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Review

Extensively used conventional and selected advanced maximum power point tracking techniques for solar photovoltaic applications: An overview

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Abstract: The lower output efficiency of the solar PV panel is due to the deviation of its operating point from the maximum power operation. And the change in the maximum power point (MPP) with the change in uncontrolled environmental conditions such as temperature and isolation make it difficult to withstand the MPP operation of the system. Different techniques and maximum power point tracking algorithms have been developed to address the issue. This paper presents a critical overview of widely used maximum power tracking techniques for photovoltaic system applications. Conventional, as well as advanced developed methods, which are less complex, robust and reliable, are discussed. However, some complexity occurs while selecting the appropriate MPPT method for a particular application. One of the contributions of this review article is to provide an outline for the selection of appropriate technique suitable for a particular application. Comparative analysis and classification of the selected MPPT methods based on various features such as type of control strategies, control variables, a converter circuit, and practical/commercial applications are presented. This review article is envisioned to serve as a useful reference for future MPPT users and PV system design engineers.

Keywords: photovoltaic array; Maximum Power Point Tracking (MPPT) techniques; Partial Shading; Slide-Mode Control; Artificial Neural Network; Fuzzy Control

1. Introduction

Recently, solar PV systems are becoming very important due to their economically sustainable and environmentally reliable behaviour over conventional fossil fuels. Solar energy is being considered as the most readily available energy resource because of low-cost PV solar module. Pollution-free energy production with low system maintenance makes solar PV system an attractive renewable power generation option [1]. For all power generation system, the efficiency of the system is a major concern, and so is with the solar PV system. The low panel efficiency, commercially 16% to 17%, results in lower system efficiency. Not only the lower panel efficiency at production level but also the climatic conditions make the power generation even worst due to varying isolation and temperature [2]. The characteristics of the PV panel is such that the maximum power can only be extracted at a single point of the curve. Since the panel efficiency is maximum at this point, therefore, the operation of the panel at this point is the desire of an efficient system [3]. The maximum power point shows nonlinear behaviour and changes abruptly with the change in isolation, temperature and shading condition of the panel. Due to this uniqueness of the maximum power point (MPP) of a panel, it is almost impossible to exactly track the MPP of the panel. The fascination of achieving maximum power operation of the system results in the development of a large number of tracking algorithms ranges from conventional simple and robust methods to highly responsive and advance algorithms [4,5].

Conventional techniques such as perturb and observe (P&O), Incremental conductance, etc. are although less efficient and reliable, but their easy implementation and robust behaviour make the highly popular in commercial applications [6]. Various improvements in conventional techniques have observed in the course of time. In [7], different improved conventional techniques and a detail critical discussion on the evaluation of different perturbative techniques are presented systematically. Various other conventional algorithms are discussed in [8], these methods are generally best suited for system operating under uniform shading condition and are incapable of efficiently achieving global maximum under complex shading as well as dynamic environmental conditions. Advance methods usually based on an evolutionary approach, on the other hand, are more efficient. And accurate in precisely tracking the maximum power point on the P-V curve even with multiple peaks and dynamic conditions [9]. These methods include Fuzzy logics controller, ANN, PSO, GA, DE, etc. and advancement in soft computing techniques makes these methods more and more reliable and efficient [10].

Abundant literature is available dealing with various conventional as well as advance MPPT techniques. Therefore it is almost impossible for the researchers and early-stage field engineers to go through all the literature in order to select the technique best suitable for their specific application. Also in many cases, the system design engineers require to use robust, easy to implement and reliable solution of efficient power tracking for their system implementation but due to different constraints they are not able to access this abundant literature. A concise and comprehensive study with proper comparative analysis of different techniques and their application is required. Addressing the need, in this work, an overview of reliable, robust and easy to implement conventional as well as selected advance tracking techniques are systematically presented.

In this paper, eighteen different MPPT techniques, which includes conventional as well as advance methods, are taken into consideration. Their performances were analyzed and compared based on various parameters. Rest of the paper is organized as follows: Section II highlights the significance of MPPT and basics operation of it. Section III deals the different MPPT techniques with their different features. Section IV deals with the comparison of different MPPT techniques based on various parameters such as control variables, control strategy, a power converter circuit, cost, and other vital features followed by the conclusion.

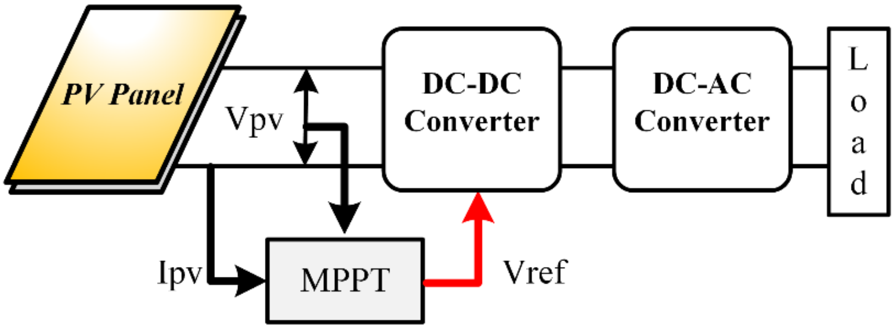

Figure 1. Block diagram representation of PV System main components.

2. PV system and MPPT fundamentals

Main components in the basic structure of a standalone PV system includes panels, power converters and power backup system, as shown in Figure 1. The requirement of the power converters depends on the type of load to which the system is feeding the power. Significance of MPPT, as well as operating principle, can be easily understood through the typical I-V and P-V characteristic of the panel under different load condition, as shown in Figure 2. For a PV system without using MPPT, the operating point is P1 when a load R1 is connected, as shown in Figure 2(b). At this point, the power output of the panel is less than the maximum power. As the load changes, such that the new operating point becomes P2, output power changes and becomes maximum. It means that in order to operate the system at maximum power, change is load is required, which is impractical. Maximum power operation can be easily achieved using DC-DC converter, in between the panel and load, which is capable of varying terminal voltage without changing the connected load by adjusting the duty cycle (D) of the converter. Different converters such as cuk-converter, Buck-Boost, Boost and Buck can be implemented depending upon the requirement and region of control shown in Figure 3. For feeding ac load dc to ac converter called an inverter is used. A significant development in the design of inverter topologies has been achieved in the last two decade. Various inverter topologies with high efficiency and reduce component count with less circuit complexity are available [11,12]. Utilization of efficient components in the system will result in improved overall efficiency and performance of the system.

