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Investigation of MPPT Techniques Under Uniform and Non-Uniform Solar Irradiation Condition—A Retrospection

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ABSTRACT A significant growth in solar photovoltaic (PV) installation has observed during the last decade in standalone and grid-connected power generation systems. The solar PV system has a non-linear output characteristic because of weather intermittency, which tends to have a substantial effect on overall PV system output. Hence, to optimize the output of a PV system, different maximum power point tracking (MPPT) techniques have been used. But, the confusion lies while selecting an appropriate MPPT, as every method has its own merits and demerits. Therefore, a proper review of these techniques is essential. A “Google Scholar” survey of the last five years (2015-2020) was conducted. It has found that overall seventy-one review articles are published on different MPPT techniques; out of those seventy-one, only four are on uniform solar irradiance, seven on non-uniform and none on hybrid optimization MPPT techniques. Most of them have discussed the limited number of MPPT techniques, and none of them has discussed the online and offline under uniform and hybrid MPPT techniques under non-uniform solar irradiance conditions all together in one. Unfortunately, very few attempts have made in this regard. Therefore, a comprehensive review paper on this topic is need of time, in which almost all the well-known MPPT techniques should be encapsulated in one paper. This article focuses on classifications of online, offline, and hybrid optimization MPPT algorithms, under the uniform and non-uniform irradiance conditions. It summarizes various MPPT methods along with their mathematical expression, operating principle, and block diagram/flow charts. This research will provide a valuable pathway to researchers, energy engineers, and strategists for future research and implementation in the field of maximum power point tracking optimization.

INDEX TERMS Maximum power point tracking, photovoltaic array, uniform solar irradiance, non-uniform solar irradiation, online and offline MPPT, hybrid MPPT methods.

I. INTRODUCTION

Global warming, fossil fuel shortage and political instability in major fuel-supplying countries and per-unit cost reduction in power generation from renewable energy technologies (RETs) have led to the conception that it can fulfil

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continuously growing energy demands. A combination of this notion with rapid RETs development has diverted power electronics manufacturers and power producers towards design development, implementation, and maximum utilization of RETs [1]. Furthermore, increasing penetration of RETs in conventional power generation systems is changing its status in the eyes of the policymakers from a secondary energy source to a primary one [2]. Amongst the other RE resources,

solar photovoltaic (PV) is a promising power generation option for sustainable energy development. But due to the seasonal weather conditions and the non-linear nature of solar irradiance, solar power generation significantly fluctuates, hence requiring a hybrid application or backup systems [3]. Solar irradiance is not highly correlated between close locations over a small time scale, which is an essential factor in PV power output fluctuation and losses [4]. In order to increase the PV system efficiency, the maximum power point tracking (MPPT) method is considered an essential component of the PV system. Because of PV array non-linear characteristics, it is inevitable to design an efficient maximum power point tracking that is not only high in efficiency but also optimizes the output power of the solar power system [1]. It is also well understood that MPPT is an operating point matching method that is installed between the PV array and power converter, as depicted in Figure 1.

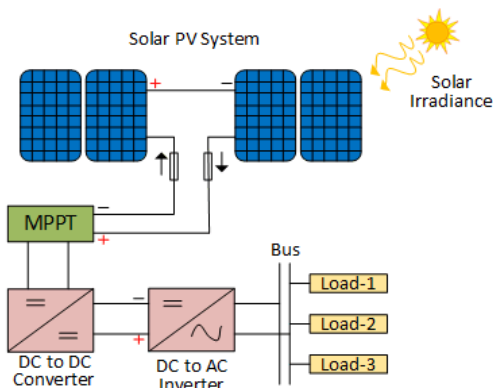


FIGURE 1. Solar PV system with MPPT.

Furthermore, PV system output efficiency is determined many internal and external factors such as series, parallel resistance and diode factor, etc. and solar irradiation, PV array surface and internal temperature, shadow, dirt, and so on. To work efficiently under the aforementioned internal and external factors, and efficient MPPT is inevitable, which can not only improve the MPPT tracking speed but also power converter output efficiency. Different MPPT methods have been proposed and practically implemented to optimize the PV output under uniform, and non-uniform solar irradiation conditions are classified in Figure 2.

To attaining maximum power from the PV system using MPPT methods, solar irradiation and temperature levels are utilized to determine the PV module power output and voltage. Regrettably, the non-linear characteristics of irradiance and temperature variation negatively affect the PV system's efficiency. Because of these reasons multiple local MPPs (LMPPs) unveiled on the current voltage (IV) and power voltage (PV) characteristic curves of the PV array when the entire array does not receive uniform solar irradiation as depicted in Figure 3. In Figure 3 (A) the PV system receives uniform solar irradiance also known as standard testing conditions (STC), but in reality, when the PV system is installed in the field, it has non-linear characteristics due

to non-uniform solar irradiance and partial shading conditions (PSC) as depicted Figure 3 (B).

In Figure 4 (A) IV and (B) PV characteristic curves of the PV system are sketched, where the black line indicates the output of Figure 3(A) which is considered under STC (25°C with 1000 Wm^{-2}), and the green, red and blue colored curves are drawn with reference to Figure 3(B) array (A, B and C) installed in field and irradiance is not highly correlated between close sites. Due to non-uniform solar irradiance and partial shading, PV output fluctuates, and multiple peaks are developing.

To optimizing the output of a PV system, different MPPT techniques have been used. But, the confusion lies while picking MPPT for particular PV system configurations and conditions, as every method has its own merits and demerits. For the ease of researchers and field engineers in the selection of appropriate MPPT for a specific PV system, numerous reviews have been published on the subject matter. Most of the researchers recognized the traditional MPPT technique as a successful method to attain maximum power from the PV system under non-uniform irradiance [1], [5]–[9]. While a few works of literature also considered partial shading or mismatching solar irradiation conditions [10]–[13]. In addition to this, Salam et al in [14] have identified soft computing MPPT techniques as a possible option. However, a minimal number of reviews [9], [15] discussed on MPPT under uniform solar irradiance and PSC conditions.

“Google Scholar” survey for last five years was conducted from 2015 to 2020 to investigate how many review article has been published on “Maximum Power Point Tracking” and “Maximum Power Point Tracking Under Uniform Solar Irradiations”, “Under Non-Uniform Solar Irradiation” and “Hybrid Optimization MPPT”. On the first search on *Maximum Power Point Tracking*, we found seventy-one review articles when the search was specified and narrowed to “Uniform Solar Irradiations” four review papers, on “Non-Uniform Solar Irradiation” seven and on “Hybrid Optimization MPPT” no review articles were found. Most of them have discussed the limited number of MPPT techniques, and none of them has discussed the online and offline under uniform and hybrid optimization MPPT techniques under non-uniform solar irradiation conditions all together in one.

Therefore, it's a need of time to write a comprehensive review paper on online and offline MPPT techniques under uniform and hybrid optimization MPPT methods under non-uniform solar irradiation conditions. This review paper will provide a valuable pathway to researchers, energy engineers, and strategists for future research and implementation in the field of maximum power point tracking optimization. Furthermore, it will enable identification of the merits and demerits of different MPPT techniques according to their scope and impact on the solar PV power generation system, and aid future research and development to ensure maximum power optimization from the PV system.

Following this introduction section, a detailed analysis of the MPPT with uniform solar irradiance in the light of

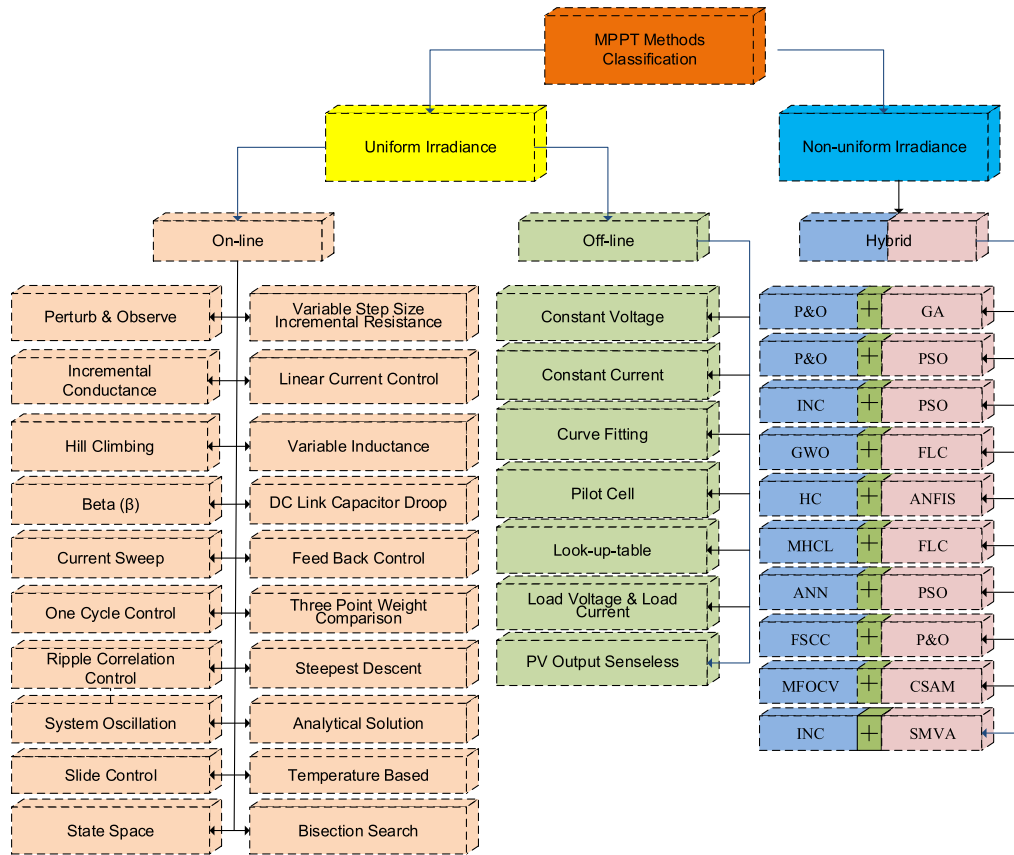


FIGURE 2. MPPT techniques classification.

the reviewed literature is presented. Both online and offline techniques are discussed in section II (A) and section II (B). In section III, hybrid optimization MPPT techniques under non-uniform solar irradiation and partial shading conditions are discussed. Based on this assessment, section IV presents a discussion, and in section V concise conclusion of this research study is presented.

II. MPPT WITH UNIFORM SOLAR IRRADIANCE

MPPT operating under uniform solar irradiance is suitable for conditions where the PV array receives uniform solar irradiance, and the IV and PV characteristic curves of the PV array exhibits a unique MPP. It is anticipated that the PV current has virtually zero ripple due to the subsequent filter and/or direct current (DC) converter, hence the maximum power is the average power of the PV system. Due to the intermittency of solar irradiation and temperature variations, the position of MPP will be changed. This section discusses different MPPT techniques developed and implemented for optimization of solar power under normal solar irradiance conditions, as classified in Figure 2.

A. ONLINE METHOD

In the online MPPT control method, usually, instantaneous values of the PV output voltage (V_{PV}) or current (I_{PV}) are

sensed to generate the control signals to track the MPP under different weather circumstances. After calculation of the PV power (P_{PV}), the generated control signal is used to determine the perturbation in P_{PV} by increasing or decreasing the ratio of the DC converter duty cycle (δ). A direct control method or proportional-integral (PI) or proportional-integral-derivative (PID) controllers are used to tune the duty cycle. The following subsection comprehensively reviews online MPPT methods under uniform solar irradiation conditions.

