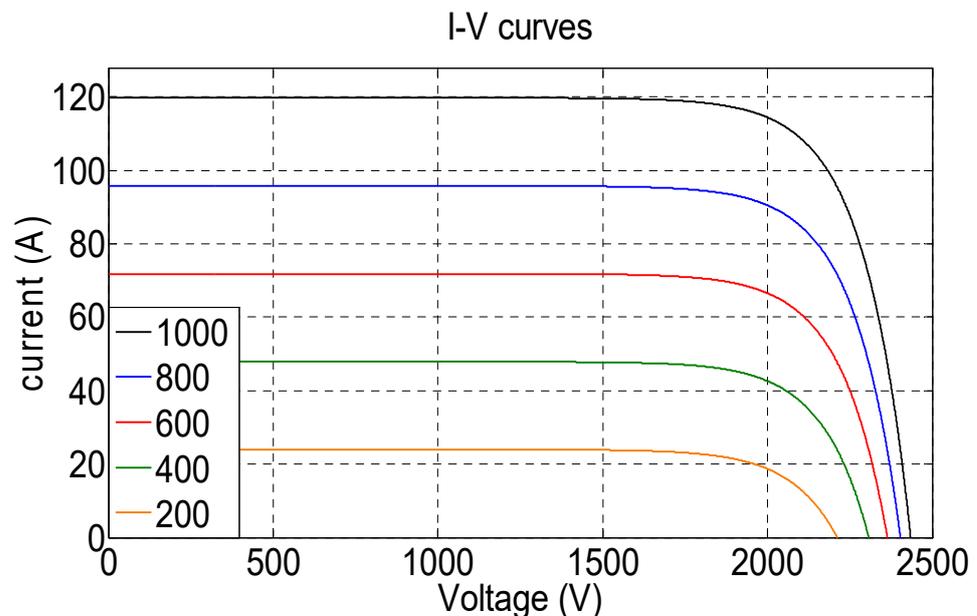


Figure 2. Current–voltage characteristics of a PV panel under different irradiation levels.

3. Maximum Power Point Tracking (MPPT) Methods for Partial Shading

PV arrays consisting of several panels are the most basic units of any PV system. Based on the I–V curve depicted in Figure 3, the PV operating point can vary from zero to the open circuit voltage. The operating point varies with the load variation and does not always stay at the maximum power point. A unique maximum power point (MPP) operating point exists in the I–V and P–V curves for every irradiation and temperature. This point keeps shifting when any atmospheric change occurs [98,99]. Thus, maximum power point tracking (MPPT) controllers are designed to keep tracking MPP, and they form an integral part of PV systems. Figure 3 also depicts the maximum operating point, P_{mp} , V_{mp} , and I_{mp} , for a PV panel. In a uniform insolation case, the total maximum output power of a PV array is equal to the sum of the maximum power values of all individual modules.

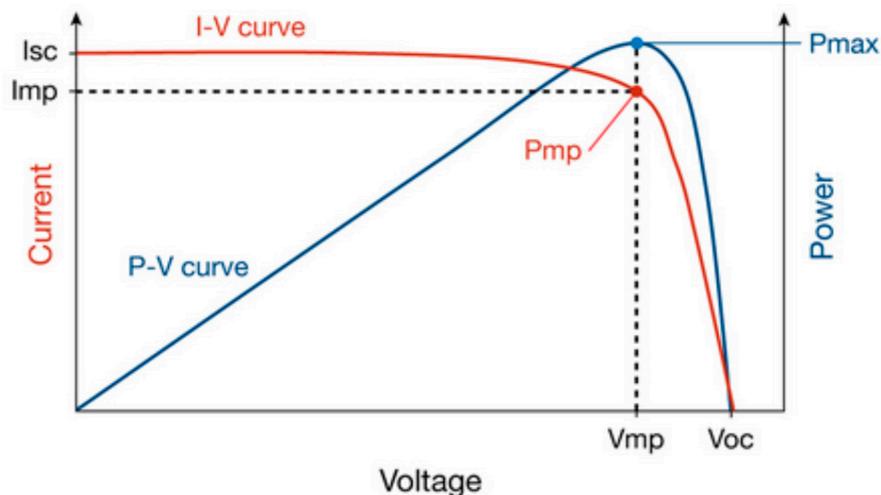


Figure 3. Maximum power point characteristics for I–V and P–V curves.

A significant impact on the operation of PV modules is shading caused by cloud cover, trees, or buildings. When one or more of the modules in a solar panel comes under the effect of shading, the module voltage drops causing it to work as a load rather than as a generator, and this causes a hot spot problem [100–102]. Each PV module is equipped with a bypass diode to overcome the hot spot formation. However, adding the bypass diode creates multiple peak points in the P–V curve.

Among the multiple peaks, one is the global maximum power point (GMPP) and the others are local maxima power points (LMPPs). Multiple maximum points can confuse traditional MPPT schemes as they can easily track and settle at a local maximum, which reduces the available power output from the PV array. A reliable technique is required to track the GMPP appropriately [103–105]. Conventional MPPT techniques cannot identify the GMPP under partial shading conditions (PSC) and usually track local peaks reducing the generated power from the PV system.

Figure 4 shows a PV module where PV modules 3 and 4 are shaded in Figure 4b due to environmental conditions. The bypass diodes provide an alternate path for the current flow, creating multiple peaks. The P–V curve shown in Figure 5 depicts the numerous maxima during PSC. Modern soft computing MPPT techniques are developed to track the GMPP as the conventional methods fail to differentiate between the GMPP and the LMPPs [106–108]. The MPPT methods for partial shading mitigation techniques will be explained in detail in the next section.

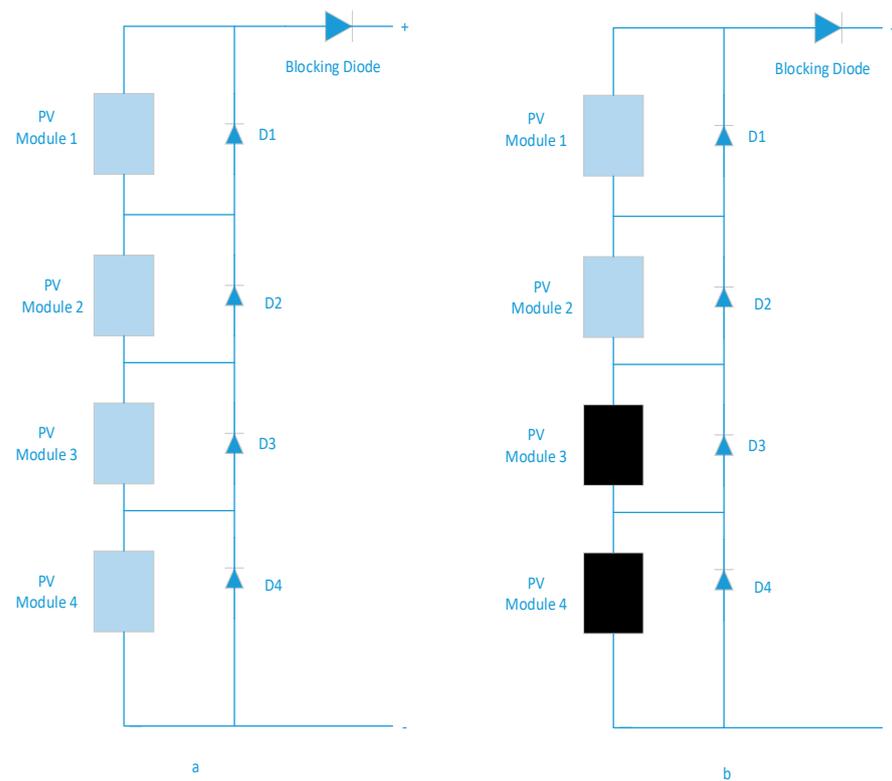


Figure 4. PV modules: (a) no shading and (b) modules 3 and 4 are shaded.