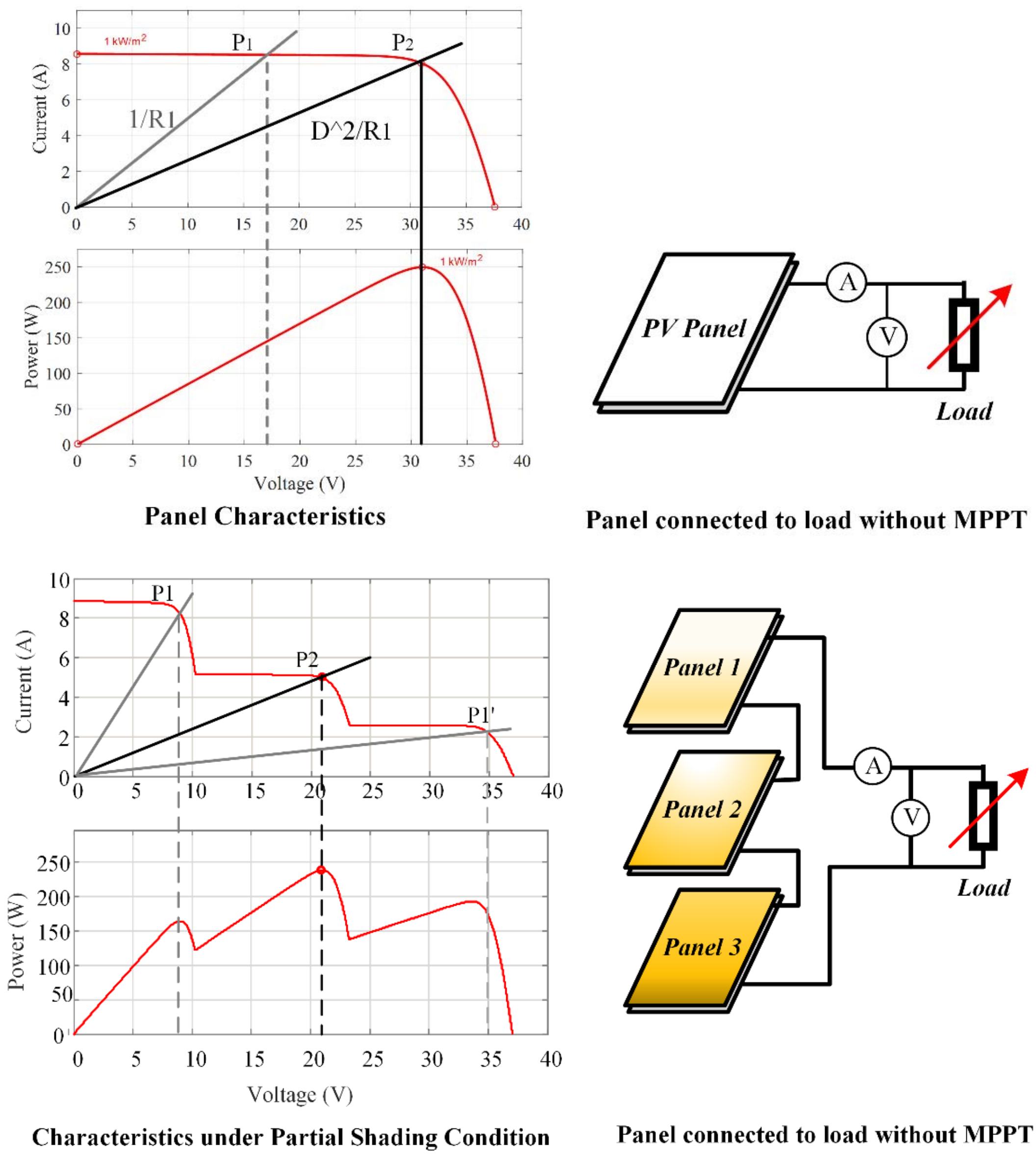

Figure 2. The relation between the load line, output power-voltage, current-voltage curve.

3. MPPT techniques

In the following sections, various MPP techniques are discussed, and their performance is analyzed considering different aspects. Apart from the conventional technique, intelligence techniques such as Fuzzy Logic Controller method, ANN method, curve fitting techniques, current sweep technique, etc. were considered. The detailed analysis and discussion of various MPPTs are as follows.