1) PERTURB AND OBSERVE (P&O) METHOD

Perturb and observe is one of the commonly used MPPT technique because of its simplicity and easiness in implementation [16]–[18]. In this algorithm, the PV array output voltage is sensed and perturbed by a little change, which results in a change of power (ΔP) as described in Table 1. In Figure 5, the IV-PV characteristic curves are depicted where P and O operate by perturbing the PV operating voltage increase and decrease, according to Table 1. The output power is observed and compared at successive perturbing cycles. Through the perturbation, if the power difference is positive, an increment is added to the operating voltage, and output power is observed again until the power difference is negative, then a decrement is added, and so on [19]. In P&O, steady-state oscillation occurs because perturbations continuously change

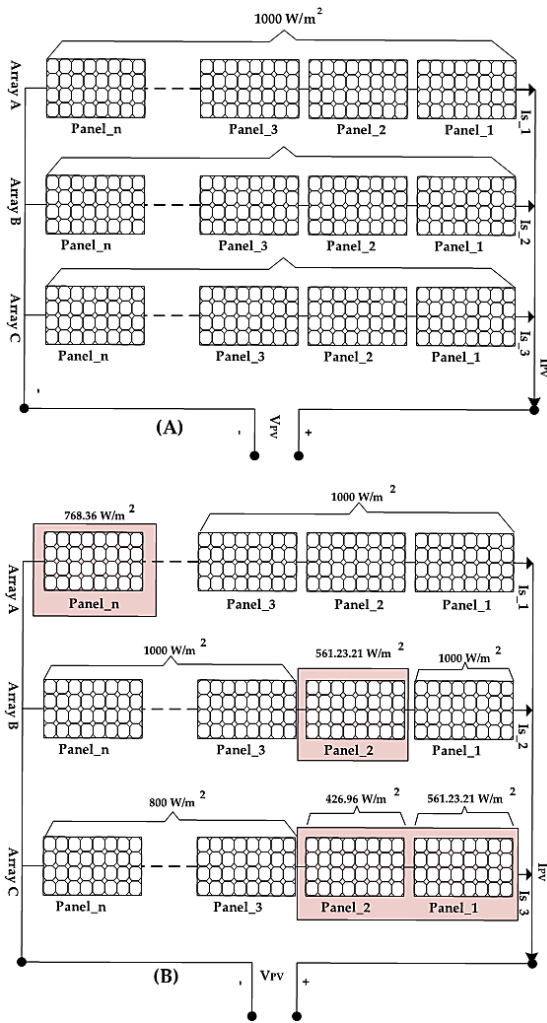


FIGURE 3. PV system under uniform and non-uniform irradiation [4].

TABLE 1. Perturb and observe algorithm.

Present perturbation (dV)	Change in power (dP)	Next perturbation direction
$dV > 0$	$dP > 0$	Positive
$dV > 0$	$dP < 0$	Negative
$dV < 0$	$dP > 0$	Negative
$dV < 0$	$dP < 0$	Positive

direction to maintain the MPP under rapidly changing solar irradiance, which reduces system efficiency and increases power losses [16], [20].

2) INCREMENTAL CONDUCTANCE (INC) METHOD

The conventional INC is driven by equations (1) to (3) to discovery the slope of the PV curve. Equation (1) defines if the operating point of the PV module is at its MPP, as depicted in Figure 6. While, equations (2) and (3) operates at left and right sides of PV curve respectively, to attain the MPP by

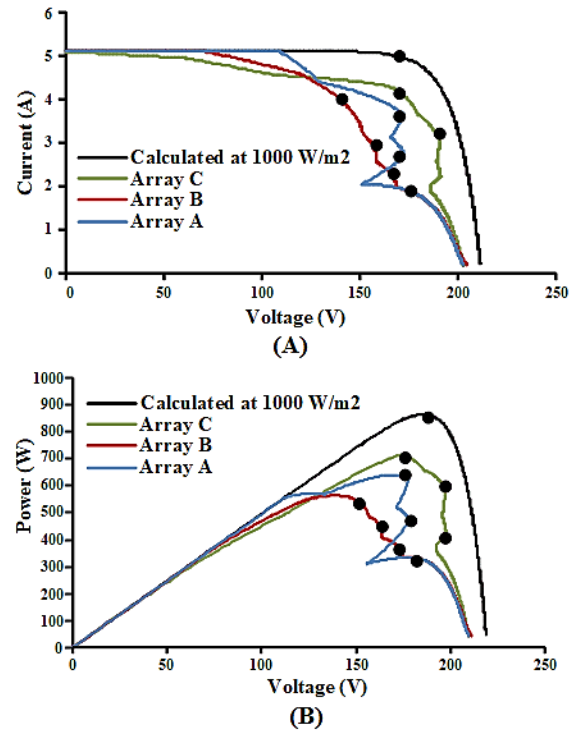


FIGURE 4. PV system IV and PV curves under uniform and non-uniform irradiation [4].

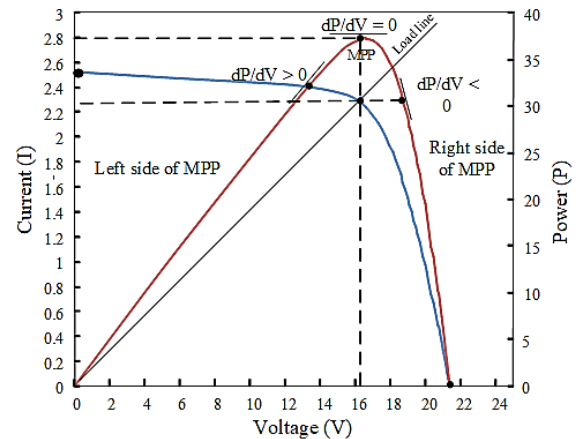


FIGURE 5. P&O MPP curve.

increasing and decreasing the duty cycle of INC controller algorithm shown in Table 2 [21]–[23].

$$\frac{dI}{dV} = -\frac{I}{V} \quad (1)$$

$$\frac{dI}{dV} > -\frac{I}{V} \quad (2)$$

$$\frac{dI}{dV} < -\frac{I}{V} \quad (3)$$

The scheme involving equations (1) to (3) assumes the slope of the PV curve at MPP is equal to zero, as described

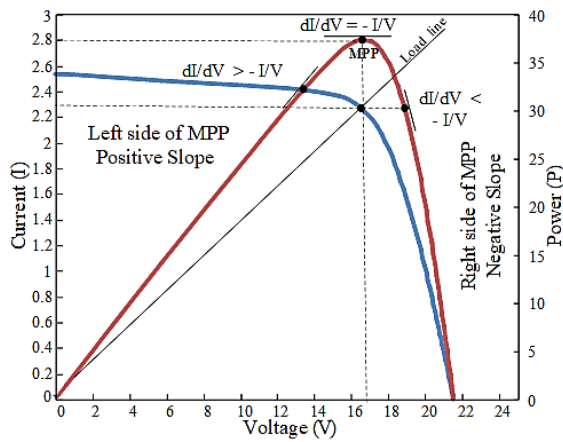


FIGURE 6. INC MPP curve.

TABLE 2. Incremental conductance algorithm methodology [15].

Mode	Perturbation	MPP Level	Status
Mode-1	$\frac{dP}{dV} = 0$	$\frac{\Delta I}{\Delta V} = -\frac{I}{V}$	At MPP
Mode-2	$\frac{dP}{dV} > 0$	$\frac{\Delta I}{\Delta V} > -\frac{I}{V}$	The left side of MPP
Mode-3	$\frac{dP}{dV} < 0$	$\frac{\Delta I}{\Delta V} < -\frac{I}{V}$	Right Side of MPP

in (4).

$$\frac{dP}{dV} = 0 \quad (4)$$

Therefore, (4) can be rewritten as

$$\frac{dP}{dV} = \frac{d(I \times V)}{dV} = V \frac{dI}{dV} + I \frac{dV}{dV} \quad (5)$$

$$\frac{dP}{dV} V \times \frac{dI}{dV} + I \quad (6)$$

Which implies

$$\frac{dI}{dV} + \frac{I}{V} = 0 \quad (7)$$

Along with P&O, INC is amongst the most utilized MPPT techniques in general [24]. Though, in INC, the slope of the PV curve influences the converter duty cycle in fixed or variable step sizes until the MPP is achieved. A bigger step size reduces MPP tracking time, but oscillation around MPP remains [25], [26]. On the other hand, a small step size lessens the fluctuation under extreme weather conditions with better efficiency, but the smaller step size results in a slower tracking speed [27], [28].

3) HILL CLIMBING (HC) METHOD

The HC method is identical to the P&O method in terms of operating principle, but the difference is the parameter

of the perturbation. The P and O senses and perturbs the voltage or current for MPP tracking, whereas the HC perturbs the duty cycle [29], [30]. One common problem in both methods is the performance trade-off between steady-state and dynamic response error. For the HC method, this problem is of a more significant worry because it controls δ instead of voltage, as depicted in Figure 7, while in the P and O method, voltage is controlled directly. The HC operational methodology is outlined in Table 3, where the fixed δ step size may be used, but this does not guarantee a fixed voltage change [31], [32]. Furthermore, the conventional HC method fails to track the MPP effectively under intermittent weather conditions because of a steady duty cycle [15].

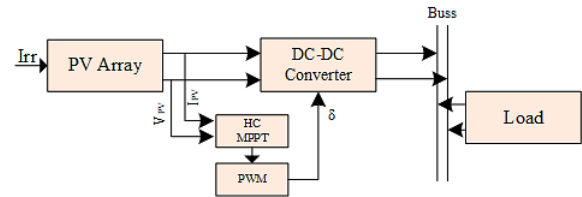


FIGURE 7. Hill climbing MPPT diagram.

TABLE 3. Hill climbing method operation methodology [1].

Present Perturbation	Change in Power	Next Direction	perturbation
Positive	Positive	Positive (duty ratio increase δ)	
Negative	Positive	Negative (duty ratio decrease δ)	
Positive	Negative	Negative (duty ratio decrease δ)	
Negative	Negative	Positive (duty ratio increase δ)	

4) BETA (β) METHOD

The theory of the beta method was demonstrated by Jain and Agarwal [33], where the coefficient beta (β) is obtained from equation (8) to find an intermediary value amongst the voltage and current to determine the MPP.

$$\beta = I_n (I_o \times C) = I_n \left(\frac{I_{PV}}{V_{PV}} \right) - C \times V_{PV} \quad (8)$$

where I_{PV} is output current, V_{PV} is the output voltage of the PV module, and C is conductance, obtained from equation (9).

$$C = \frac{q}{\eta k T} \quad (9)$$

where q is an electronic charge, k is Boltzmann's constant, η is diode quality factor, and T is the ambient temperature in Kelvin.

For better efficiency and faster MPP tracking, the β method is used in conjunction with any conventional MPPT method like P&O, INC, HC, etc. The first step in the β algorithm is to

measure the V_{PV} and I_{PV} values from the PV array/module. From which β is calculated and checked as to whether β is in a steady-state or not. If β is in the steady-state range, then it is switched to a conventional MPPT method. Conversely, if β is not in steady-state or it is not in its usual range, the error provided in equation (10) is used to regulate the duty cycle, and then the assessment procedure is repeated for β calculation [34], [35].

$$Error = \beta_{min} - \beta_{max} \quad (10)$$

The β method is considered as a suitable, reliable optimization option to track the MPP in conjunction with other conventional MPPT methods. The major drawback of this technique lies in its implementation and coordination regarding calculating the β value. Also, its traceability with V_{PV} , and I_{PV} to track the MPP that complicates the approach.

5) CURRENT SWEEP (CS) METHOD

In the current sweep method, the I - V characteristic curve of the array/module is drawn by using the module's existing operating conditions [25]. This method extracts the voltage and current and manipulates them as a predetermined function of time presented in equation (11):

$$i(t) = f(t) \quad (11)$$

The CS MPP tracking cannot be performed continuously as it deals with the array current and interprets the I - V characteristic of the PV system to determine the MPP. This technique is only carried out when the change in the manipulated determined power is more significant than a set threshold, which should be around (5% -10%) of the PV system maximum power (P_{MAX}). The threshold value cannot be too big or too small. If set too high, current sweeping will rarely be carried out. If too small, current sweeping will be near-continuous. The CS controller holds the computed voltage as representing the PV array/module operating voltage, until the next current sweep when the new MPP is determined [36], [37]. The current is swept rather than the voltage since the current is more sensitive to variation in solar irradiance.

6) ONE CYCLE CONTROL (OCC) METHOD

The OCC method is a non-linear MPPT method that is mostly used in a single-stage grid-connected PV system [38]. In the OCC method, the reference voltage and current are considered to regulate the output current of the single-stage inverter to attain the MPP, as depicted in Figure 8 [25], [39]. The output current of the single-stage inverter can be regulated according to the PV array voltage (V_{PV}) to fetch maximum output power from the PV system [40], [41].