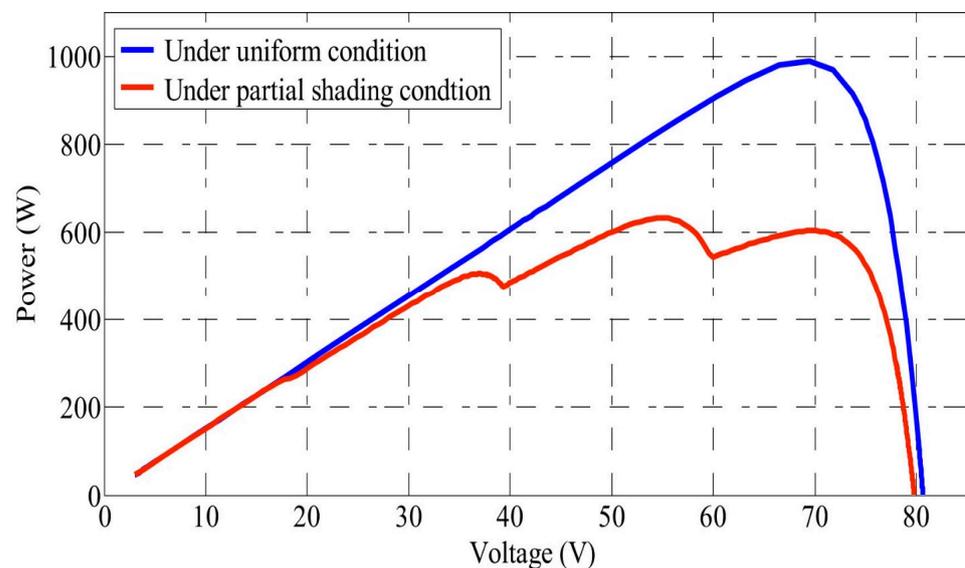


Figure 5. PV array output power characteristics under normal and partial shading.

4. Dynamic Tracking under Partial Shading

Partial shading reduces the overall efficiency of the PV system. To generate the maximum available power from the PV system under this non-uniform environmental condition, partial shading mitigating techniques are essential for the PV system working in grid-connected or standalone modes. Conventional MPPT methods have fixed step sizes and usually become trapped in local peaks, and they fail to dynamically track the MPP under partial shading conditions.

Partial shading mitigation techniques are broadly classified into two major groups. The first group includes all the MPPT-based methods, which have been further classified into

modified conventional, soft computing, and hybrid techniques, and the second group comprises circuit-based topologies. The classification of MPPT techniques under partial shading is provided in Figure 6. The conventional MPPT methods under uniform irradiation, such as P&O, IC, and HC, are thoroughly discussed in the literature and will not be covered in this paper. This section provides MPPT techniques under partial shading conditions.

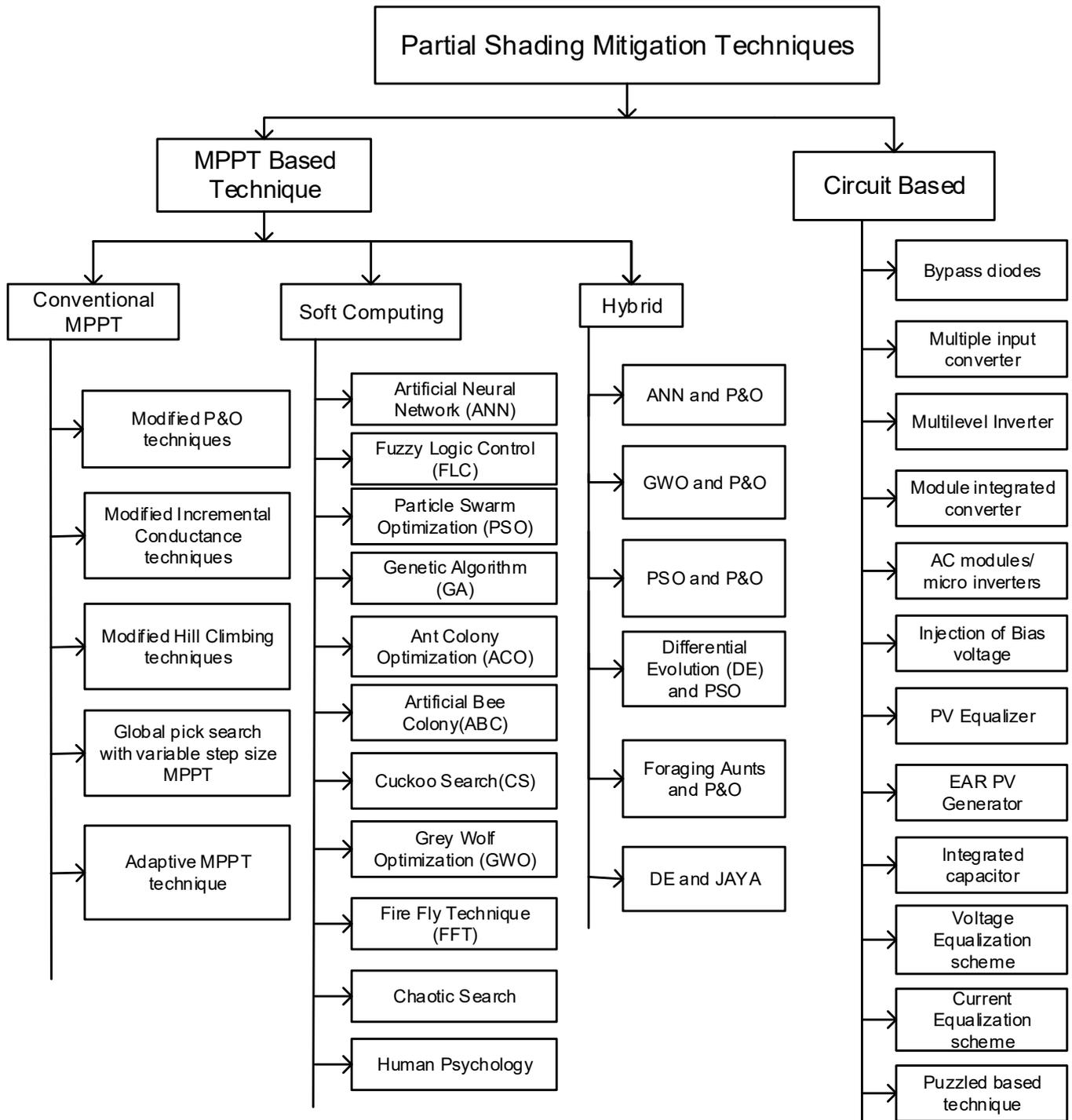


Figure 6. Classification of different MPPT schemes for shading mitigation.

4.1. MPPT-Based Techniques

4.1.1. Conventional MPPT

1. Modified Perturb and Observe (P&O) technique

The conventional P&O MPPT method has limitations during partial shading; hence, overcoming this limitation is required to track the global peak. Figure 7 depicts the flow chart of a modified P&O proposed by [109], where two routines are used. The first routine is the main program and sets a reference voltage close to the open circuit voltage. The main routine scans almost 80% of the P–V curve not to miss the potential global peak. The second is the global peak-tracking routine, which is called into action after executing the main program. Although the proposed method efficiently tracks the international peak, the tracking speed is compromised since the algorithm scans almost the entire P–V curve. Another modified P&O, by comparing two instantaneous power values presented in Equation (8), is proposed in [110].

$$\frac{P_m(t) - P_{ref}(t)}{P_m(t-1)} < \varepsilon \quad (8)$$

where

$P_m(t)$ is the instantaneous measured power and
 $P_{ref}(t)$ is the instantaneous reference maximum power.