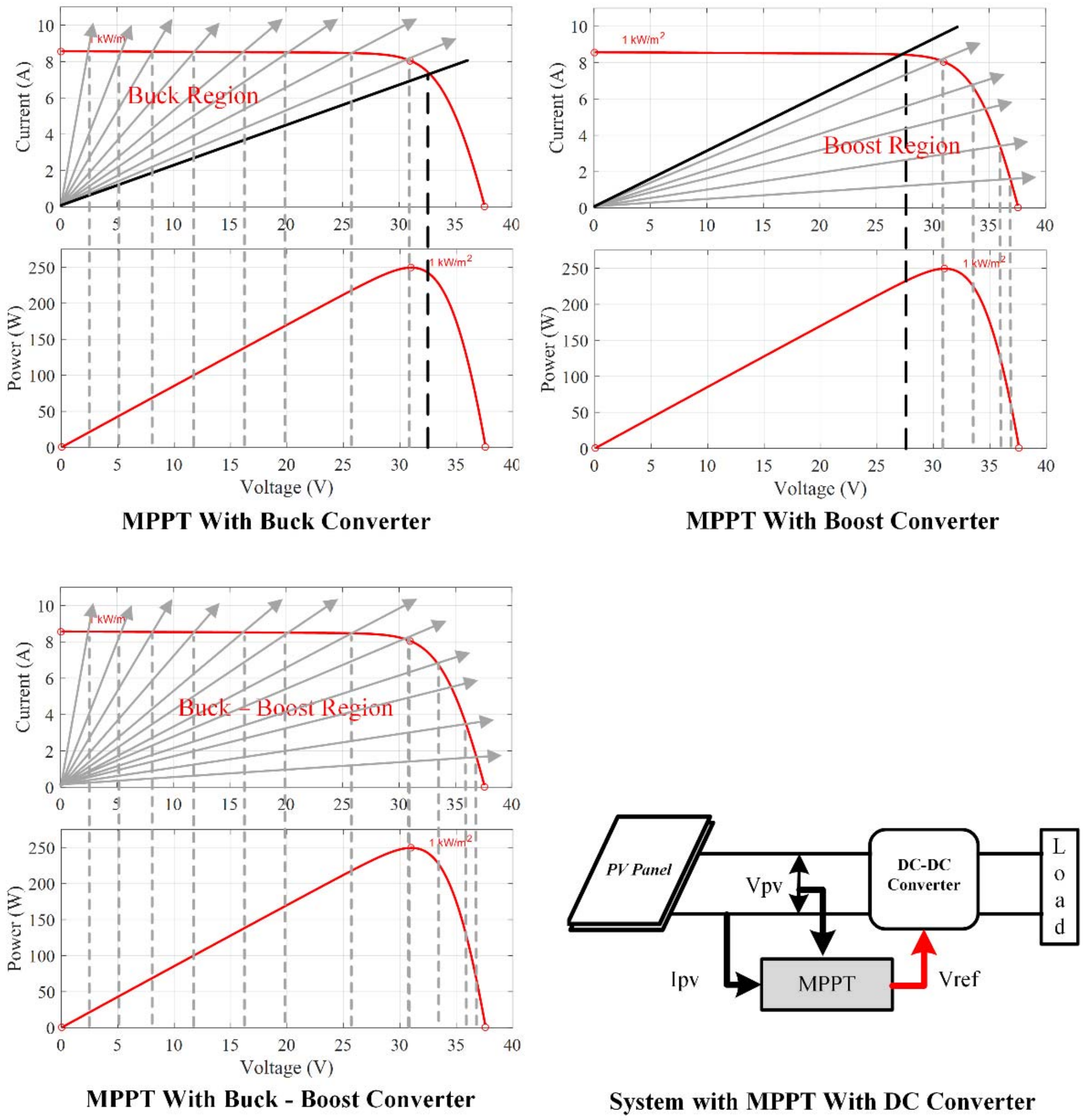

Figure 3. Panel with MPPT and DC Converter Connected to load.

3.1. Perturbation and observation technique

P&O is one of the simplest and broadly used algorithms for the tracking of the maximum power from the PV system. One sensor, i.e., voltage sensor, is used in it. The implementation cost of this method with the voltage sensor is not much; therefore, this method possesses easy implementation [7]. This algorithm operates by perturbing the duty cycle and therefore increasing or decreasing output power of the array and then comparing this power with that of the previous perturbation cycle. On small perturbation, the output power changes. If the change in power is such that the value of the power obtained is higher than the previous power, then the perturbation will move in the positive direction; otherwise, the perturbation moves in the reverse direction [7]. The process continues until maximum power is achieved.

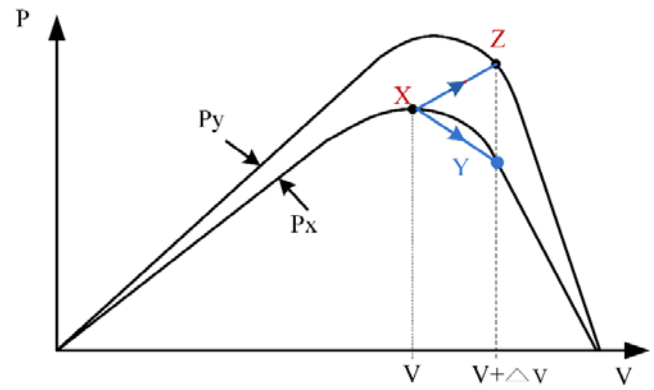

Figure 4. Deviation of P&O algorithm from MPP.

Although this conventional method is widely used in many applications due to its simple implementation, there are lots of limitation associated with it. One of the limitations of this technique is the oscillation of its operating point around the desired maximum power operating point is the tracking. Therefore after reaching the MPP, the power always oscillating around the maximum and reduces the PV system power output. One of the ways of damping out this oscillation is by reducing the perturbation step size. However, it will increase the accuracy as well as damp out the oscillation in the power of the PV system, but the tracking speed of the tracker reduces as the step size is reduced. As in this situation, a number of loops required to execute by the algorithms in achieving the maximum power operating point will be increased, and this will take extra time. To avoid the above-said situation, variable perturbation step size method is provided as an option, where the size of the step gets smaller as the operating point moves towards the MPP [7]. The other limitation of the P&O algorithm is that it fails to respond quickly when the changes in environmental condition as well as under partial shading condition when multiple peaks are there in P-V curve, which causes deviation from the exact MPP [7]. Effect of change in environmental condition can be demonstrated in Figure 4. Suppose, the operating point of the PV curve is 'X' with the power curve $P_X$when there is no variation in irradiation and temperature. But, if there is a perturbation (ΔV) occurs in PV array voltage, the operating point will shift from X to Y, and PV power decreases. But, at the same situation if the irradiation level increases, the power curve P_X will be shifted to the power curve P_Y and the new operating point will be Z even the perturbation is constant. Figure 5 shows the flowchart of the P&O algorithm.