7) RIPPLE CORRELATION CONTROLLER (RCC) METHOD

The RCC method uses the converter's internal ripple (which is present in all switched-mode power converters) as an alternative source of perturbation to optimize the PV panel output power and efficiency [42]. In RCC, the MPP is usually

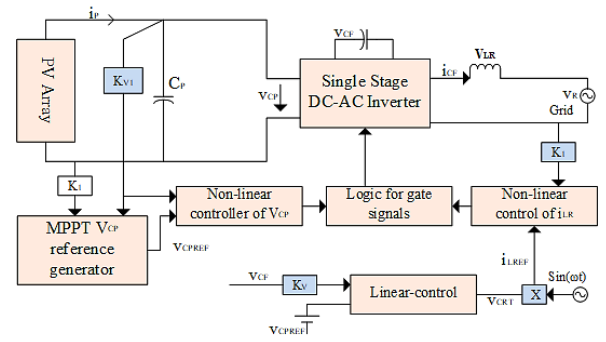


FIGURE 8. OCC single-stage inverter schematic diagram [39].

attained by correlating the derivative of the PV array/module power with the current or voltage ripple waveform as defined by equation (12).

$$\frac{dP}{dt} \times \frac{dV}{dt} \quad \text{or} \quad \frac{dP}{dt} \times \frac{dI}{dt} = 0 \quad (12)$$

The ripple correlation method operates by using the 1st order function of a high pass filter (HPF) to generate the voltage and power ripple from the measured PV voltage (V_{PV}) and power (P_{PV}), respectively. Then a 1st order low pass filter (LPF) function attenuates the ripple produced by V_{PV} and P_{PV} ripple, as depicted in Figure 9 [43].

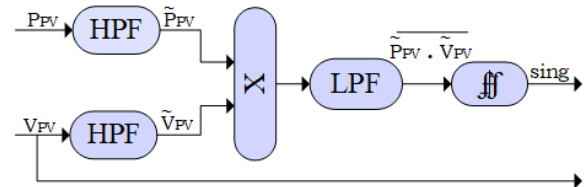


FIGURE 9. Schematic diagram of ripple correlation method [43].

8) SYSTEM OSCILLATION (SO) METHOD

The system oscillation method, instead of using an explicit perturbation source to track the MPP, an oscillation in a perturbation is used to locate the module MPP. It is compared with the alternating current (AC) components' oscillation due to the change of duty ratio ($\Delta\delta$). This is done to calculate the average converter input voltage to determine the duty ratio [44], [45]. Figure 10 illustrates the block diagram of the SO method where the error amplifier (EA) is a PI controller, designed to obtain the system oscillation and the AC component is obtained at the high pass filter output where the components of switching frequency are removed by employing a band-pass filter (BPF) of fourth-order [46]. Furthermore, a peak detector (PD) is used to remove the AC component peaks, and the output of the EA determines the duty cycle via a pulse width modulator (PWM).

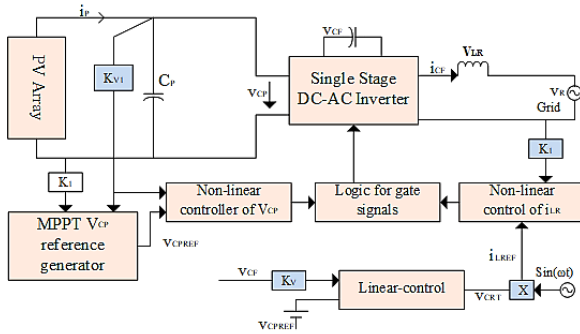


FIGURE 10. Schematic diagram of system oscillation method.

9) SLIDE CONTROL (SC) METHOD

The slide control mode method is suitable for controlling the switched-mode converters. This method is simple to implement and exhibits high stability and fast response in non-linear control systems [47]. In SCM, one fast and one slow control loops are configured as depicted in Figure 11. The fast loop tracks the MPP surrounding area with an excellent vibrant response, while the slow loop decreases the steady-state error by using a little step-size increment in the MPPT algorithm [48].

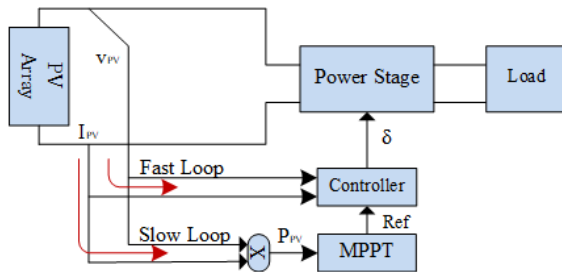


FIGURE 11. Block diagram of slide control mode [47], [48].

10) STATE SPACE CONTROL (SS) METHOD

The state-space control method uses a linearized state equation to track the MPP under non-linear module characteristics. It is used to configure DC-DC converters and delivers a precise small-signal model at reasonably lesser frequencies. The method supports in approximating the system by transforming it into a linear model and then take advantage of linear control methods [49], [50].

$$\dot{x}(t) = Ax(t) + B(t)u(t) + D\varepsilon(t) \quad (13)$$

It has been extracted from the research work of Ioannidis et al in [51] that the choice of formal variables, the inductor current (i_L) or the capacitor current (i_C) has an influence on both the overall performance and practical deliberations of the system. In more or fewer conditions i_C is preferred over i_L as the formal variable for the reason that the feedback advantages are more oblivious to output resistance deviations for the case of a capacitor than for inductor feedback. It is anticipated to track the MPP accurately with a constant output

voltage in the event of instabilities such as variation in V_{PV} or I_{PV} due to solar irradiance, temperature, and load variations.

11) VARIABLE STEP SIZE INCREMENTAL RESISTANCE (VSSIR) METHOD

The variable step size incremental resistance method is generally used in conjunction with the perturb and observe MPPT method to trade-off the main shortcoming of operating point oscillation around the MPP during steady and dynamic state conditions. These operating point oscillations result in wastage of some harvestable energy, hence, leading towards lower system efficiency [52]. The VSSIR technique adjusts the perturbation value automatically depending on how far it is operating from the MPP and how much variation exists. A feature that makes the VSSIR unique is the derivative ($\partial P/\partial V$ or $\partial P/\partial I$) as it can be used to determine and control the variable increment value according to equation (14) [53].

$$\begin{aligned} \delta(k) &= \delta(k-1) \pm N \times \left| \frac{\partial P}{\partial V} \right| \\ &= \delta(k-1) \pm N \times \left| \frac{P_{PV}(k) - P_{PV}(k-1)}{V_{PV}(k) - V_{PV}(k-1)} \right| \end{aligned} \quad (14)$$

where δ and $\delta(k-1)$ are the converter duty cycles at instants k , and $(k-1)$, respectively. In equation (14), a scaling factor N is used to regulates the input signal to an appropriate scale before the formation of the subsequent step size [54].

12) LINEAR CURRENT CONTROL (LCC) METHOD

Both solar photovoltaic generation and the conversion system have non-linear features because of the I - V characteristics, uneven solar irradiance, temperature change, and time-variant. This nonlinearity is one of the most discussed and investigated problems in MPPT design and development. In a linear current control method, a simplified linearization process is used for the successful linearization of non-linear problems [55]. The LCC or linearized method identifies the intersection between two curves. The first curve is the power-current curve under different irradiance levels, denoted by $f(P, I) = 0$ and the second is the V_{MPP} curve at $\frac{dP}{dI} = 0$, where the maximum output power point line is intersected and treated as a linear line as depicted in Figure 12 [56].

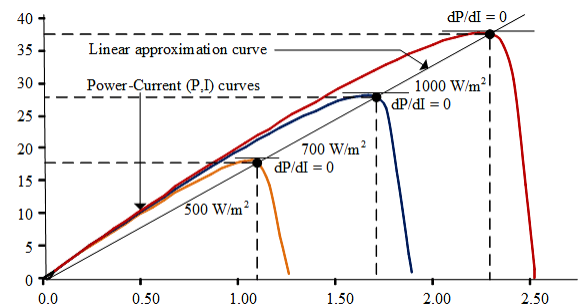


FIGURE 12. Linear current control curve with current linearization.

13) DC-LINK CAPACITOR DROOP CONTROL (DC-LINK CDC) METHOD

The DC-link capacitor droop control technique is used with a DC-DC converter, using the power equilibrium principle to determine the duty cycle ratio is given by equation (15) for stable output and power quality improvement [57], [58]. The PV system is parallelly coupled with the AC system, as depicted in Figure 13, where V_{cell} is the PV cell, and V_{link} are the voltages across the DC link.

$$\delta = 1 - \frac{V_{cell}}{V_{Link}} \quad (15)$$

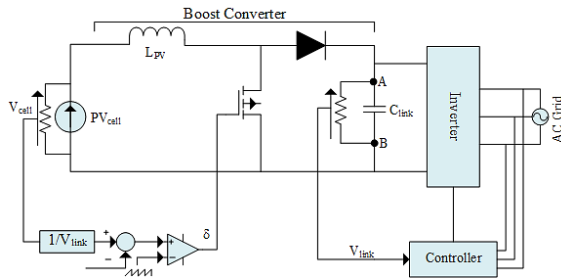


FIGURE 13. DC link-CDC circuit diagram.

If V_{link} is maintained persistently; the output of the DC-DC boost converter can be augmented by increasing the inverter input current [59]. Although the inverter current is increasing, the V_{link} voltage can be retained persistent if the power required by the inverter does not exceed the maximum power available from the PV system; otherwise, the V_{link} starts to drop. Just beforehand the dropping point, the current controller command of the inverter is at its highest level, and the PV system operates at the MPP. The AC system line current is fed back to DC-link to prevent V_{link} from drooping and δ is optimized to achieve MPP, as shown in Figure 13. This technique is restricted only to a PV system that is connected to the AC system line [60].

14) FEEDBACK CONTROL $\frac{dP}{dV}$ OR $\frac{dI}{dV}$ METHOD

In this method to compute the MPP slope ($\frac{dP}{dV}$ or $\frac{dI}{dV}$) of the PV curve, the feedback control is used to drive it to zero, as depicted in Figure 14. The method is independent of the cell characteristics and can track the MPP quickly [61]. Several ($\frac{dP}{dV}$ or $\frac{dI}{dV}$) feedback control methods have been proposed like the incremental MPPT method varies duty step size according to dP/dV and to compute dP/dV by using linearization techniques [62], [63]. A few previous computed signs can be stored to determine the next duty cycle; either it is incremented or decremented depending on stored cycles data to reach MPP, as stated in Figure 14.

15) THREE-POINT WEIGHT COMPARISON (TWC) METHOD

In TWC method, the PV module terminal voltage (V_{PV}) is perturbed at three different points A, B, and C to track the MPP and reduce the oscillation around it for which TWC is a viable option [64]–[66]. A modified perturb and observe

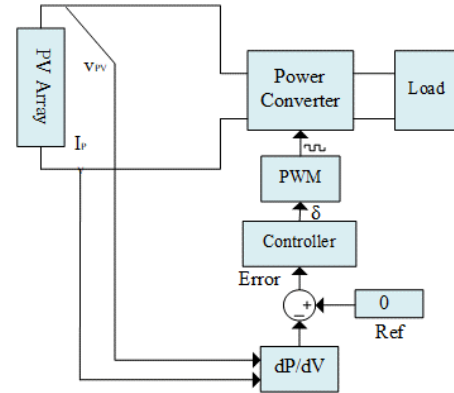


FIGURE 14. dP/dV feedback control Method.

method with TWC is reported in [67], where P and O compare the perturbation at three terminal voltages A, B and C to determine the duty cycle (δ). The perturbation can be performed from nine possible step size cases as given in Figure 15. For strong perturbation among the nine possible step sizes, the control variable is perturbed three times separately for A, B, and C.