The algorithm efficiently tracks the global peak; however, new coefficients are introduced that complicate the overall MPPT process. The authors in [111] proposed another modified P&O MPPT method by periodically changing the PV array voltage from maximum to minimum. A microcontroller is used to store the operating voltage and current. The P&O is used to maintain the operation of the PV system after identifying the region of the global peak.

2. Modified Incremental Conductance (IC)

The conventional incremental conductance fails to track and recognize the true MPP as the method is based on derivative characteristics. In both global and local peaks, the derivatives dP/dV or dP/dI are zero; hence, the IC method should be modified to identify the true MPP. A two-stage IC method similar to the modified P&O is proposed in [112], wherein in the first stage, the value of the maximum voltage and current are used to force the PV system to operate close to the global peak. Equation (9) describes the first stage as:

$$R_{MP} = k \frac{V_{MP}}{I_{MP}} \quad (9)$$

where

k is the correction factor, and

V_{MP} and I_{MP} are approximately 80% of V_{OC} and 90% of I_{SC} , respectively.

V_{OC} and I_{SC} are the open circuit voltage and short circuit current, respectively.

The second stage moves the operating point toward the global peak. A linear function to track the global peak is presented in [113] and is expressed as:

$$V_* = \frac{V_{grid}}{I_{out}} I(k) \quad (10)$$

where

V_{grid} is the output grid voltage and

I_{out} is the output grid current.

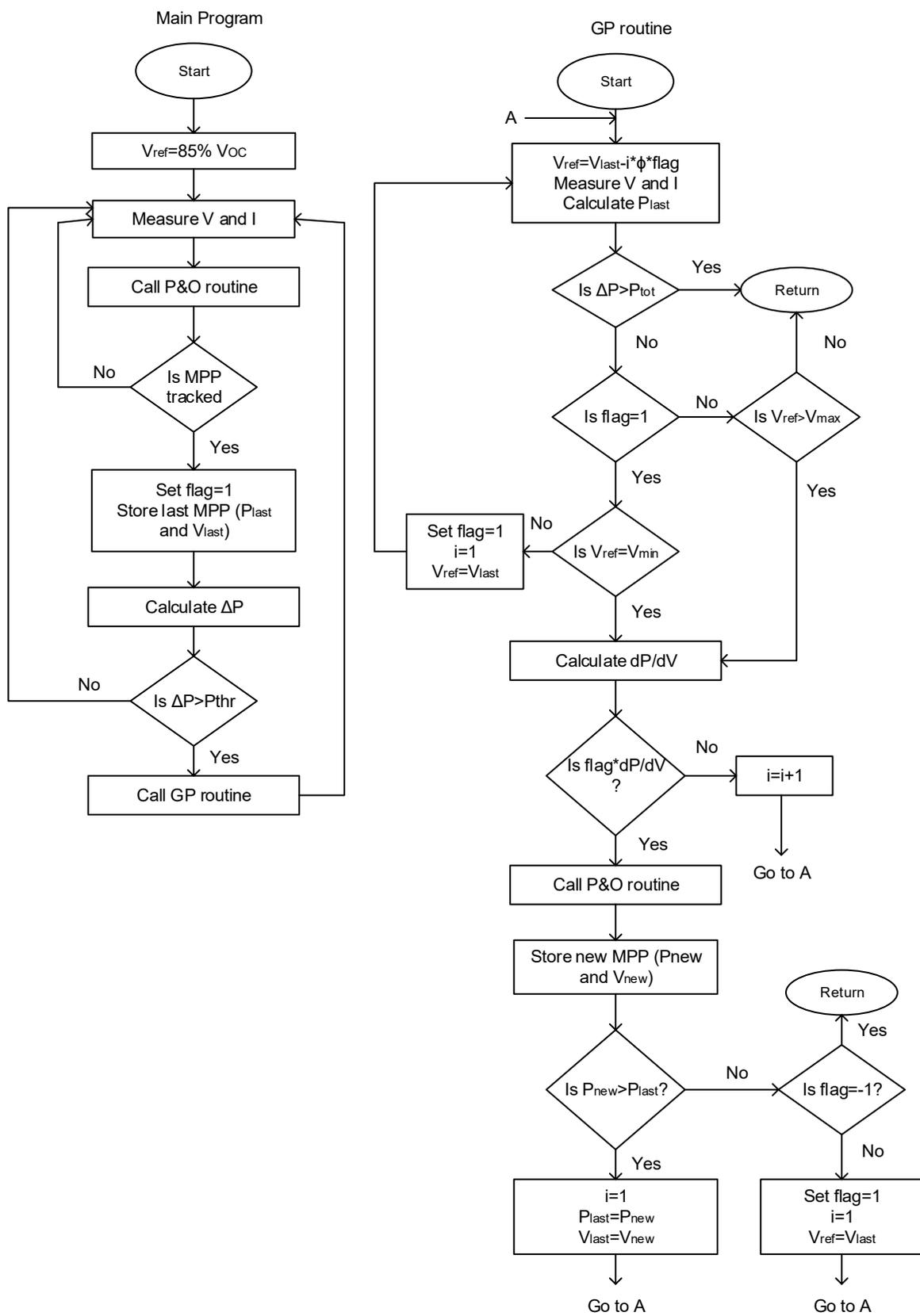


Figure 7. Modified P&O.

Equations (11) and (12) are used to detect the occurrence of partial shading and activation of the linear function.

$$V(k) - V(k - 1) < V_{thr} \quad (11)$$

$$\frac{I(k) - I(k - 1)}{I(k - 1)} < I_{thr} \quad (12)$$

Although the proposed technique efficiently tracks the global peak, it can be applied only for grid-connected PV systems.

3. Modified Hill Climbing (HC)

Like the other conventional methods, the hill climbing method also fails to track the global peak. Several authors proposed a modified HC method to track the maximum available power under partial shading. A modified HC method based on sweeping the duty cycle is presented in [114]. Equation (13) is used to determine the initial value of the duty cycle as:

$$D = 1 - \sqrt{\frac{R_{MP}}{R_{Load}}} \quad (13)$$

where R_{Load} is estimated using the rating of the PV array.

Similar to the modified IC, this method must also scan over 80% of the P–V curve. A multiple-input boost converter for micro-inverters based on modified HC is discussed in [115].

4.1.2. Soft Computing MPPT Techniques

1. Artificial Neural Network (ANN)

Artificial neural networks (ANNs) provide a mechanism to use environmental conditions such as irradiation, temperature, and shading to predict the PV system operation point corresponding to the MPP [116–118]. The input parameters for the ANN are usually PV voltage (V_{PV}), PV current (I_{PV}), irradiation, and temperature. After processing the input variables, the ANN provides an output signal: the optimal voltage V_{MPP} , optimal current I_{MPP} , and duty cycle [119,120]. The ANN is trained based on the experimental measurements and simulation results and mostly uses a back-propagation (BP) training algorithm [121–123]. Figure 8 presents the ANN structure.