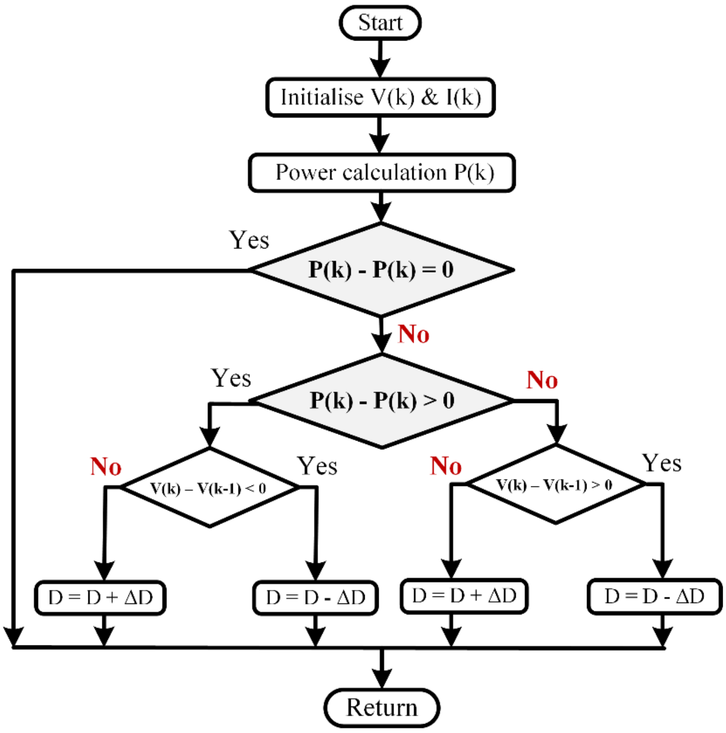

Figure 5. Flowchart of P&O algorithm.

3.2. Incremental conductance method

In the Incremental Conductance (IC) method, the voltage and current of the PV array are sensed. IC method uses both voltage and current sensors [13]. Here, the comparison between instantaneous conductance (I / V) and the incremental conductance (dI / dV) is made for tracking the MPP, which explained in the flowchart. At MPP, the slope of the PV curve is zero.

$$\left({}^{\mathrm{do}}/_{\mathrm{dV}}\right) \mathrm{MPP} = {}^{\mathrm{VdI}}/_{\mathrm{dV}}\ \mathrm{MPP} + \mathrm{I} \tag{1}$$

$$-\ {}^{\mathrm{I}}/_{\mathrm{V}} = {}^{\mathrm{dI}}/_{\mathrm{dV}}\ \mathrm{MPP} \tag{2}$$

The right-hand side of the equation is instantaneous conductance of the solar PV array. The MPP is obtained when the instantaneous conductance becomes equal to the incremental conductance of the solar PV array [13]. When the operating point is at the right of the MPP, then $\left({}^{dI}/_{dV}\right) + {}^{I}/_{V} < 0$, whereas when the operating point is at the left of MPP, then $\left({}^{dI}/_{dV}\right) + {}^{I}/_{V} > 0$ [12]. Unlike P&O method, this method of tracking yields good performance under varying atmospheric conditions. Since in this technique, both the voltage and current are sensed simultaneously and thus eliminates the error due to the change in radiation [14]. However, the method involves a complex circuit and also, the cost of implementation is high.

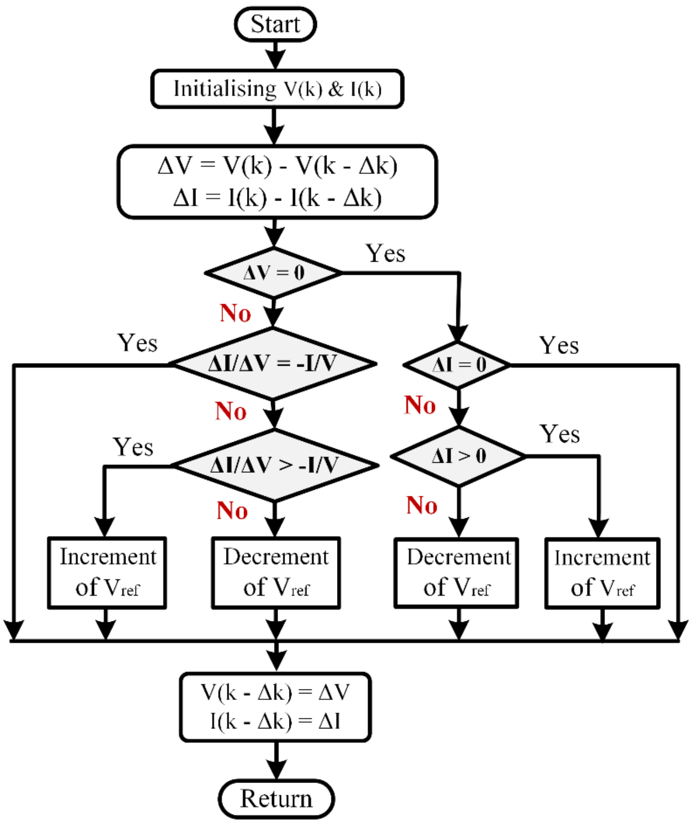

Figure 6. Flowchart of incremental conductance algorithm.

3.3. Short-Circuit pulse method

In short-circuit pulse method, the reference current is given to the power converter to achieve MPP. The nonlinearity behaviour of V-I characteristics of a solar PV system is constructed with the help of numerical approximation or mathematical equation [15]. So, based on V-I characteristics, the construction of mathematical relation between I_{MPP} & I_{SC} is done since there is a linear relation between I_{MPP} & I_{SC} shown by the given formula.

$$I_{MPP} \approx K_{SC}\, I_{SC} \tag{3}$$

where, K_{SC} is a proportional constant. The value of K_{SC} is often noticed to be varied between 0.65 and 0.85 [16]. The principle of short- current pulse method is developed based on the relation: the optimal operating current for M_{MPP} Is linearly dependent on the short-circuit current with varying temperature and irradiance condition. The value of K_{SC} is obtained by analyzing the solar radiation and temperature under wide range [16]. Figure 7 shows the flowchart of the short circuit pulse method.