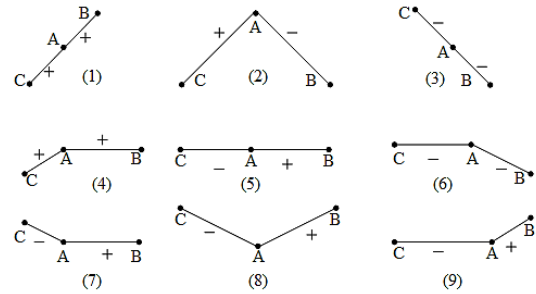


FIGURE 15. Three-point weight comparison possible cases in step size perturbation [64]–[67].

The TWC method operates periodically by perturbing the V_{PV} and comparing it with P_{PV} at three points that are A, B, and C. At the first step, the perturbation starts from point A to B, subsequently point A to C and perturbed in the reverse direction from point B to A and C to A respectively to determine the duty cycle step size. According to these TWC possibilities for points A to B, if the calculated wattage of B is higher than or equal to A, the status will be positive, if not, negative. For points A to C, if the calculated power in watts of point C is less than A, the resultant will be positive and, in the opposite case, negative. From the three measurements, if two of them are positive, the converter duty cycle (δ) will be increased. Otherwise, it will be decreased. In the third condition, if one measured value is positive, and one is negative, meaning that the MPP is achieved and the duty cycle remains constant [64].

16) STEEPEST DESCENT (SD) OR GRADIENT DESCENT (GD) METHOD

The steepest descent technique, also known as the gradient descent scheme, is an applied mathematics optimization

technique [68]. In SD, a single derivative optimization algorithm of the PV power system is used to determine the MPP in steps [69], established on the gradient of the function $f(V, P) = \frac{dP}{dV}$. The steepest descent MPPT technique is used to determine the nearest local MPP based on equation (16).

$$V_{k+1} = V_k + \frac{\left| \frac{dP}{dV} \right|_{V=V_k}}{k_\epsilon} \quad (16)$$

where $\frac{dP}{dV}$ is a derivation and k_ϵ is a step size corrector used to determine the next step size, which is proportional to the gradient value [68], [69]. This method is appropriate for non-linear weather circumstances to improve the MPPT tracking time. The gradient descent computational calculations use the PV open-circuit voltage (V_{OC}), and the operating voltage (V) is in the range of $0 \leq V \leq V_{OC}$. The change in power is a decreasing function with reference to voltage $\left(\frac{dP}{dV} \right)$ and $\left(\frac{d^2P}{dV^2} \right)$.

17) ANALYTICAL SOLUTION (AS) METHOD

In the analytical solution method, the real analysis means value theorem is used to track the MPP. The MPP is obtained with the exact expression of a point inside a small radius ball (ϵ), which lies in a small neighborhood circle [70]. The PV array V_{OC} and I_{SC} are observed and based on these observations, a ball of the small radius (ϵ) is chosen for the MPP. The exact small ball location in radius is calculated utilizing equation (17).

$$i = -\frac{I_L}{V_{OC}}v + I_L \quad (17)$$

where I_L is solar cell current to plot a straight line L_1 , which depends on V_{OC} and I_{SC} , another parallel straight line L_2 is drawn according to equation (18), which is tangent to the current curve to calculate ϵ .

$$\epsilon > (V_{PV}^* + i_{PV}^* R_s) - (V_{MPP} + i_{MPP} R_s) \quad (18)$$

where $\epsilon > 0$ and v_{PV}^* , i_{PV}^* the intersection points of L_2 , which is near the real maximum power point [71]–[73].

18) TEMPERATURE BASED METHOD

In the temperature-based method, the PV array/module surface temperature T is used to track the MPP according to the voltage/temperature coefficient β value provided in equation (19) [74].

$$V_{MPP(T)} = V_{MPP(T_{REF})} + u_{VMPP} (T - T_{REF}) \quad (19)$$

where $V_{MPP(T)}$ is the MPP voltage at standard testing conditions and $V_{MPP(T_{REF})}$ is maximum power point voltage according to the datasheet, and u_{VMPP} is the temperature coefficient [75]. A current sensor is replaced by a temperature sensor which is adjusted on the surface of the PV panel along with the voltage sensor for the voltage control converter, as depicted in Figure 16. The voltage control converter maintains the desired output voltage, by deciding the optimum voltage from the surface temperature of the PV module and

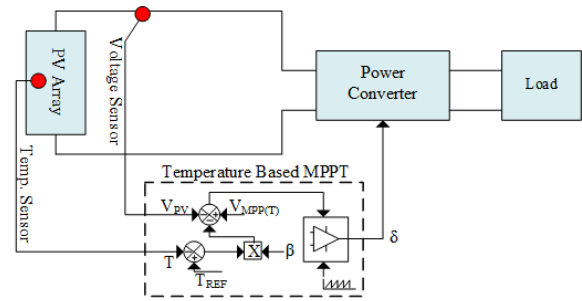


FIGURE 16. Schematic diagram of a temperature-based method.

instantaneously regulating the input voltage of the converter to uphold the optimum voltage, the MPP point will be confined without tracking failure [76].

19) BISECTION SEARCH THEOREM (BST) METHOD

The BST algorithm is a root-finding a mathematical method based on the intermediate value theorem (IVT), which repeatedly bisects an interval to find a sub-interval to track the MPP point. In BST method, the function $y = f(x)$ is used to locate the root of any interval for the real variable (x), where f is a continuous function defined within the interval $[a, b]$, where $f(a)$ and $f(b)$ have opposite signs. This method methodically changes the endpoints of the interval nearer and nearer within the bisecting interval for each step till an interval of subjectively small width bracketing zero is gained, as depicted in Figure 17 [77]–[79]. An interval that contains a zero of f is reduced in width at each step. The process is continued until the interval is sufficiently small to identify the MPP.

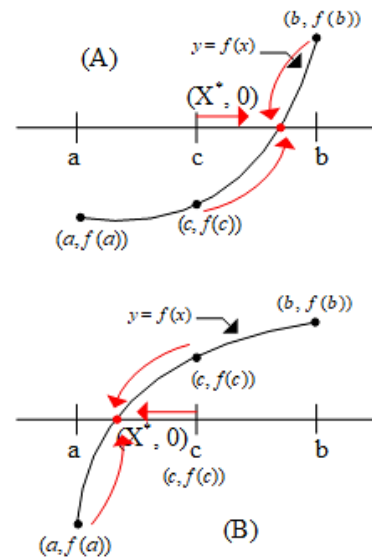


FIGURE 17. Bisection search theorem method [77].

20) VARIABLE INDUCTANCE (VL) METHOD

In the variable inductance method, the MPP is achieved under stable operation by impedance matching with a DC-DC

converter in the continuous conduction operation mode. Here, the required output inductor (variable inductor) has a specific inductance against the current characteristic. Also, the inductance decreases with the increasing current about change in solar irradiance. In [80]–[82], the inductor core gradually saturates with increasing current to track the MPP and reduces the overall inductor value by up to 75% with an increased operating range of MPPT at lower solar irradiance levels utilizing the variable inductor method.

B. OFFLINE METHODS

Offline MPPT is also well known as a model-based method. One or more of the solar PV panel's physical characteristic data (viz. V_{PV} , I_{PV} , P_{PV} , V_{OC} , I_{SC} , and temperature) are used to design the control algorithm, where the operating system point is forced towards the optimal conditions by following the user-defined limits to track the MPP.

1) CONSTANT VOLTAGE (CV) METHOD

The CV technique is also known as the fractional open circuit voltage (FOCV) method. This system works on the estimation of the MPP voltage ratio established on the defined V_{OC} limits. The V_{OC} point occurs between 72% and 78% at standard atmospheric conditions, and PV array operates within the defined ratio levels [83]–[85]. The converter duty cycle ratio (δ) confirms that the defined value of reference voltage (V_{REF}) is equal to V_{OC} .

$$V_{REF} = K_1 \times V_{OC} \quad (20)$$

where $K_1 = 0.72-0.78$

The method depends on the type of PV panel or array configuration, whereas V_{REF} is calculated according to equation (20) and V_{OC} is sampled when short circuit current (I_{SC}) is set to zero and V_{OC} is given as an input to the sampling circuit, as depicted in Figure 18. During each sampling period, V_{REF} is kept constant with a holding circuit, and the duty cycle ratio is adjusted to make V_{PV} equal to V_{REF} , and this process is continually repeated. The CV technique is straightforward and easy to implement but has limited accuracy because V_{OC} is measured to determine the MPP, with changes in temperature or irradiance conditions. The load is disconnected periodically to measure V_{OC} and to

calculate the operating voltage. This is considered as one of the significant disadvantages of this method.

2) CONSTANT CURRENT (CC) METHOD

The constant current technique uses the same operational phenomenon as the constant voltage method and is also known as the fractional short circuit current (FSCC) method [86], [87]. It assumes that the MPP power is proportional to the I_{SC} ratio, which remains between 78% and 92% of the short circuit current I_{SC} according to equation (21). The current is measured periodically when the PV array/module is under a short circuit condition via a power switch.

$$I_{REF} = K_2 \times I_{SC} \quad (21)$$

where $K_2 = 0.78-0.92$

In both CV and CC methods, only one sensor is required (voltage or current) [46]. The accuracy of both methods is affected by the accuracy of the proportionality factor between the V_{OC} and I_{SC} of the PV module.

3) CURVE FITTING (CF) METHOD

The CF is an offline MPPT technique established on the non-linear characteristic of the PV module due to weather intermittency. All the manufacturing details and data are required to develop a mathematical model and equation to describe the output characteristics [88], [89]. The PV module characteristic is calculated with equation (22), where a , b , c , and d are the coefficients determined by sampling the V_{PV} , I_{PV} , and P_{PV} [89]. When these coefficients have been calculated, the voltage at which the power becomes maximum is obtained through equation (23).

$$P_{PV} = aV_{PV}^3 + bV_{PV}^2 + cV_{PV} + d \quad (22)$$

$$V_{MPP} = \frac{-b \pm \sqrt{b^2 - 3ac}}{3a} \quad (23)$$

The disadvantage of a curve fitting method is that it requires a large amount of system data and accurate MPP calculation, which requires accurate knowledge of physical parameters. This makes this method slow and inefficient, given the variation in ideal and practical situations.

4) PILOT CELL (PC) METHOD

In a PC algorithm, a CV or CC method is used, where the V_{OC} is calculated from a pilot cell rather than the PV array/module [25], [90]. The V_{OC} of the pilot cell is calculated by multiplying it with a constant (K_3), as shown in equation (24). The constant is predefined so that it tracks the MPP of the array in response to any changes in temperature or insolation.

$$V_{REF} = K_3 \times V_{OC(pilotcell)} \quad (24)$$

where $K_3 \approx \text{constant} < 1$

Also, the pilot solar cell parameters must be harmonized to those of the PV module it denotes. Thus, respectively every pilot cell or solar module need be calibrated, increasing the energy cost of the system [91].

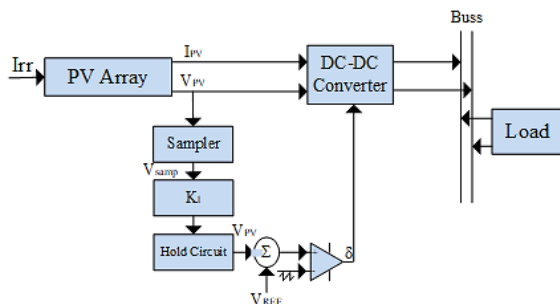


FIGURE 18. C MPPT with PV system.

5) LOOKUP TABLE (LT) METHOD

In the lookup table method, the PV module voltage (V_{PV}) and current (I_{PV}) are calculated to track the maximum PowerPoint. The technical data of the PV panel is stored for different environmental conditions, including the PV panel output voltage for different irradiance and temperature levels. Then the lookup method compares the calculated V_{PV} and I_{PV} with the stored data to track the MPP. Therefore, for accurate MPP tracking and higher efficiency, a large amount of data is stored in lookup memory [25], [92]. A big quantity of data collection, storing, and several sensors to track the accurate MPP makes this method complicated and error-prone.

6) LOAD VOLTAGE AND LOAD CURRENT (LV & LC) MAXIMIZATION METHOD

In LV & LC method, the MPP is tracked when it is connected to a power converter, either by sensing the load voltage or load current, rather than the PV voltage (V_{PV}) or current (I_{PV}) as depicted in Figure 19 (A) [93].