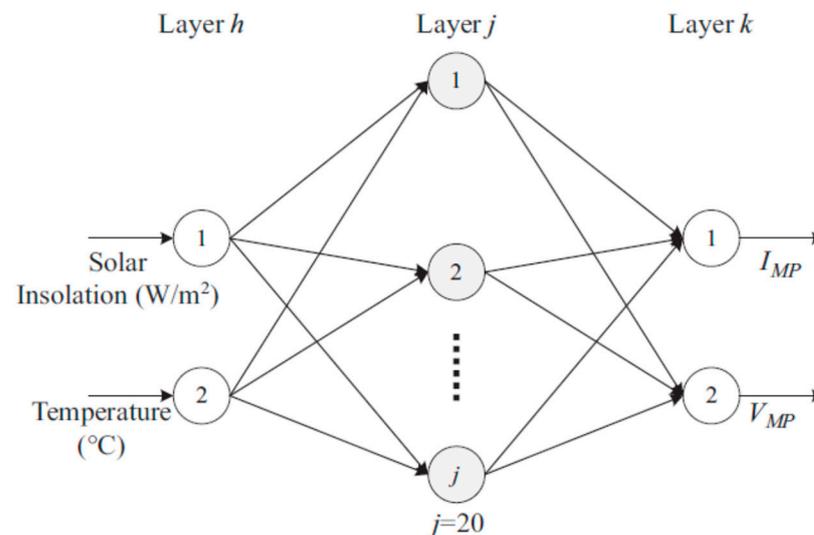


Figure 8. ANN structure [124].

2. Fuzzy Logic Control (FLC)

Similar to ANNs, the FLC does not need the internal parameter and mathematical model of the system. However, prior knowledge of the relationship between input and output is required. Figure 9 presents the control structure of the FLC. Besides input and output, the typical control structure has four control blocks: fuzzification, rules inferences, rule table, and defuzzification. The rule inference performs the calculation based on the rule table [125,126]. Error E and change in error ΔE are the usual input signals for the FLC-based MPPT. Equations (14) and (15) present the error and change error input signal calculation.

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \text{ or } E(k) = \frac{P(k) - P(k-1)}{I(k) - I(k-1)} \quad (14)$$

$$\Delta E = E(k) - E(k-1) \quad (15)$$

After being converted to a linguistic variable, the error and change in error will be used as input variables to the FLC. The FLC provides output signals in the form of a change in voltage (ΔV), change in current (ΔI), or change in duty cycle (ΔD).

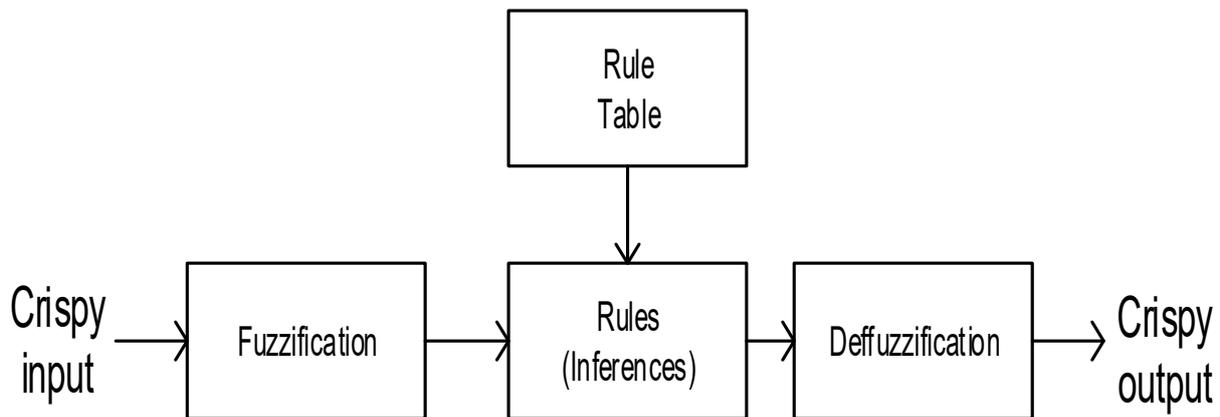


Figure 9. FLC structure.

3. Particle Swarm Optimization (PSO)

PSO is a population-based search method modeled after the behavior of bird flocks [127]. PSO has been popular to optimize and solve nonlinear problems in the last decade. It works by assigning random initial values to the particles in the boundary limits. The particles represent the duty cycle of the DC–DC converter and are optimization solutions. Particles move around the search space, and its best movement in the initial phase is called P_{best} . The overall best movement in the subsequent iteration is called G_{best} . Each particle is represented in the search space by its velocity (V_i) and position (X_i), and these parameters are updated in each iteration until the best solution is found [128,129]. The particles' velocity and position are updated using Equation (16):

$$\begin{aligned} V_i(k+1) &= WV_i(k) + C_1 rand_1 * (Pbest_i(k) - X_i(k)) + C_2 rand_2 * (Gbest_i(k) - X_i(k)) \\ X_i(k+1) &= X_i(k) + V_i(k+1) \end{aligned} \quad (16)$$

where

$V_i(k+1)$ is the particle velocity at $k+1$ th iteration,

W is the inertia weight,

$V_i(k)$ is the particle velocity at the k th iteration,

C_1 is the acceleration component associated with G_{best} ,

$X_i(k+1)$ is the particle position at $(k+1)$ th iteration,

$X_i(k)$ is the particle position at the k th iteration,

C_2 is the acceleration component associated with P_{best} , $rand_1$ and $rand_2$ are random numbers from zero to one, G_{best} is the best position of all particles, and P_{best} is the best position of the particle.

The objective function of the PSO optimization is to find the global voltage and power in the P–V characteristics curve. It is started by initializing parameters such as the swarm size (N), maximum iteration, and the voltage and power variable dimension that must be optimized. The global voltage with respect to Equation (16) is given as:

$$X_i(k) = V_g = [V_{g1}, V_{g2}, V_{g3}, V_{g4} \dots V_{gj}] \quad (17)$$

$$j = 1, 2, 3, \dots, N$$

The best value of voltage and power that the PSO has found so far will be stored in P_{best} , and the process continues until G_{best} , the best solution, is found.

The disadvantage of PSO is that since the initial position of the search agent is randomly provided depending on the boundary limit, there is a delay in the convergence. This can sometimes trap the algorithm to settle to local MPP during partial shading conditions [130,131].

4. Grey Wolf Optimization (GWO)

The GWO imitates the hunting techniques of grey wolves using a meta-heuristic optimization approach [132–135]. Four parameters, alpha (α), beta (β), delta (δ), and omega (ω), are used to represent the attaching techniques of the wolves. The fittest solution in the optimization is assumed to be α and followed by β . The third and fourth fit solutions are δ and ω , respectively. Figure 10 presents the flow chart of the GWO algorithm. Equation (18) presents the model of the hunting mechanism of grey wolves.

$$\vec{E} = \left| \vec{C} \cdot X_p - X_p \right| \quad (18)$$

$$\vec{X}(t+1) = \vec{X}(t) - \vec{F} \cdot \vec{E}$$

where

E, F , and C are the coefficient vectors,
 X_p is the position vector of the hunting prey,
 X is the position vector for the Grey wolf, and
 t is the current iteration.

The vectors C and F are calculated as follows:

$$\vec{F} = 2 \cdot \vec{a} \cdot r_1 - \vec{a} \quad (19)$$

$$\vec{C} = 2 \cdot r_2$$

The GWO fitness function is calculated as follows:

$$d_i(k+1) = d_i(k) - F \cdot E \quad (20)$$

$$P(d_i^k) > P(d_i^{k-1})$$

where

d is the duty cycle,
 k represents the iteration count,
 i is the number of the current individual grey wolves, and P is the power.

The major advantages of the GWO technique are higher tracking efficiency and elimination of transient and steady-state oscillations [136,137].