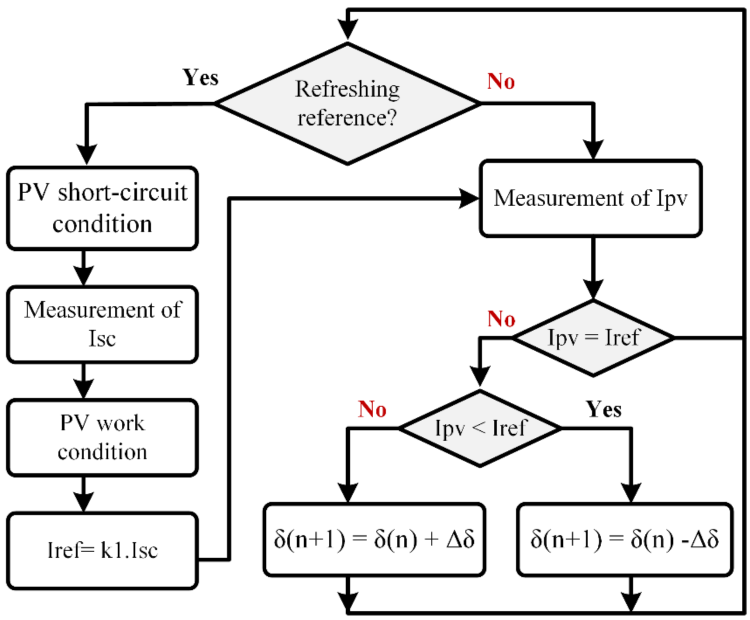

Figure 7. Flowchart of short circuit pulse method.

3.4. Open-Circuit voltage method

This technique generally follows the following imperial relation.

$$V_{MPP} \approx K_{OC} V_{OC} \tag{4}$$

where K_{OC} is a proportional constant value and varies between 0.79 & 0.92 [15]. And can be obtained by analyzing the solar PV system under various range of temperature and solar irradiation. The method uses 76% of V_{OC} as V_{REF} (reference value) and tries to achieve MPP. The V_{OC} is measured by the open circuit of the solar PV system at the load side for very less time. A series switch is placed in between the solar array and the converter to measure V_{OC}. Finally, with the help of the above equation V_{MPP} is measured. The disadvantage of this method is that, to measure the V_{OC} periodic load shedding is done, so there is an issue of power losses. To avoid power losses, the pilot cell can be used, but it should be chosen very carefully so that they can represent the characteristics very close to the solar PV array. Also, the above equation is only an approximation. Therefore, the solar PV array never operates at exact MPP. Otherwise, the method is simple and easy to implement [15]. Figure 8 shows the flowchart of the open-circuit voltage method.

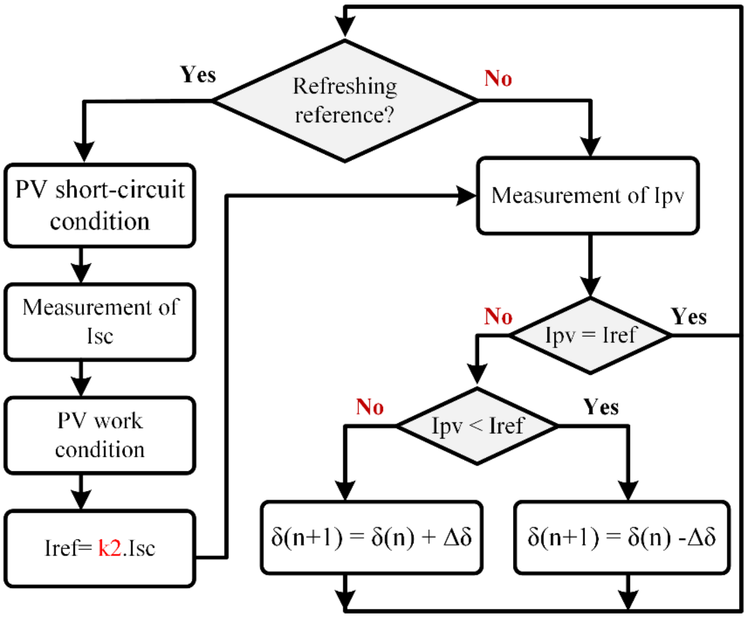

Figure 8. Flowchart of open-circuit voltage method of MPPT.

3.5. Lookup table algorithm

This technique involves a large number of recording activities to record the new MPP. It requires PV system technical data knowledge, analysis of the material, and PV array characteristics at the different atmospheric condition to be collected and stored [17]. According to the environmental condition of a particular location, the power is calculated with the help of calculated current and voltage; then the power is compared with the previously stored data. Therefore, the new MPP is tracked based on the lookup the table, and then the operating point is shifted there [17]. As the method requires a large number of stored data at different geographical condition, the system becomes complex and need a huge memory. Also, the number of sensors required is more, and convergence speed reduces as well as the technique is not much accurate [9].

3.6. Temperature based MPPT

Maximum power is tracked by sensing the temperature in this technique. The open-circuit voltage V_{OC} of the solar PV cell is linearly dependent on the temperature, and the short circuit current is proportional to the irradiation, as shown in Figures 9 and 10, respectively. This is a very simple offline technique [18]. It has the limitation such as the temperature of the system is not uniform; the calibration of the temperature sensor is a big issue which causes inaccuracy in the measurement. This method has an application in PV/T systems.