The method maximizes the PV power (P_{PV}) in four different load connected combinations (viz. 1. voltage source, 2. resistive source, 3. resistive and voltage source, and 4. current source), as depicted in Figure 19 (B). For LV, the load current (I_{out}) is maximized to reach the MPP. For LC, the load voltage (V_{out}) is maximized. For resistive source and voltage source load types, either V_{out} or I_{out} can be used for maximization purposes. The LV & LC maximization methods are suitable for all loads with one load sensor. The disadvantage of this method is that often the MPP cannot be achieved because of converter losses.

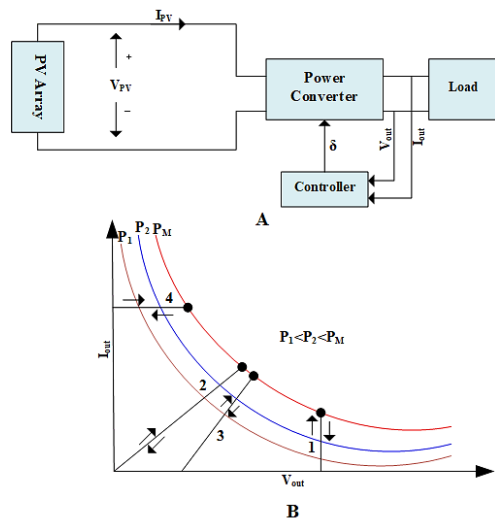


FIGURE 19. (A). Block diagram of load voltage and load current maximization method and (B). different load mechanism combinations [93].

7) PV OUTPUT SENSELESS (PVOS) METHOD

In the traditional maximum power point tracking control method, both V_{PV} and I_{PV} are needed to be sensed to track the MPP, which is complex and may fail to track the MPP

effectively under non-linear weather conditions. Therefore, the PVOS method is used for large scale PV systems to tracking the MPP without sensing the V_{PV} and I_{PV} [94]. This method senses the load current only and uses as feedback to determine the change in duty cycle ratio ($\Delta\delta$) regarding the change in load current, as depicted in II [95]. The load power is assumed to be proportional to the PV array power (source power) to track the MPP. The change in duty cycle ratio ($\Delta\delta$) is observed to determine whether to increase or decrease the load current concerning the PV array/module output voltage.

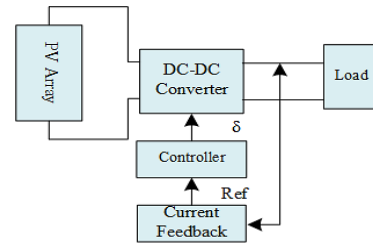


FIGURE 20. The block diagram of the PV output senseless method.

III. HYBRID OPTIMIZATION MPPT UNDER NON-UNIFORM SOLAR IRRADIANCE AND SHADING CONDITIONS

When the solar power systems installed on a large scale, non-uniform solar irradiance or partial shading condition ensues, because of nearby buildings shadow, utility poles, trees and moving clouds, etc. The IV-PV characteristic curve of the PV system under non-linear shading conditions reveals multiple peaks that affect the PV string output immensely, as depicted in Figure 4 (A & B). Because of multiple peaks, the MPPT operation is distracted to track the global maximum power point (GMPP), which causes overall output power reduction. To track the GMPP successfully under extreme weather conditions is a significant issue and the conventional MPPT methods are ineffective and most likely to be trapped in between LMPPs. One practical approach to track GMP under non-uniform solar irradiance and partial shading are through the use of optimization (hybrid) algorithms. Therefore, in this section, hybrid optimization MPPT methods under non-uniform and shaded solar conditions are investigated to overcome the shortcoming mentioned above.

A. PERTURB AND OBSERVE WITH GENETIC ALGORITHM (P&O-GA) & PERTURB AND OBSERVE WITH PRACTICAL SWARM OPTIMIZATION (P&O-PSO)

Perturb and observe is one of the commonly used MPPT technique for a reason that of its simplicity and ease of implementation. But due to some shortcoming to track the GMPP under continuous changing solar irradiance and partial shading conditions reduces overall system efficiency and increases power losses. To overcome these shortcoming hybrid P&O MPPT with a genetic algorithm (GA) is discussed in [96] and in [97], [98] hybrid P&O and PSO with reduced power oscillation in string inverters are introduced. Both the hybrid optimization methods aim to track the GMPP under

intermittent and partial shading conditions and to improve the performance in terms of easiness of constraint tuning and to lessen in steady-state oscillations, tracking time, and the number of iterations. In [96] P&O-GA method, initially, on average, six chromosomes are taken between the range of 10% to 90% as six duty ratios, which are uniformly disseminated. The genetic algorithm then executes the first three chromosomes and the duty ratio to determine the maximum output power of the solar photovoltaic power generation system, which is then considered as an initializing point for the hybrid Perturb and Observe algorithm. For practical, accurate and faster convergence to global MPP. The step sizes of the P&O are changed as the step length decreases, and the search proceeds. The following equation (25) is used to update the step size length in the P&O algorithm for next move to track the GMPP.

$$d_k = d_{k-1} + \Delta d_k \quad (25)$$

where $\Delta d_k = \alpha \cdot \Delta d_{k-1}$ is the step size, $\alpha = 0.9$.

For further and better understanding flow chart of the hybrid P&O with GA is given in Figure 21.

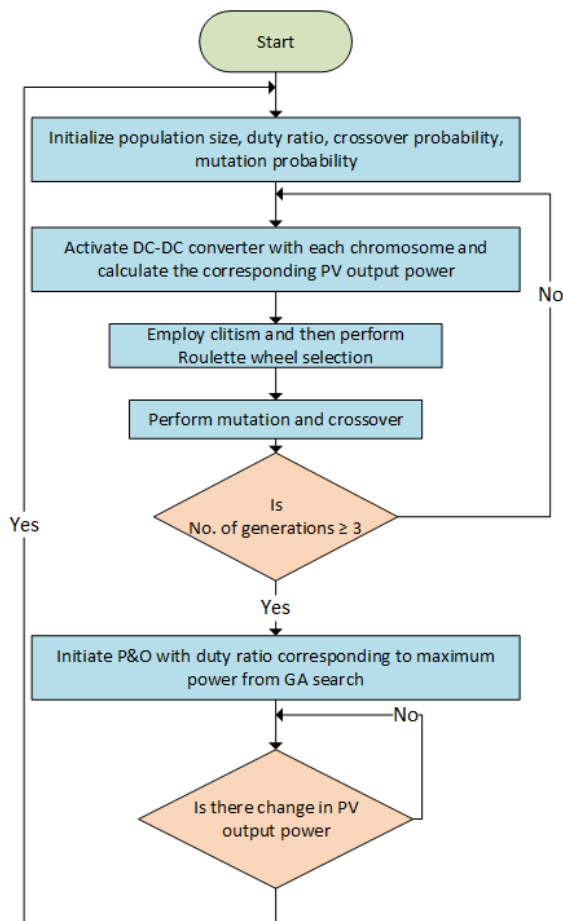


FIGURE 21. Perturb and observe with genetic algorithm.

The flowchart of the hybrid P&O and PSO with reduced power oscillation [97] is given in Figure 22. In this method, until the system senses the manifestation of partial shading,

it retains the operational point at the GMPP using conventional Perturb and Observes method (steps 2 and 3). When the GMPP tracking is done, it starts to store the data, i.e., voltage, current and power (step 4). It then compares the current and voltage values with the updated current and voltage values for perceiving partial shading (step 5). Once partial shading is sensed, the process will check whether the rightmost or the (first peak) is the GMPP or not (step 6). If the power difference limit becomes

true, then the existing GMPP is considered effective; if not, the “Main Process” will start again to track the GMPP and re-calls the subroutine” (step 7) for “global peak tracking. In this process, a suitable voltage window will be designated. Then the Particle Swarm Optimization method will search this area (step 8) and then proceeds to (step 9). The inevitability to track the other peaks are inspected in (step 10). If the power difference restrictions are satisfied, then the value of the global MPP is confirmed by matching all the stored data values of the MPP. In this whole process, if the condition flops, the whole process will be repeated until all the local peaks are taken into consideration to determine the global peak. When the “global peak tracking subroutine” returns, the Perturb and Observe method retains the operating point at the global MPP.

B. INCREMENTAL CONDUCTANCE WITH PRACTICAL SWARM OPTIMIZATION (INC-PSO)

In [99], hybrid incremental conductance with practical swarm optimization (INC-PSO) maximum power point tracking method is discussed. This INC-PSO method is based on two stages, as depicted in Figure 23. In the first stage, the conventional INC method is employed to track the first Local MPP. In INC, the solar PV voltage (V_{PV}) is incremented or decremented with a small change after every control cycle to track the GMPP in the right direction. A detailed operational description of conventional INC is discussed in section-II (A). In the second stage, the practical swarm optimization (PSO) will be activated to track the global MPP under extreme weather conditions. The preliminary condition of the first PSO particle is set to the converged value (V_{con}). The preliminary settings of the further cycles are set with $(n - 1)$, PSO particles values are set ranging from the previous V_{con} to the higher bound of the search space. Since the PSO particles number remains the same during these whole cycles, so the INC-PSO hybrid MPPT method is anticipated to track the global MPP in a lesser time than that taken by the only PSO method.

C. HYBRID GREY WOLF OPTIMIZATION WITH FUZZY LOGIC CONTROLLER (GWO-FLC)

Based on the literature, the Grey Wolf Optimization (GWO) MPPT method individually or standalone suffers from fluctuation and oscillation around the global MPP under non-uniform and partial shading conditions [100]. In[101] Grey Wolf Optimization is Hybridized with the Fuzzy Logic Controller (GWO-FLC) controller to lessen the fluctuation

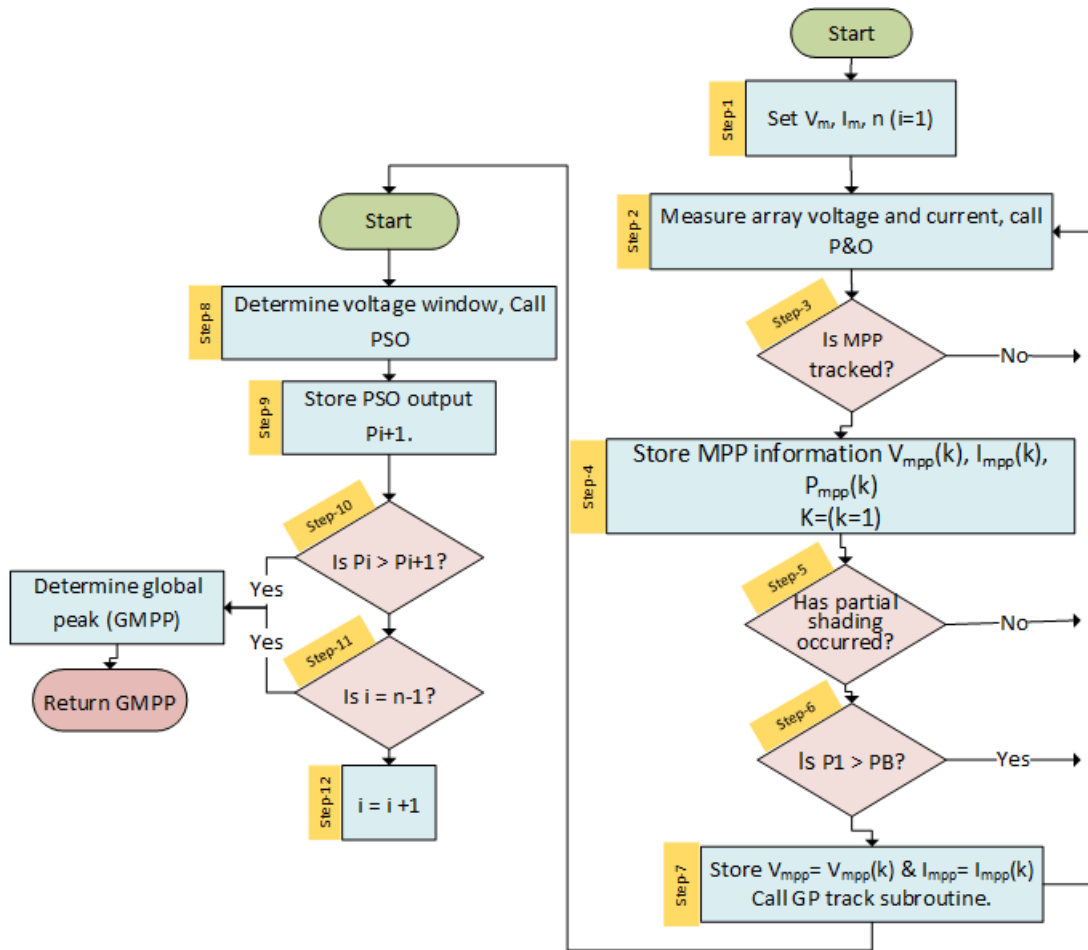


FIGURE 22. Perturb and observe with practical swarm optimization.

and oscillation around the global MPP under extreme weather conditions. This GWO-FLC hybrid method is developed on two variants; the first is based on predefined time (T_{PD}), which depends on the frequency of partial shading conditions of the site and the second is based on change in partial shading. Flow chart of both the methods is given in Figure 24.