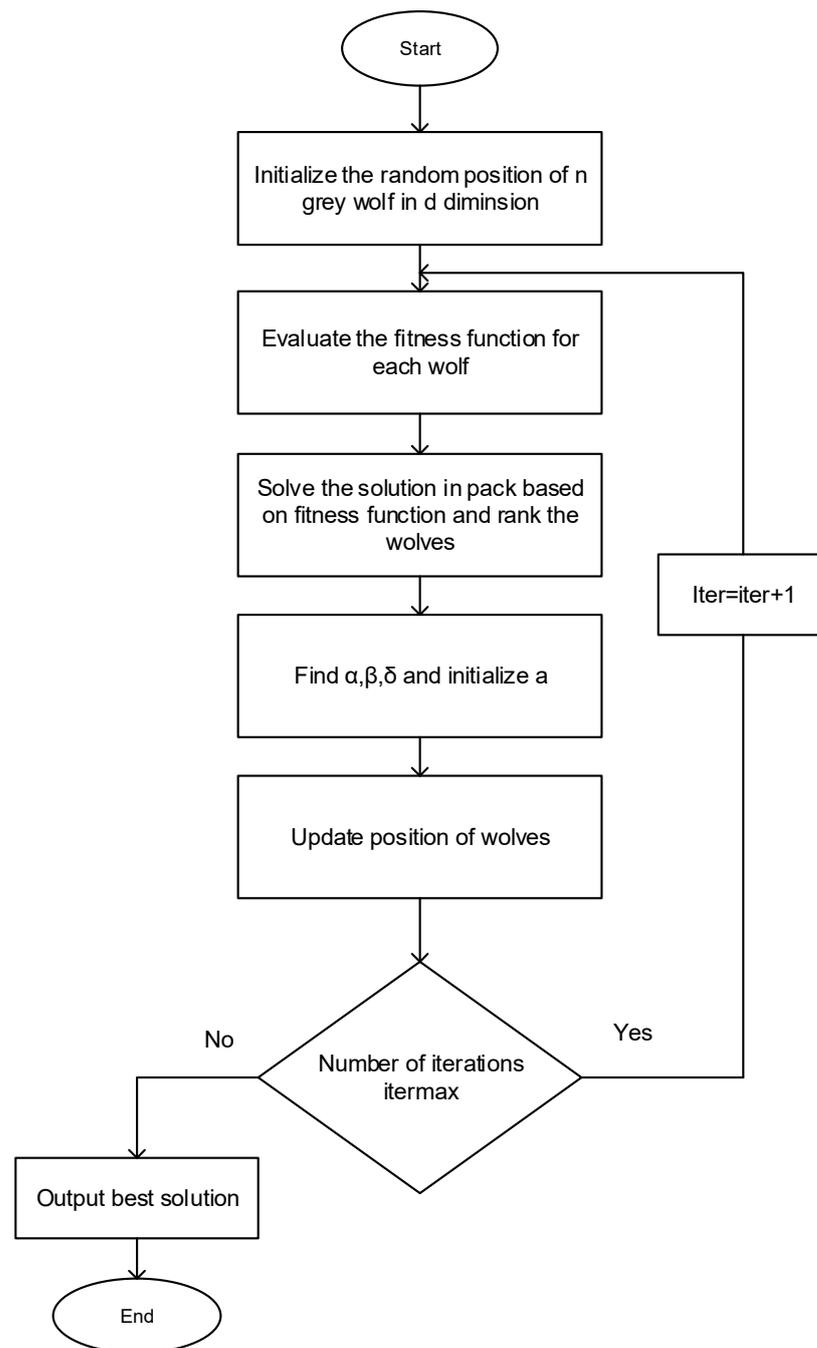


Figure 10. Flowchart of Grey Wolf Optimization.

5. Firefly Algorithm (FA)

The Firefly algorithm is developed from the characteristic relationship between line intensity and fireflies [138]. Different authors proposed a FA that can track the global peak of PV systems under partial shading. Two variables, namely γ , the light absorption coefficient, and α , the random coefficient, are used to randomize the first position of the firefly. A modified version of FA called simplified firefly algorithm (SFA) is proposed in [139,140], where the initial position of the firefly is selected between zero and one. The optimization equation of SFA is represented as:

$$X_i^{t+1} = X_i^t + \beta(X_j - X_i) \quad (21)$$

where

X_i represents the position of the less bright firefly,
 X_j represents the position of the brighter firefly, and
 β is the firefly attractiveness factor.

The objective function of SFA is to generate the maximum available photovoltaic output power, and the firefly position represents the duty cycle d .

6. Ant Colony Optimization (ACO)

ACO is an optimization technique based on the food-searching behavior of ants. ACO is an efficient and robust MPPT tracking the global peak of PV systems during partial shading conditions [141]. Different researchers evaluated the technique under varying irradiance and different shading patterns. The algorithm has a fast tracking speed of around one-tenth of the conventional MPPT methods for partial shading conditions [142,143].

7. Artificial Bee Colony (ABC)

Similar to ACO, ABC algorithms are an optimization technique based on the food-searching behavior of bees. The advantage of this algorithm is that it uses few parameters, and the convergence criteria are not dependent on the initial condition of the system [74]. The disadvantage of this method is that it is complex for practical implementation, and the tracking speed is slow compared to other MPPT methods used for partial shading conditions. The algorithm sometimes settles at the local peak rather than tracking the global peak [144]. The algorithm classifies the artificial bees into three categories: employed bees, onlooker bees, and the last scouts. Figure 11 depicts the flow chart of ABC, where the algorithm has four phases. The first phase initializes the algorithm by setting the different parameters. The second phase activates the employed bees searching for food, and the third phase activates the onlooker bees waiting in the hive to decide. The fourth phase is the scouting phase, where the bees search for random food sources. All three groups communicate and coordinate to obtain the optimal solution quickly. In the algorithm, the food source is the maximum power, and the duty cycle of the DC–DC converter is the food position. For implementing ABC in MPPT for PV system, the duty cycle for the DC–DC converter is calculated as follows:

$$\begin{aligned} d &= d_{\min} + \text{rand}[0, 1](d_{\max} - d_{\min}) \\ \text{newd} &= d + \phi_e(d - d_p) \end{aligned} \quad (22)$$

where

d is the current duty cycle,

d_{\min} is the minimum value of the duty cycle,

d_{\max} is the maximum value of the duty cycle),

ϕ_e is a constant between $[-1, 1]$, and

d_p is the previous duty cycle.