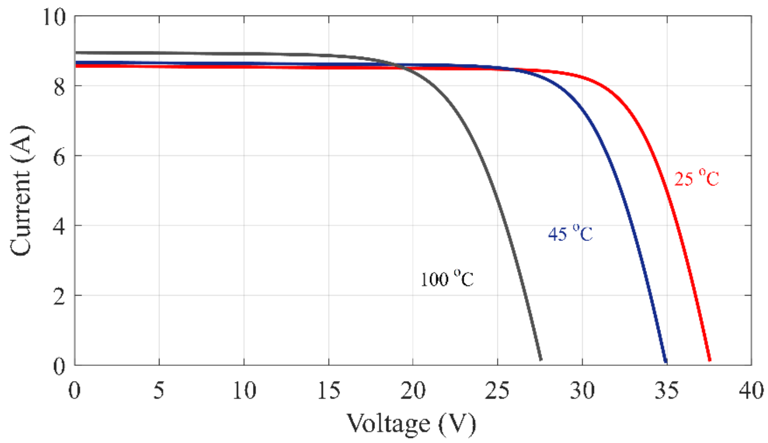

Figure 9. I-V characteristics of PV array with varying panel temperature.

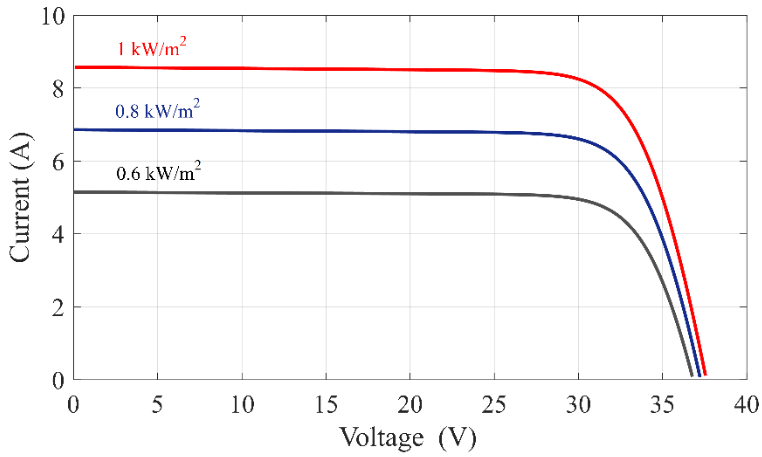

Figure 10. I-V characteristics of the PV array with varying irradiation.

3.7. Curve fitting technique

In the curve fitting technique, firstly the PV curve is obtained and predicted. Since the PV curve has the peak value that is called MPP. Numerical approximation and mathematical equation are used to predict the PV curve [19]. Third-order polynomial given by Eq (5) can be used to obtain the exact PV curve fitting

$$\mathrm{P} = aV^3 + bV^2 + CV + d \tag{5}$$

where all the coefficients a, b, c, and d are known by sampling the solar PV voltage and power in some intervals. By differentiating Eq (5)

$$\frac{dP}{dV} = 3aV^2 + 2bV + C \tag{6}$$

At MPP,

$$\frac{dP}{dV} = 0 \quad (7)$$

Therefore, the voltage of the PV array at MPP as follows

$$V_{mpp} = \frac{-b \pm \sqrt{b^2 - 3ac}}{3a} \quad (8)$$

In this method, the value of coefficients is sampled periodically in the interval of a few milliseconds.

3.8. One cycle control (OCC) method

OCC is a very simple nonlinear MPPT technique. A single-stage inverter is used in the technique [20]. Accordingly the solar PV voltage at the inverter output current (I_{out}) can be changed to achieve the MPP [21]. The parameter (L, C) in the system must be tuned so that they cannot affect the system accuracy [22]. OCC arrangement is represented in Figure 11.

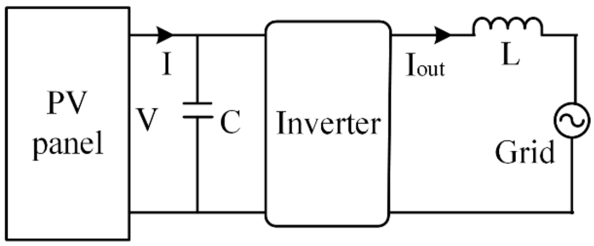

Figure 11. Block diagram of OCC technique.

3.9. Feedback voltage or current technique

Feedback method is used in the system with no battery bank. Without any battery, a controller is used to keep the voltage of the bus at the constant value [23]. Figure 12 shows the simple arrangement of the MPPT controller with a PV system. In this method of tracking, voltage and current are measured and compared with the reference which will adjust the duty ratio of the converter. This adjustment of the converter matches the impedance to achieve the desired operating point of approximately [24].

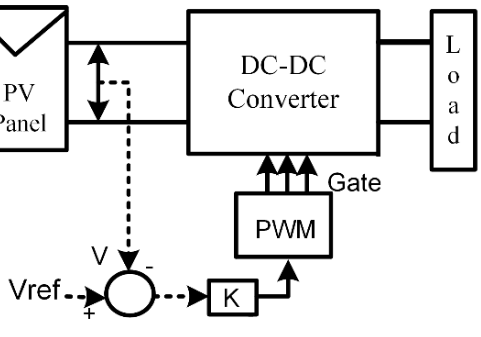

Figure 12. Block diagram representation of the voltage-feedback method.

3.10. *Feedback of power variation with voltage technique*

This technique is very much similar to the feedback voltage method of tracking except that in this power variation with voltage (dP/dV) is considered to obtain control. This approach involves to measure & maximize the load terminal power [25,26].