The main features of this GWO-FLC technique are to use the qualities of both GWO and FLC techniques together and to elude their shortcomings. The Grey Wolf Optimization technique is considered one of the most effective in terms of fast convergence in tracking the GMPP under seasonal weather conditions. On the other hand, it has a higher oscillation issue around the GMPP at the steady-state condition. However, the Fuzzy Logic Controller is opposite to GWO in terms of advantages and disadvantages, where, it may stick to one of the local MPP. Still, it has very little oscillation around the global MPP. For this purpose, the Grey Wolf Optimization technique is used at the start to track the GMPP in a fast and efficient way. Afterwards, the FLC starts working to reduce the oscillation around the GMPP, which has been tracked by GWO. So, the qualities of Grey Wolf Optimization in tracking the GMPP, and prevention of dropping into one of the LMPPs at the start of the algorithm is exploited. Furthermore, the

disadvantage of higher oscillation is overcome by giving a chance to FLC to work in very low oscillations at this GMPP.

D. HILL CLIMBING WITH ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM (HC-ANFIS)

In the category of conventional maximum power point techniques, HC is considered one of the most prevalent and straightforward online MPPT methods after INC and P&O [102]. But HC has some demerits in performance trade-off between steady-state and dynamic response error [31], [32]. To overcome its demerits, HC is hybridized with ANFIS in [103].

This innovative HC-ANFIS based hybrid technique is capable of approximating and regulating the DC-DC boost converter duty ratio to the optimal value, which agrees to MPP transfer from the PV system. In this hybrid method, the ANFIS technique is employed to approximate the offline duty ratio, which takes the PV system operating point nearby to the maximum PowerPoint. However, the HC method makes an online adjustment to refine the tuning of the approximated duty ratio previously set by ANFIS to bring it at the optimal MPP. This ANFIS support provides relief to the

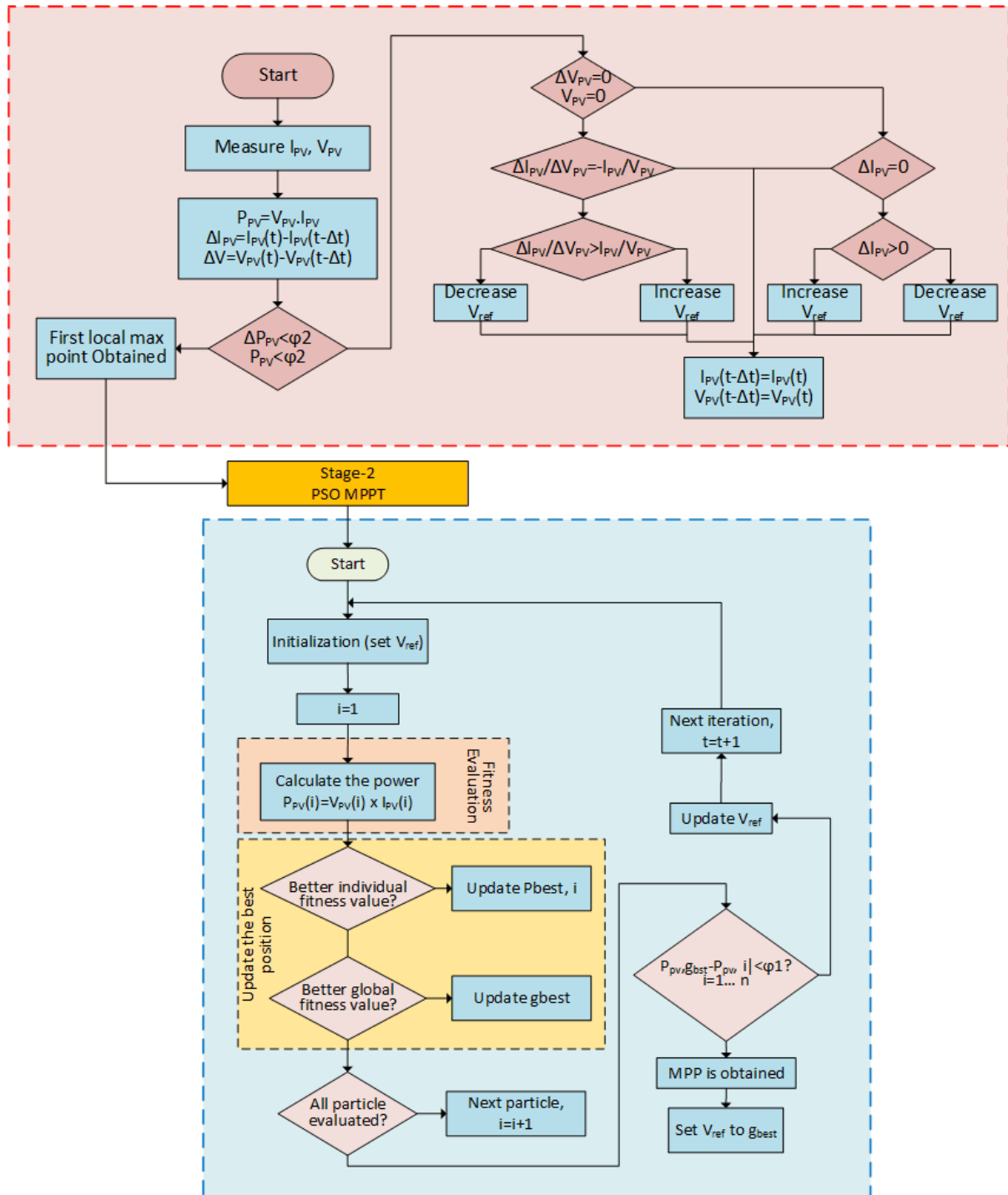


FIGURE 23. Incremental conductance with practical swarm optimization.

HC method from the difficulty of seasonal weather changes. As the ANFIS technique approximates the offline MPP duty ratio, it helps to minimize the amplitude of associated power oscillations by smaller duty ratio perturbation steps. Thus, a trade-off between the rapidity of reaching steady-state power and the amplitude of power oscillations is made by ANFIS, as depicted in Figure 25.

E. MODIFIED HILL-CLIMBING WITH FUZZY-LOGIC-CONTROL (MHCL-FLC)

Hybrid modified HCL with a fuzzy logic controller (MHCL-FLC) MPPT for a standalone micro-grid with a PV system is introduced in [104].

In this paper, the shortcomings of traditional HCL are examined. The proposed MHCL-FLC is skillful of exploiting

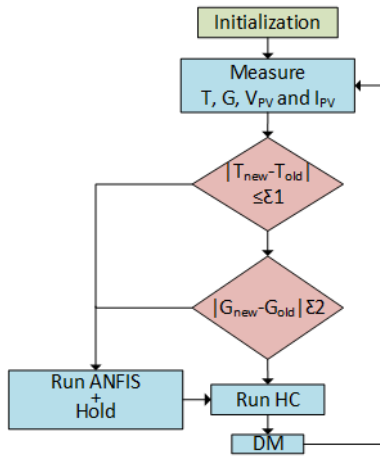


FIGURE 25. Hill-climbing with ANF.

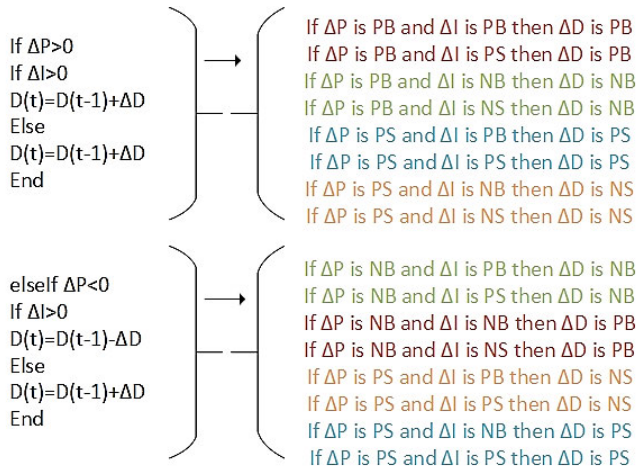


FIGURE 26. MHC with FLC.

inputs and outputs are divided into four FL subsets: positive big (PB), negative big (NB), positive small (PS), and negative small (NS). Thus, the fuzzy rules algorithm requires 16 fuzzy control rules; these rules are based on the regulation of HCL.

F. IMPROVED ARTIFICIAL NEURAL NETWORK WITH PARTICLE SWARM OPTIMIZATION (IANN-PSO)

In [105] improved artificial neural network-based particle swarm optimization (IANN-PSO) MPPT algorithm is introduced. The features of this hybrid MPPT technique is to optimize the output power of the PV system under partial shading and non-uniform solar irradiation conditions to accelerate the global MPP tracking speed with better efficiency. Basically, ANN is a scheme that executes a mapping among the input and output patterns instead of a problem statement. Therefore, ANN-based MPPT is useful for forecasting the behavior of non-linear systems, which can be estimated by multi-layer neural networks. The IANN-PSO MPP tracking

efficiency η_{MPP} is given by equation (26):

$$\eta_{MPP} = \frac{\text{Avg}(P_{ss})}{\max(P_{EC})} \quad (26)$$

where $\text{Avg}(P_{ss})$ is the average output power under steady-state conditions and $\max(P_{EC})$ is the maximum available power in certain environmental conditions.

And IANN output is given by equation (27):

$$\theta_{IANN} = \sum e_i w_i + \theta \quad (27)$$

where e_i is the input error function and w_i is the weight function of the corresponding input.

The particle gained from this method will have an updated position on higher value, and then the particle may be found outside the search area. A flowchart illustrating the optimized IANN-PSO method is given in Figure 27.

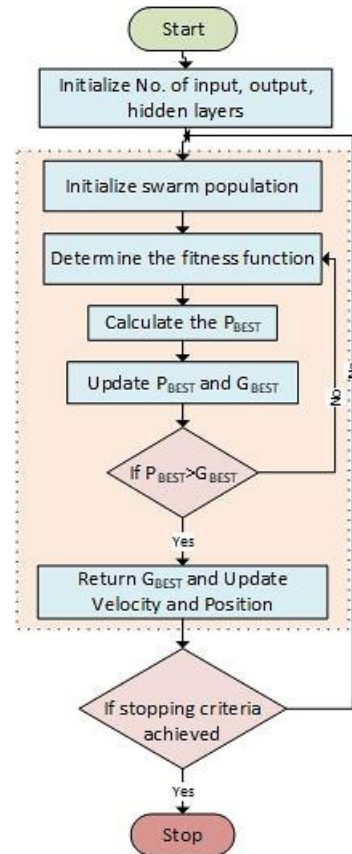


FIGURE 27. ANN with PSO.

G. FRACTIONAL SHORT-CIRCUIT CURRENT MEASUREMENT WITH PERTURB AND OBSERVE (FSCC-P&O)

Under any particular weather conditions, the solar PV MPP current (I_{mpp}) has nearly a linear relationship with I_{sc} as conveyed in the equation (28) given below:

$$I_{MPP} \approx k I_{SC} \quad (28)$$

where k is the constant of the fraction.