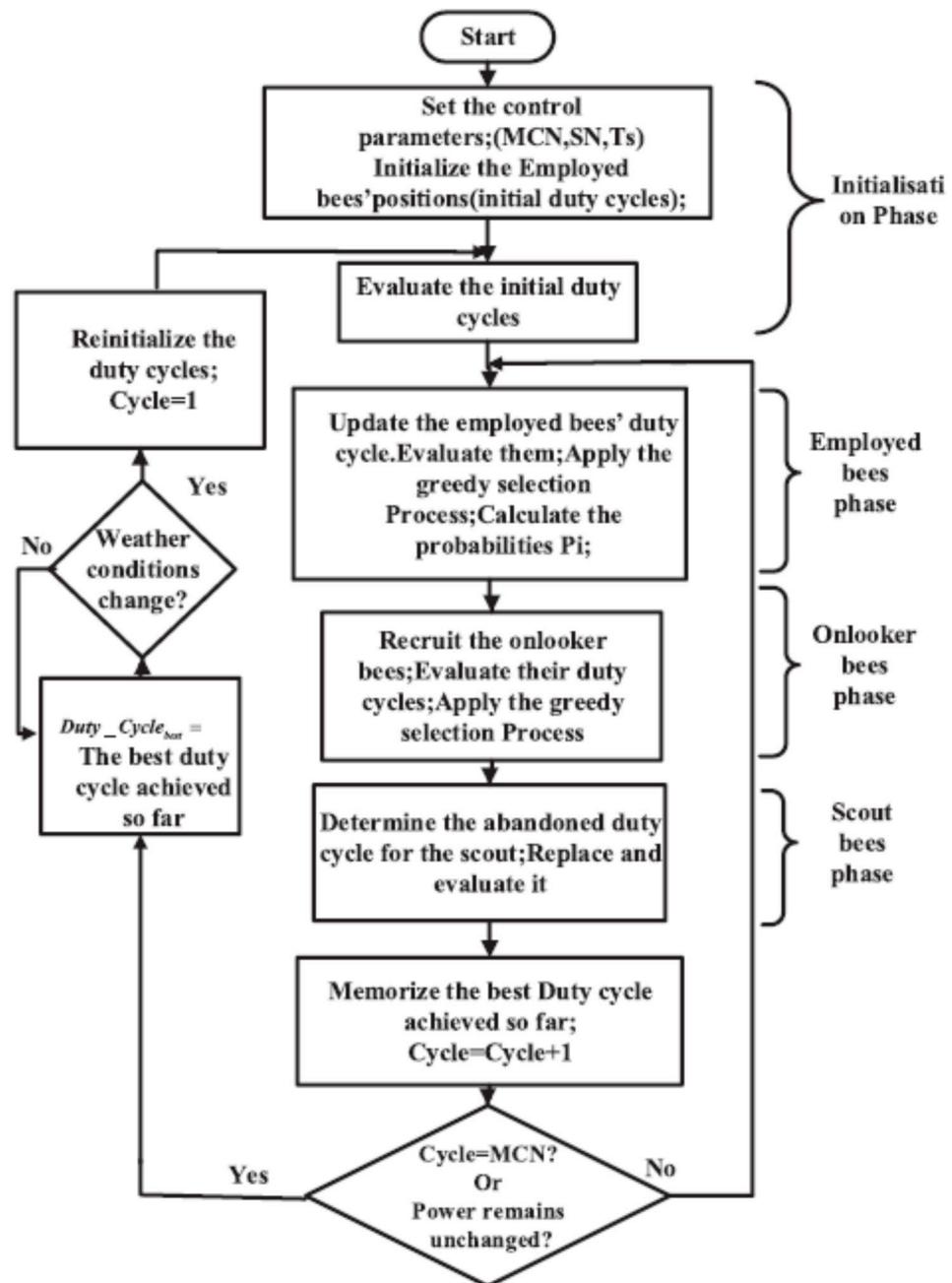


Figure 11. Flow chart of artificial bee colony optimization [145].

8. Cuckoo Search (CS)

The CS method is another optimization technique based on the levy flight mechanism of cuckoo birds [146,147]. The levy flight mechanism algorithm represents the cuckoos' search for a nest. The algorithm is a modified form of PSO with robust performance, high convergence speed, and efficiency. CS needs less tuning variables compared to PSO [148].

9. Jaya Algorithm (JA)

R.V. Rao introduced JA, which is based on animal activities [149]. The algorithm is based on the distinct feature of animals or humans from the population. Naturally, humans or animals try to mimic the elite members of society and want to distance themselves from the lazy group. Figure 12 presents the flow chart of the JA. The candidate solution moves towards the best solution and tries to move away from the worst solution. The algorithm's

simplicity and fast convergence make it the primary choice by different researchers to solve various engineering problems [150,151].

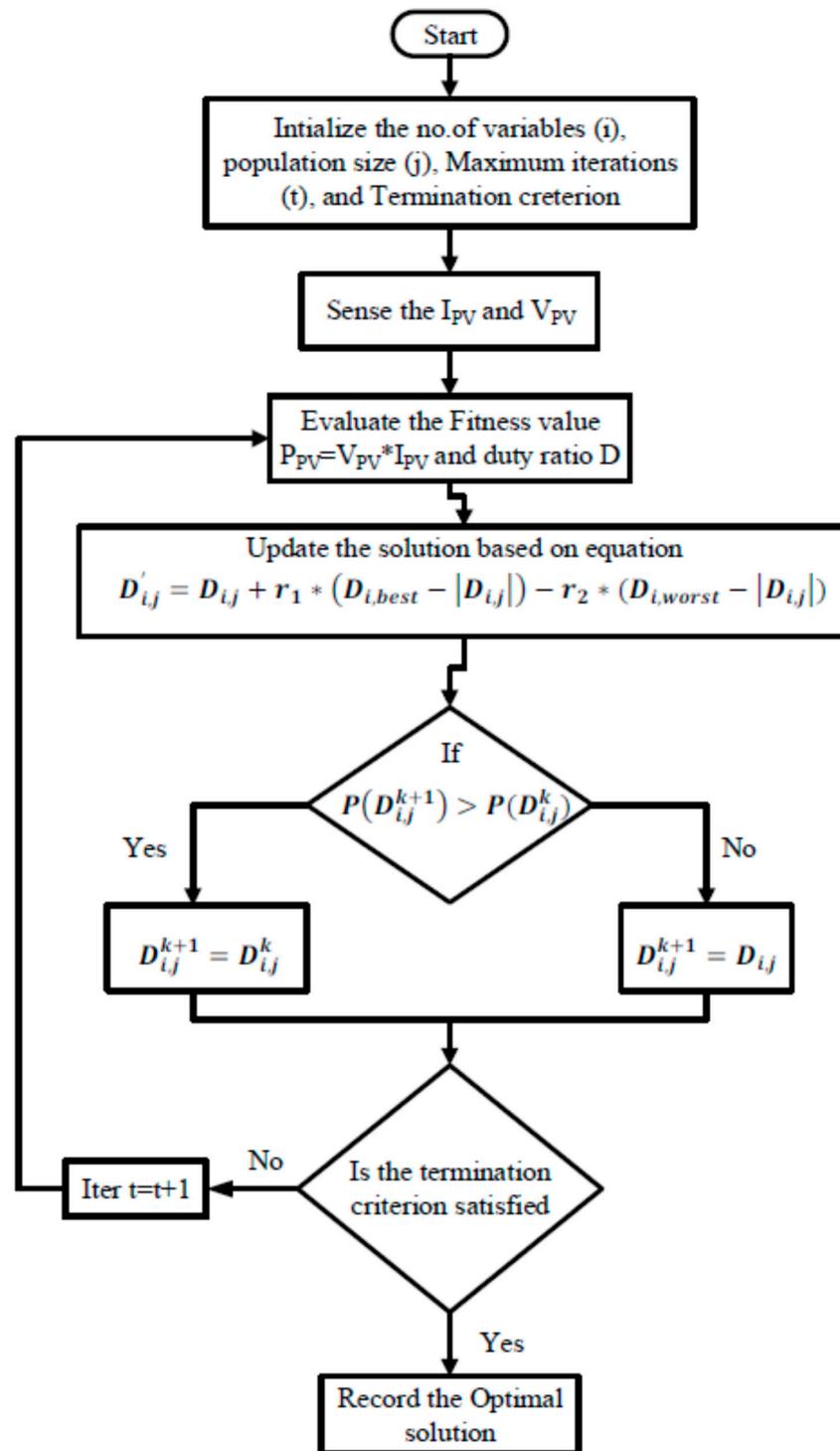


Figure 12. Flow chart of Jaya algorithm [152].

4.1.3. Hybrid MPPT Techniques

1. Hybrid GWO and P&O MPPT Algorithm

The authors in [84] combined P&O and GWO to enhance the performance of the MPPT control of the PV system under partial shading. The method works in two phases. In the first phase, GWO is implemented, and P&O is activated in the second phase to enhance

the tracking speed. The computational burden and search space have been reduced by hybridizing the two techniques. This hybrid algorithm of GWO and P&O has several advantages, including fast-tracking speed, high efficiency, and high-tracking capability. Figure 13 presents the flow chart of the hybrid method where GWO is executed in the first phase and P&O in the second phase.