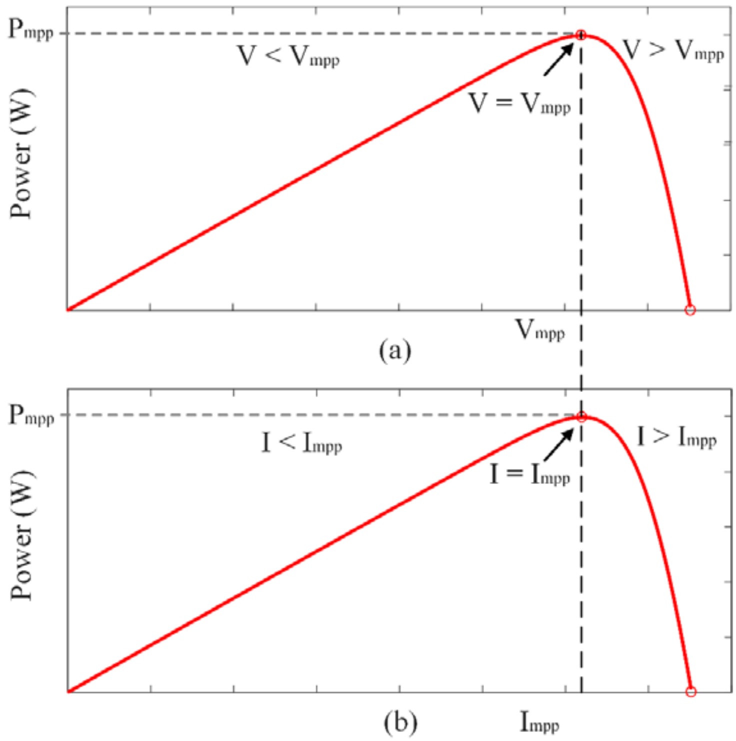

Figure 13. Output power variation with panel terminal voltage and current is shown in (a) and (b) respectively.

3.11. Fuzzy Logic Controller (FLC)

This technique is one of the attractive techniques which come under artificial intelligence techniques. Knowledge-based data is used in this technique [27,28]. Generally, the fuzzy logic method involves three subconcepts: fuzzification, decision making, and defuzzification. E is the error, and CE is the change in error. E and CE are the inputs, and the duty cycle D is the output of the FLC [29].

$$\text{Error} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{9}$$

$$\text{CE} = E(k) - E(k-1) \tag{10}$$

where P and V are the power and voltage of the photovoltaic system, respectively, the variables E, CE and the output D are expressed in terms of a linguistic variable or special labels such as PB (positive big), PM (positive medium), PS (positive small), ZE (zero error), NB (negative big), NM (negative medium), NS (negative small). After calculating the E and CE and converting them to the linguistic label, the output of the FLC, i.e., D of the power converter can be determined from the rule of the fuzzy system shown in Table 1. The triangular membership function is used for input and output variable both. Figure 14 shows the block diagram of FLC [30,31].

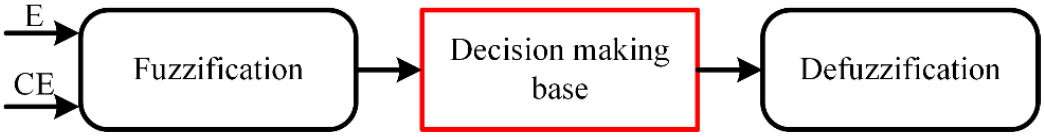

Figure 14. Block diagram of fuzzy logic.

Table 1. Rules for the fuzzy system [32].

	Change in error (ΔE)						
Error (E)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Fuzzification: In this process, all the numerical values are converted into a linguistic variable as the fuzzy logic controller requires that all the input and output should be represented in the linguistic module.

Inference method: During this process, the mapping of fuzzified variable takes place. Fuzzy logic rules as applied to obtain the corresponding membership functions. In other words, the inference method involves the process of obtaining the membership function from FLC rule.

Defuzzification: Defuzzification is a process of converting the fuzzy subset back to the numerical values. Because of the reason that the system is compatible with the non-fuzzy value of control, so the process of defuzzification is necessary. The height defuzzification is a speedy and simple process and is given as:

$$\Delta D = (\sum_{k=1}^{m} p(k) * w_k) / \sum_{k=1}^{m} w_k \quad (11)$$

where ΔD the change of duty cycle is, $p(k)$ is the peak value of each output and w_k is the height of the kth rule [33]. In some applications, hybrid techniques were developed by the combination of fuzzy and neural network algorithms [34,35], it will further improve the performance of the tracking algorithms.

3.12. Artificial Neural Network (ANN) MPPT technique

Nowadays, immense interest and attraction have been found towards the implementation of ANN techniques to track the MPP. This method is being considered as an attractive way to get the solution to complex problems [8]. There are several ANN based MPPT techniques reported in the literature [9]. Figure 15 present the architecture of an ANN-based method which consists of three layers, namely Input layer, Hidden layer and output layer. Input layer generally consists of inputs parameters as in case of MPP tracking of a PV system these parameters are PV voltage, PV current, temperature, and measured irradiation to the network. The second layer is like the heart of the ANN network. The sigmoid function is the activation function of this layer. The third layer is the output layer and represents the duty cycle. A linear function is the activation function of this layer [36].

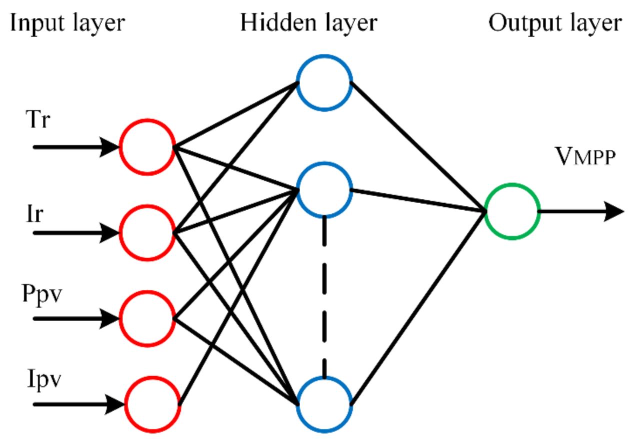

Figure 15. ANN architecture specify different parameters and layer structure.