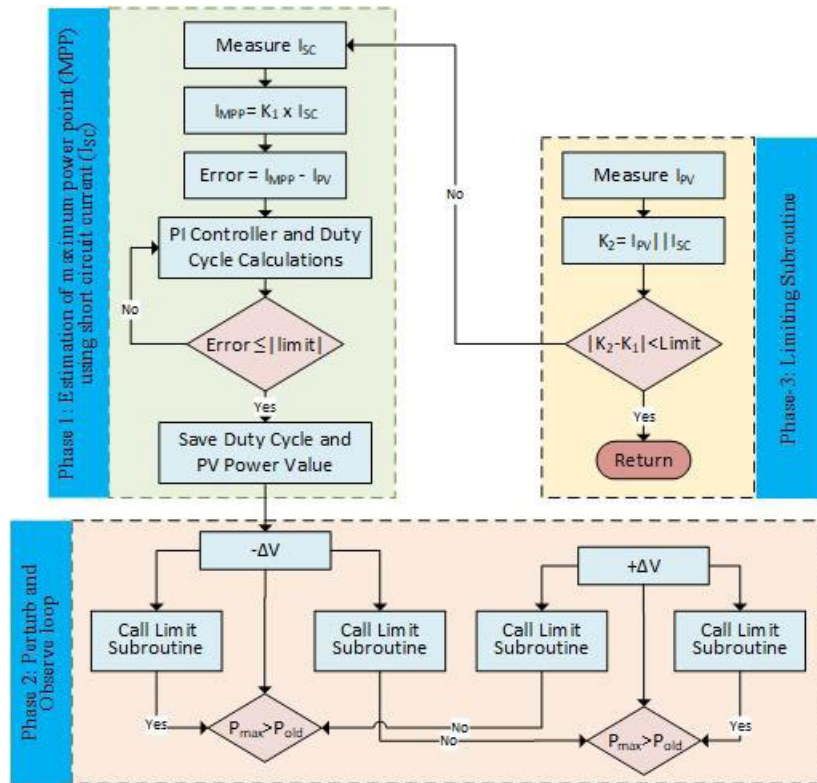


FIGURE 28. FSCC measurement with P&O.

The value of k is generally inimitable for every PV modules. Usually, it fluctuates from 0.72 to 0.92. As it is a ballpark figure, so it does not track the real global MPP. But, the tracking speed of the FSCC method is fast, with a justifiable efficiency of up to 90% [106]. FSCC is easy to implement and cheap as it requires only one current sensor. It only needs random measurements of short circuit current I_{sc} to track the estimated global MPP, which tend to temporary power losses of the system.

To alleviating FSCC power losses under fluctuating weather conditions, a hybrid FSCC-P&O MPPT method is discussed in [107]. The flowchart of the FSCC-P&O is sketched in Figure 28. FSCC-P&O hybrid MPPT method has three distinct phases to track the GMPP effectively, as discussed below:

Phase 1: Estimation of maximum power point using short circuit current

The FSCC-P&O MPPT algorithm commences with the approximation of GMPP using PV module short circuit current (I_{sc}). When the first loop began, it is secluded to measure and store the I_{sc} . Then the value of maximum power point current (I_{mpp}) is calculated by following $I_{mpp} \approx kI_{sc}$. Afterwards, the PV panel output current (I_{pv}) is measured and computes the error difference among I_{mpp} and I_{pv} . The resulting value is given as an input to compensator to calculate the required duty cycle.

Phase 2: Perturb and Observe loop

At phase-2 P&O loop is activated loading the duty cycle, once the algorithm touches the compensator block of

the phase-1. When the error comes to zero levels, the Perturb and Observe loop began tracking the MPP. The foremost benefit of applying the phase-1 is that a minimal step size for the P&O loop is conceivable. This ensued in insignificant power oscillations around the MPP.

Phase-3: Limiting Subroutine

The intellectual mechanism of this subroutine regulates the moments of I_{sc} measurement throughout the execution of the FSCC-P&O MPPT method. Phase-3 holds the stored value of short circuit current and uninterruptedly updates the instant values of I_{pv} . Then, it computes and updates the constant (k_2) and calculates the differences amongst (k_1 and k_2). This whole practice is repetitive until the difference outstrips the limits.

H. MODIFIED FRACTIONAL OPEN-CIRCUIT VOLTAGE WITH CURRENT SENSOR-LESS AUTO-MODULATION (MFOCV-CSAM)

A hybrid Modified FOCV with Current Sensor-Less Auto-Modulation (MFOCV-CSAM) is discussed in [108]. In this hybrid MFOCV-CSAM method at first, MFOCV is aimed to determine the MPP with fast to approach; after that, the CSAM is used for fine-tuning the MPP under non-linear weather conditions. Flowchart of Hybrid MFOCV-CSAM is given in Figure 29.

As elaborated in the MFOCV-CSAM flowchart. At first, if the operational point is away from the MPP, at that time, the MFOCV algorithm will detect the PV array voltage (V_{pv}) and compares the V_{pv} with V_{mppL} and V_{mppH} . After that,

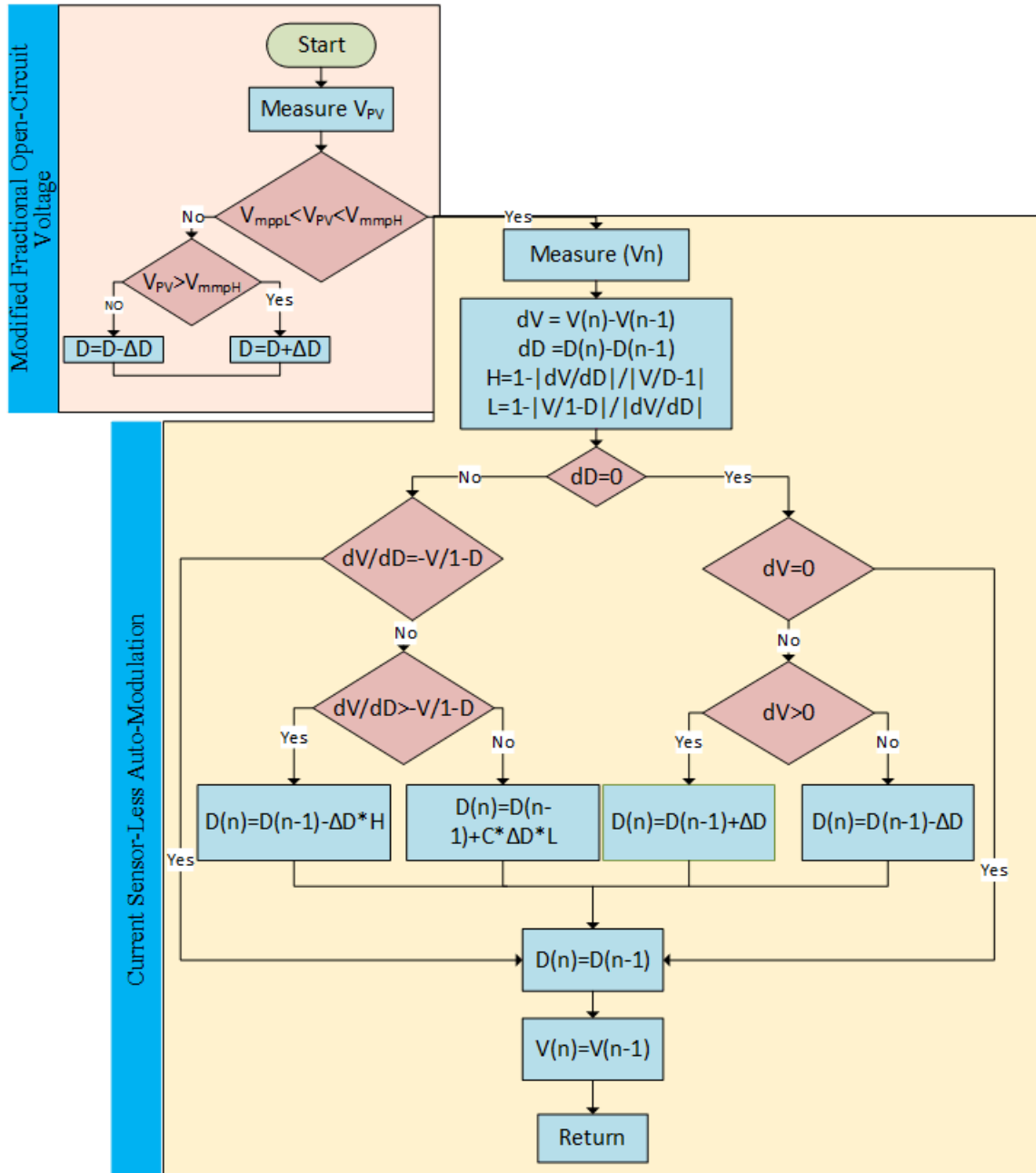


FIGURE 29. Modified FOCV with CSLAM.

change in the duty ratio (D) is estimated in reference to the change in V_{mmpL} and V_{mmpH} , and the changes in duty ratio are denoted as ΔD , as shown in the first part of Figure 29. Once it is determined that operating point is nearby the MPP, the CSAM algorithm the second part of the hybrid MFOCV-CSAM will take over the execution process for MPP tracking by following the condition of equation (29):

$$\frac{dV_{PV}}{dD} = -\frac{V_{PV}}{1-D} \quad (29)$$

To improve the tracking process and to refine the tuning, CSAM uses the equation (30) and guarantees fast response

under extreme weather conditions.

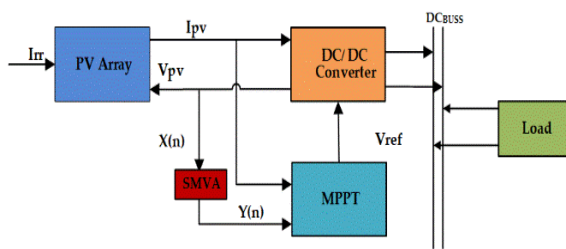
$$\begin{aligned} \frac{dV_{PV}}{dD} &< -\frac{V_{PV}}{1-D}, & D &= D + \Delta D \\ \frac{dV_{PV}}{dD} &= -\frac{V_{PV}}{1-D}, & D &= D \\ \frac{dV_{PV}}{dD} &> -\frac{V_{PV}}{1-D}, & D &= D - \Delta D \end{aligned} \quad (30)$$

On the basis of the above equations, MPPT duty ratio step size defines how fast the MPP tracking is attained.

TABLE 4. Comparison of on- and offline MPPT techniques under a uniform solar irradiance.