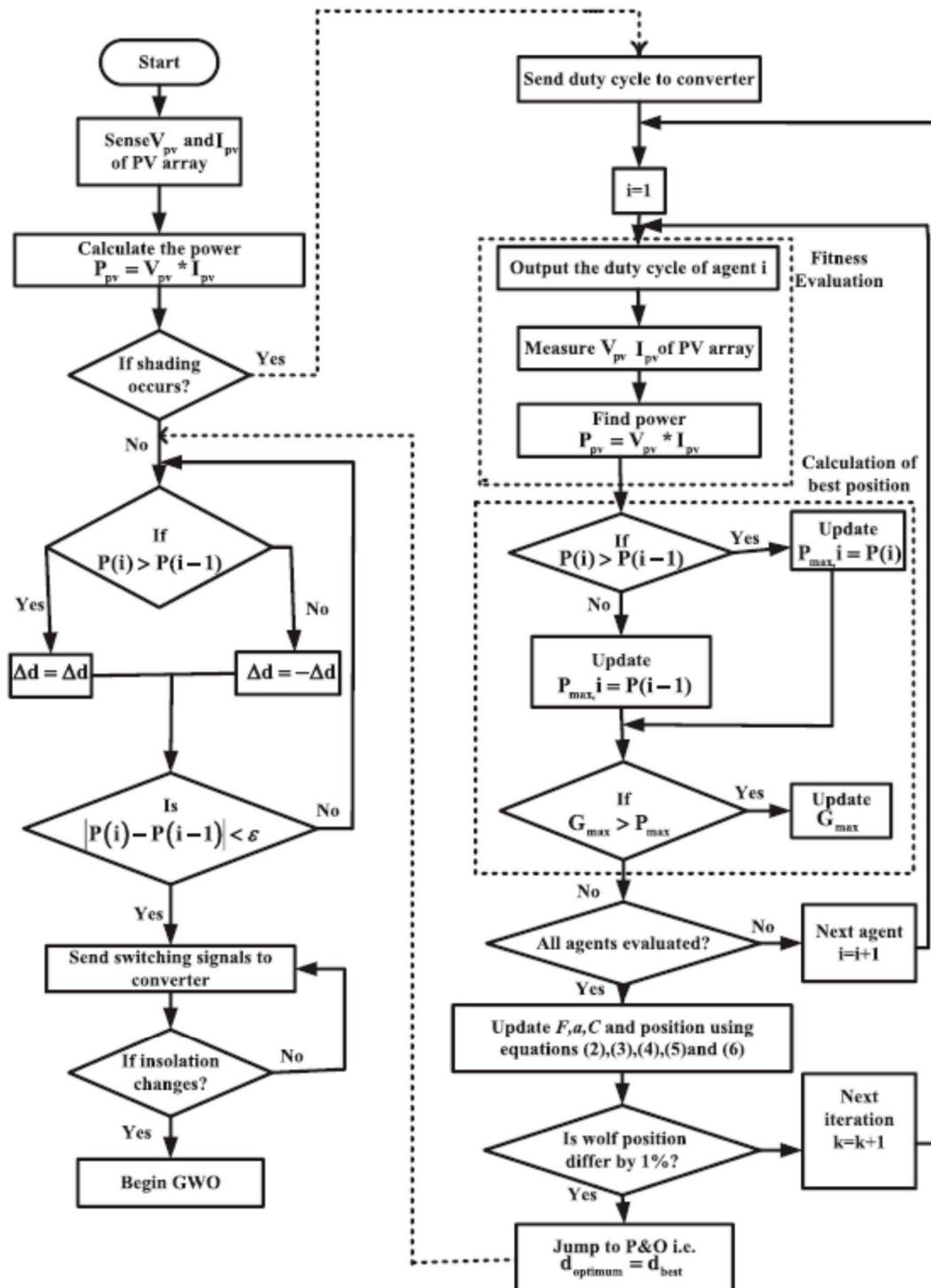


Figure 13. Flowchart of hybrid GWO and P&O algorithm [153].

2. P&O combined with PSO

Another hybrid MPPT technique for partial shading mitigation based on the combination of P&O and PSO is proposed in [154,155]. PSO is used in the initial phase to track the global peak, and then P&O is executed in the final phase. Compared to the conventional PSO, the advantage of this method is that it can track the global peak in a shorter time and has a faster convergence time with better dynamic performance. The hybrid approach has been tested in [154] with different shading scenarios, and to reduce the ripple current, the boost converter is modified to have an interleaved topology.

3. Differential Evolution and PSO (DEPSO)

The PSO, combined with differential evolution (DE), creates an algorithm efficient in tracking the global peak during partial shading conditions [156]. The advantage of the algorithm is that it is system independent and has fast tracking speed. Equation (23) is used to initialize the algorithm using the power fluctuation due to changes in irradiation.

$$\left| \frac{J(X_{q+1}) - J(X_q)}{(X_q)} \right| > \Delta P \quad (23)$$

where $J(X_q)$ is the output power of the PV panel. The algorithm efficiently differentiates the local and global peaks using the power mismatch.

4.2. Circuit-Based Approach

Power converters interface the generated power from the PV system to the grid or local loads. These power converters control the power flow and can enable MPPT controllers under partial shading at different levels of the PV system such as the PV cell, module or array [157]. Besides the power converters, changes in the PV system architecture and converter topology improve the performance of the PV system under partial shading. Some of the techniques the researchers implemented under this category are distributed MPPT, monitoring the bypass diode voltage, differential power processing, and power electronics equalizer, as described below.

4.2.1. Monitoring Bypass Diode Voltages

Monitoring the voltage of the bypass diode is effective in detecting the occurrence of partial shading. Under normal operation, the bypass diode is inactive, however during partial shading it will become active, and a voltage drop will appear across it [158]. Conventional (classical) MPPT techniques such as P&O, IC, and HC are implemented during normal irradiation conditions. Global search to track the global peak can be activated once a voltage drop is sensed in the bypass diode. The method works for module-integrated converters where the PV modules are directly connected to the power converters such as DC–DC converters or DC–AC inverters. The advantage of this method is that, unlike other MPPT methods where periodic scanning of the P–V curve is necessary, this technique is activated by sensing the bypass diode voltage. The drawback of this method is that it works for PV systems where the string voltage is accessible for measurement.

4.2.2. Distributed MPPT

Depending on the connection of the DC–DC converter and the DC–AC inverter used to integrate the PV system-generated power into the grid, there are two types of architectures: central and distributed. In central inverter architecture, one highly rated DC–DC converter and one DC–AC inverter are used where the DC–DC converter performs the MPPT, and the inverter is used for grid integration. This type of architecture does not generate the maximum available power in partial shading. On the other hand, distributed architecture alleviates this problem by providing the MPPT converter for each module. This type of arrangement provides greater flexibility, and the power generated from the PV system is better than from central-based architecture. The distributed-based partial shading mitigation technique connects the DC–DC converter and MPPT for each PV system cell,

module, or array [159,160]. Each system unit works and tracks the MPP independently as a distributed sub-unit. The distributed and centralized MPPT architecture is provided in Figures 14 and 15, respectively. To reduce the cost and complexity of the MPPT for the distributed architecture, conventional MPPT methods such as P&O and IC are used. The advantage of this method is that the system reliability increases as each unit has its controller, and the failure of one of the sub-units does not affect the entire system.

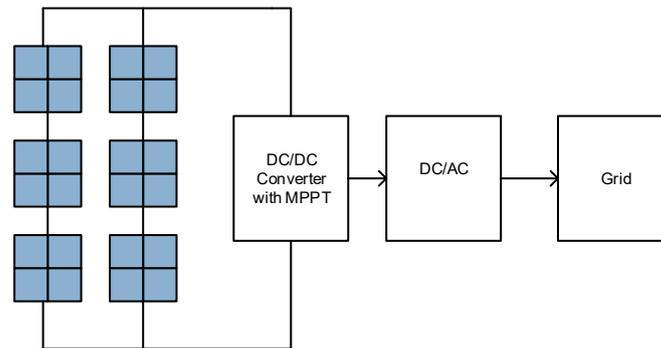


Figure 14. Centralized MPPT architecture.