Technique	PV Array Dependency	Sensor			Online Methods			Circuitry		Application	
		V	I	T	Tracking Speed	Tracking Accuracy	Efficiency	A	D	Stand Alone	Grid Connected
Perturb and observe	No	✓	✓		S	Moderate	Hi	✓	✓	✓	✓
Incremental conductance	No	✓	✓		M	High	Hi		✓	✓	✓
Hill climbing	No	✓	✓		S	Moderate	Hi	✓	✓	✓	✓
Beta	No	✓	✓		F	Moderate	Hi		✓		✓
Current sweep	No	✓	✓		M	Medium	M	✓	✓	✓	
One cycle control	No	✓	✓		F	Moderate	Hi	✓	✓	✓	✓
Ripple correlation control	No	✓	✓		F	Moderate	Hi	✓			✓
System oscillation	No	✓			M	Moderate	Hi	✓		✓	
Slide control	No	✓	✓		F	Medium	Hi		✓	✓	✓
State-space	Yes	✓	✓		M	Moderate	Hi		✓	✓	✓
Variable step size incremental resistance	No	✓	✓		F	Moderate	Hi		✓	✓	✓
Linear current control	Yes	✓	✓		F	High	Hi		✓	✓	
DC-link capacitor droop	No	✓	✓		M	Moderate	Hi		✓	✓	✓
Feedback control	No	✓	✓		M	Moderate	Hi	✓	✓	✓	
Three-point comparison weight	No	✓	✓		S	Moderate	Hi	✓		✓	✓
Steepest decent	Yes	✓	✓		M	Moderate	Hi		✓	✓	
Analytical solution	No	✓	✓		M	Moderate	Hi	✓		✓	
Temperature based	Yes	✓		✓	M	Moderate	Hi	✓		✓	
Bisection search theorem	No	✓	✓		M	Moderate	Hi		✓	✓	✓
Variable inductance	No	✓	✓		M	Medium	M	✓	✓	✓	✓
Constant voltage	Yes	✓			F	Less	Lo	✓	✓	✓	
Constant current	Yes		✓		F	Less	Lo	✓	✓	✓	
Curve fitting	Yes	✓		✓	F	Less	M	✓	✓	✓	
Pilot cell	Yes	✓			F	Medium	Lo	✓	✓	✓	
Lookup table	Yes	✓	✓		F	Low	M		✓	✓	
Load voltage and load current	No	✓	✓		S	Moderate	M	✓		✓	✓
PV output senseless	Yes		✓		M	Moderate	Hi		✓	✓	✓

V-Voltage, I-Current, T-Temperature, F - Fast, M - Medium, S - Slow Hi - High, M - Medium, Lo - Low, A-Analog, D-Digital

**FIGURE 30.** INC-SMVA PV system interconnection.

I. INCREMENTAL CONDUCTANCE WITH SIMPLE MOVING VOLTAGE AVERAGE (INC-SMVA)

In [4], [19], [109], A Fixed step direct control INC MPPT with simple moving voltage average (INC-SMVA) is introduced. The main features of this INC-SMVA to reduce oscillation and recover oscillatory effect such as ripples in V_{PV} under non-uniform solar irradiation conditions. INC-SMVA algorithm is motivated by the merits of a simple moving average economics model, which is often used in “forex-trading” to predict a trend following previous indicators. The proposed INC-SMVA is used to determine the V_{PV} voltage direction with a small delay because it is centered on solar irradiation to calculate and average the irradiance signal in time series analysis as depicted in Figure 30. which is

showing the configuration of the PV system with the proposed method model. Where $X(n)$ and $Y(n)$ are input and output signal of the system and (N) is the magnitude of the moving average buffer, with a defined number of samples. The buffer will hold the samples coming from $X(n)$ as an input signal and computes them by following the averaging method and generates the output signal $Y(n)$, which is given as input to MPPT by following the equation (31 and 32). The working principle flow chart of INC-SMVA is given in Figure 31. This algorithm is not only capable of recovering the oscillation around the MPP but also improve the design efficiency of the system.

$$\sum_{n-(N-1)}^n X(k) = \sum_{n-N}^{n-1} X(k) - X(n-N) + X(n) \quad (31)$$

$$Y(n) = \frac{1}{N} \sum_{n-(N-1)}^n X(k) \quad (32)$$

IV. DISCUSSION AND COMPARATIVE ANALYSIS

In literature, many maximum power point tracking techniques can be found. This paper discussed a wide-ranging of literature presented on MPPT techniques under uniform and non-uniform (shading) solar irradiance conditions. These techniques are classified in main two collections; one is conventional (online and offline), and the other is hybrid

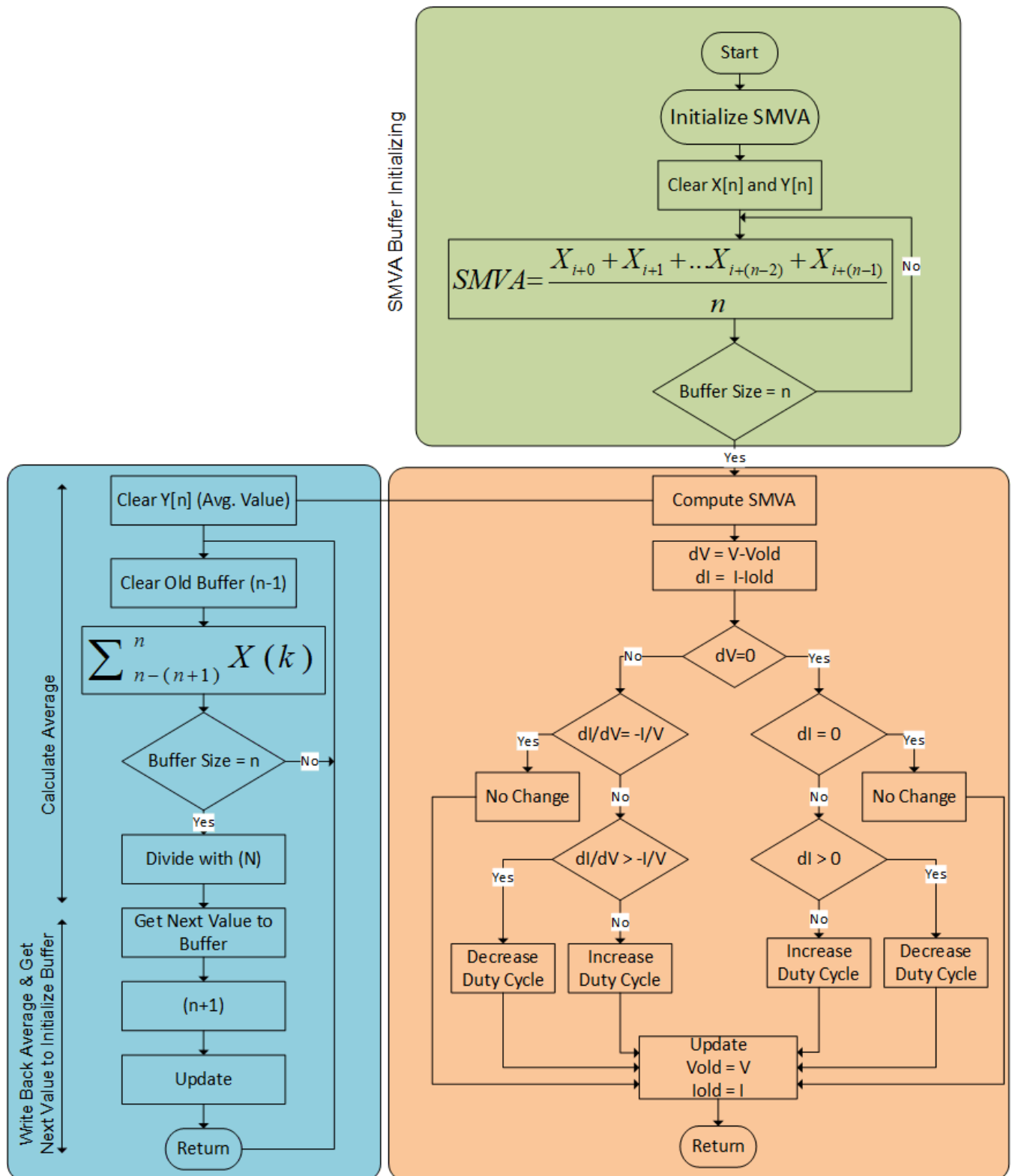


FIGURE 31. INC-SMVA flow chart.

optimization MPPT techniques. Both the MPPT methods have the same aim to optimize the PV system output power unrelatedly. In this section, the discussion is made into the

following factors, namely the capability to track the GMPP, convergence speed, design complexity and sensitivity to the environmental changes.

TABLE 5. Comparison of hybrid optimization MPPT techniques under a non-uniform solar irradiance.

Hybrid Optimization Methods											
Technique	PV Array Dependency	Sensor			Tracking Speed	Tracking Accuracy	Efficiency	Circuitry		Application	
		V	I	T				A	D	Stand Alone	Grid Connected
Perturb and Observe with Genetic Algorithm	No	✓	✓		VF	VH	VH	✓	✓	✓	✓
Perturb and Observe with Practical Swarm Optimization	No	✓	✓		VF	VH	VH	✓	✓	✓	✓
Incremental Conductance with Practical Swarm Optimization	No	✓	✓		VF	H	VH	✓	✓	✓	✓
Hybrid Grey Wolf Optimization with Fuzzy Logic Controller	No	✓	✓		VF	VH	H	✓	✓	✓	✓
Hill Climbing with Adaptive Neuro-Fuzzy Inference System	No	✓	✓		F	H	H	✓	✓	✓	✓
Modified Hill-Climbing with Fuzzy-Logic-Control	No	✓	✓		F	H	H	✓	✓	✓	✓
Artificial Neural Network with Particle Swarm Optimization	No	✓	✓		VF	VH	VH	✓	✓	✓	✓
Fractional Short-Circuit Current Measurement with Perturb and Observe	No	✓	✓		VF	VH	H	✓	✓	✓	✓
Modified Fractional Open-Circuit Voltage with Current Sensor-Less Auto-Modulation	No	✓	✓		VF	VH	H	✓	✓	✓	✓
Incremental Conductance with Simple Moving Voltage Average	NO	✓	✓		VF	VH	VH	✓	✓	✓	✓

V-Voltage, I-Current, T-Temperature, F - Fast, M - Medium, S - Slow Hi - High, M - Medium, Lo - Low, A-Analog, D-Digital

A. CAPABILITY TO TRACK THE GMPP

As the solar PV system does not receive uniform solar irradiance even between very close locations at a short time scale, there are also chances of partial shading that could occur due to any unavoidable circumstances. These conditions could be a cause to form the multiple LMPPs on the IV-PV characteristic, which will affect the tracking efficiency of the MPPT. Conventional MPPT algorithms are not good in tracking the GMPP under non-uniform and shading conditions, while Hybrid optimization MPPT algorithms are prepared with the competency to track the GMPP over multiple LMPPs.

B. CONVERGENCE SPEED

An efficient MPPT algorithm must have the ability to converge to the required current and voltage with good speed and accuracy, irrespective of a steady or radical change of solar irradiance. Reasonably, the traditional maximum power point tracking takes more time to converge to the GMPP as compared to hybrid techniques. In addition, the hybrid algorithms converge the GMPP at minimal or negligible oscillation.

C. DESIGN COMPLEXITY

The selection of a suitable MPPT, keeping because of its design complexity for a particular PV system is considered one of the imperative factors. The complexity of the MPPT technique depends on how accurately the algorithm is searching for the true GMPP in the existence of different LMPPs. Otherwise, the maximum solar energy will not be harvested by the PV system. Besides, configuration and implementation of the MPPT also depend on the user knowledge in handling

the device, in which someone is good at dealing with analog-circuits while the other chooses digital-circuits. However, hybrid optimization-based MPPT algorithms are instigated in digital form, which requires computer programming and software experts.

D. SENSITIVITY

A good MPPT algorithm must have enough sensitivity to operate under any condition and atmospheric changes. It must have the capability to react speedily and track the GMPP of the particular PV system at the given condition.

In Tables 4 and 5, all the techniques discussed in this paper are surmised based on their properties.

V. CONCLUSION

Because of the abundant availability of sunlight, solar PV is considered the most promising source of energy in the renewable power generation system. However, it has certain limitations like weather intermittency, low efficiency, and high upfront cost. Therefore, to fetch the maximum power from the PV system under uniform and non-uniform, shading conditions, MPPT is used as a power electronics interface. So far, extensive research is done on enhancing the efficiency of MPPT power extraction from the PV system under different weather conditions. But it's always been challenging to choose the right MPPT for the particular PV system configurations and conditions. For this purpose, in this review, we have discussed and analyzed the most important and recent techniques presented in the literature, revealing the features of each technique under uniform and non-uniform,

shading conditions. After the appropriate assessments of all studies, a summary table was developed, which gives an overview of the results based on sensor used, complexity, application, and convergence speed.

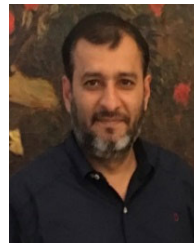
After the detailed assessment of all the online, offline, and hybrid optimization MPPT methods. It has been concluded that most of the conventional MPPT algorithms are useful to track the GMPP under normal solar irradiance conditions but fails to obtain accurate GMPP under rapidly changing and partial shading conditions. However, hybrid optimization algorithms are fast and accurate to track the GMPP under partial shading and rapidly changing solar irradiance conditions. But, they are complex algorithms and, therefore, difficult to implement using embedded technologies.

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