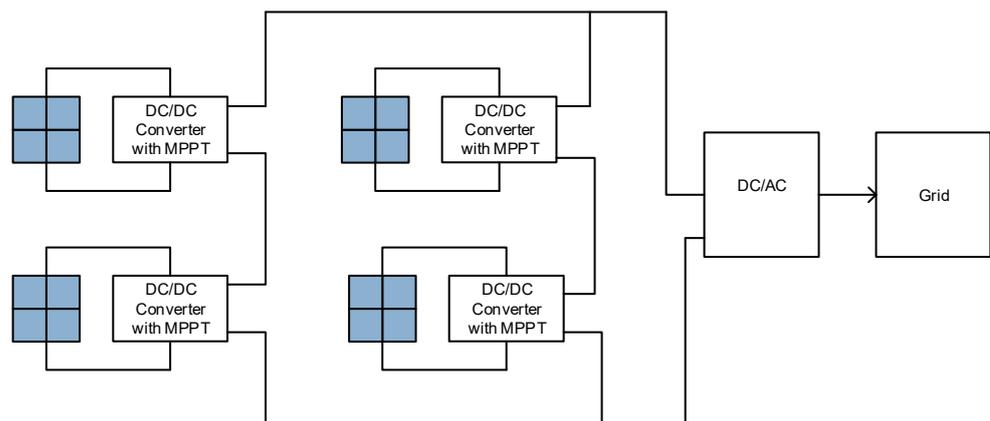


Figure 15. Distributed MPPT architecture.

4.2.3. Differential Power Processing

This method works by placing DC–DC converters between adjacent PV modules [161]. Figure 16 depicts the differential power processing method where the adjacent converters provide the current difference that appears between the current at the MPP of the two modules. The converter will be active when there is a difference in the power generated between the two adjacent modules. Conventional MPPT methods such as P&O and IC are employed for the modules. Compared to the distributed MPPT, this method, where a dedicated converter is connected for each module, minimizes the conversion losses and cost. The differential power processing method also has a better overall conversion efficiency and performs well during the partial shading condition by overcoming the challenges associated with the mismatch MPP current. Moreover, this method tracks the global peak with less power loss as the converter only processes the difference [162].

Table 1. MPPT-based methods comparison (soft computing and hybrid methods).

Method	Complexity	Tracking Speed (s)	Efficiency (%)	Converter	Application
ANN	High	-	-	Boost	Island mode
FLC	High	0.3	-	Boost	Island mode
PSO	Medium	1.5	-	Buck-boost	Island mode
ABC	Low	0.2	-	Boost	Island mode
ACO	Low	1.1	≈100	Boost	Island mode
Jaya	Low	1.18	99.99	Boost	Island mode
FA	Low to medium	1.3	98.8	Boost	Island mode
GWO	High	-	99.92	Boost	Island mode
CS	Medium	0.3	-	Boost	Island mode
DE-PSO	Medium	0.44	-	Boost	Island mode
PSO-P&O	Medium	0.9	-	Boost	Island mode
GWO-P&O	Medium	0.015	100	Boost	Island mode

Table 2. Circuit-based MPPT methods comparison.

Method	Complexity	Tracking Speed	Steady-State Oscillation	Dependency on System Parameter
Bypass diode	High	Slow	No	No
Distributed MPPT	Moderate	Variable	Sometimes	No
Differential Power Processing	Moderate	Variable	Sometimes	No
Power Electronics Equalizer	High	Fast	No	Yes

Table 3. Comparison of conventional and soft computing methods.

Method	Advantages	Disadvantages
Conventional Methods		
P&O	<ul style="list-style-type: none"> Simple in construction Easy to implement Less sensor requirement 	<ul style="list-style-type: none"> Oscillations around MPP Increased perturbation rate
IC	<ul style="list-style-type: none"> Simple and highly reliable Highly efficient for uniform irradiation 	<ul style="list-style-type: none"> Poor convergence Frequency oscillations around MPP
HC	<ul style="list-style-type: none"> Easy to implement Efficient for slow changes in irradiation 	<ul style="list-style-type: none"> Slow response during high irradiation Efficient only for low-power applications
Soft Computing Methods		
Fuzzy Logic Control	<ul style="list-style-type: none"> Robust Effective in error detection Effective if combined with other conventional methods 	<ul style="list-style-type: none"> Poor convergence during the dynamic change in irradiation Rules cannot be changed
Artificial Neural Network	<ul style="list-style-type: none"> Accurate Effective 	<ul style="list-style-type: none"> Needs large memory Prior training is required High computational time
Artificial Bee Colony	<ul style="list-style-type: none"> Needs few parameters Independent convergence criteria with system parameters 	<ul style="list-style-type: none"> Slow tracking speed Complex
Particle Swarm Optimization	<ul style="list-style-type: none"> Reliable Simple and effective for handling non-linearity Effective in tracking global peak Wide search space usage 	<ul style="list-style-type: none"> Difficult initializing particle parameters. Large computation burden for a large population
Cuckoo Search	<ul style="list-style-type: none"> Robust Fast tracking speed Faster convergence Less parameters 	<ul style="list-style-type: none"> Time-consuming calculation Solution and convergence speed deteriorates
Ant Colony Optimization	<ul style="list-style-type: none"> Low cost Fast convergence speed 	<ul style="list-style-type: none"> Complex
Grey Wolf Optimization	<ul style="list-style-type: none"> Robust Fast tracking speed No steady state and transient oscillations 	<ul style="list-style-type: none"> High cost High computational time Needs a large search space

6. Conclusions

This paper presented comprehensive MPPT techniques capable of tracking the global peak during partial shading conditions. The partial shading mitigation technique has been classified as MPPT-based and circuit-based methods. The MPPT-based method is further categorized as modified conventional MPPT, soft computing, and hybrid methods. The modified conventional methods are based on modifying the operation of traditional MPPT methods, such as P&O and IC, so that they can track the global peak efficiently. The soft computing methods are based on optimization and are fast and efficient compared to the modified conventional techniques. Researchers have received PSO well among the optimization methods because of its robustness, simplicity, and easy implementation. FLC and ANN need a lot of training data, and their practical implementation is also complex. The hybrid methods combine soft computing with conventional techniques and are receiving more attention. Circuit-based partial shading mitigation techniques are also discussed. The advantages and disadvantages of different optimization techniques are also discussed to help readers choose a suitable MPPT under partial shading conditions. From the various methods discussed to mitigate partial shading conditions, it is very challenging to pick the best one. The current developed robust methods face high computational time and are complex for practical implementation. Cost of implementation, accuracy, number of sensors required, response time, and efficiency are some of the limitations associated with the currently available MPPT methods and should be addressed in future research. This comprehensive review of the MPPT methods is expected to provide utilities and researchers with a beneficial tool as a reference and guideline to select the best GMPPT method for partially shaded PV systems based on their effectiveness.

Author Contributions: M.Y.W., M.R.E. and M.A.H. contributed to identifying and classifying the MPPTs, manuscript writing, and conclusions; M.A.H., M.S., M.R.E. and L.S.M. contributed to reviewing the MPPTs, manuscript writing, and revisions; M.S., M.R.E., L.S.M. and M.I.H.; contributed to reviewing and classifying MPPTs, manuscript writing, and editing; and M.Y.W., M.I.H. and M.A.A. participated in revising the manuscript, editing, and conclusions. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the support provided by the Interdisciplinary Research Center for Renewable Energy and Power Systems (IRC-REPS), Research Institute, King Fahd University of Petroleum and Minerals, through project #INRE2323.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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