To track MPP, using ANN, the inputs of the ANN can be PV voltage, PV current, atmospheric data like temperature and irradiation, or any combination of the above parameter. On the other hand output of the ANN can be tracked maximum power or can be a duty cycle, which is then fed to the electronic converter to obtain MPP [37,38]. The input and output data of the ANN can be collected from model-based simulation results or experimental results [39]. In [40], to improve the dynamic behaviour of the system under fast-changing isolation, a hybrid combination of ANN and GA is used.

3.13. Load parameter based MPPT

This method is simple, which involves indirect process and is suitable for all kind of practical loads. To track the MPP, this method controls the load parameters instead of monitoring the output parameter of the solar PV system. Here, tracking of power means to track output current and output voltage. If the output current and output voltage are increasing, then the power will also increase [41]. The maximum power is obtained by controlling the output voltage and sensing the output current and by increasing both the output current and output voltage simultaneously. The method has the advantage of involving a simpler controller [7].

3.14. Ripple Correlation Technique (RCC)

Due to the switching function of the power converter, voltage and current ripples on solar PV panel occur. The RCC technique tracks the MPP with the help of these ripples. External perturbation is not required as the ripples are naturally present because of the switching converters. The technique RCC tries to make the ripples at zero levels and PV current and voltage to MPP level approximately [42]. Here, there is a process of correlation between dp/dt with either dv/dt or di/dt and thus, with the help of the following relation, the voltage and current of the PV panel is determined and analyzed whether the value is above or below the MPP level.

$$\frac{dv}{dt} > 0 \text{ or } \frac{di}{dt} > 0 \text{ and } \frac{dp}{dt} > 0 \rightarrow \text{V} < \text{V}_{\text{MPP}} \text{ or I} < \text{I}_{\text{MPP}} \tag{12}$$

$$\frac{dv}{dt} > 0 \text{ or } \frac{di}{dt} > 0 \text{ and } \frac{dp}{dt} < 0 \rightarrow \text{V} > \text{V}_{\text{MPP}} \text{ or I} < \text{I}_{\text{MPP}} \tag{13}$$

Any power converter topology can be used for this technique, such as boost converter can be taken as an example where the current has adjusted accordingly. As the inductor current i_L and PV current (I) both are equal. At particular irradiation and temperature, i_L can be adjusted and may have $\text{P} = \text{V}i_L$. Thus the above equation can be written as

$$\frac{di_L}{dt}\frac{dp}{dt} > 0 \rightarrow i_L < \text{I}_{\text{MPP}} \tag{14}$$

$$\frac{di_L}{dt} > \frac{dp}{dt} < 0 \rightarrow i_L > \text{I}_{\text{MPP}} \tag{15}$$

The RCC technique possess advantages like accuracy, high tracking speed, the process starting time is quite better than the perturbation & observation method, incremental conductance method, a temperature-dependent technique [4]. The technique is having the limitation of complex implementation due to electromagnetic interference issue [43].

3.15. Current sweep technique

Sweep waveform of a PV array current is used in this technique. Then with the help of this waveform, the I-V characteristics of PV array are obtained. The I-V curve is used to calculate theV_{MPP}. With the help of sweep waveform, which keeps updating after every fixed interval of time, the I-V characteristics are also able to update periodically [7]. The equation showed the function which has been chosen for sweep waveform

$$i(t) = k_0 \frac{di(t)}{dt} \tag{16}$$

k_0 is a proportionality constant. The solution of the above equation is

$$i(t) = k_1\, e^{t/k_0} \tag{17}$$

Here k_1 is taken as I_{MPP}. The power of the PV array is as follows:

$$p(t) = v(t)i(t) \tag{18}$$

At MPP,

$$\frac{dp(t)}{dt} = \frac{d\big(v(t)i(t)\big)}{dt} \tag{19}$$

Also,

$$i(t)\frac{dv(t)}{dt} + v(t)\frac{di(t)}{dt} = 0 \tag{20}$$

By using the above equations,

$$\frac{dp(t)}{dt} = \left(k_1 \frac{dv(t)}{dt} + v(t)\right) \frac{di(t)}{dt} = 0 \quad (21)$$

Thus by updating the reference point periodically and choosing the value of k_0 and k_1 properly the technique can give satisfactory result [44].

3.16. Slide mode control

In this technique, slide mode observe used to obtain current array values and is used to generate the reference for control signal. Linear-model control fails to track the MPP under varying parameter values in such situations sile Mode control based MPPT can be implemented with better perform [45]. To obtain the MPPT, the buck-boost converter is being used. 'u,' is the switching function of the converter and its function is based on the condition that when $\frac{dP}{dV} > 0$ then it is on the left of the MPP and when $\frac{dp}{dv} < 0$ then on the right of the MPP; u is given as

$$u = 0 \quad S \geq 0 \quad (22)$$

$$u = 1 \quad S < 0 \quad (23)$$

Here if u = 0, it means the switch is open and if u = one the switch is also closed S can be expressed as

$$S = \frac{dP}{dV} = \frac{dVI}{dV} \quad (24)$$

$$S = I + V \frac{dI}{dV} \quad (25)$$

The microcontroller is used to sense the solar PV panel voltage, and current and the control of this method is implemented with the help of microcontroller [46].

3.17. The Three-Point weight comparison algorithm

In perturb and observe (P&O) method, which is commonly used to track the maximum power point, there is always an issue of oscillation. To avoid the oscillation, the three-point weight comparison method is used. Comparing with perturbing and observe method which compares two points only and that two points are existing operating point and another point is any perturbation point. The power of the existing operating point and the perturbation point is compared and then decided which power is greater and closer to MPP [47]. Figure 16 shows the three-point weight comparison algorithm where the output power corresponding to three points are obtained and compared. In the three-point weight comparison method, the points are as, X is the existing operating point, Y is the next perturbed point from point X, and Z is the point which is in the opposite direction of Y.

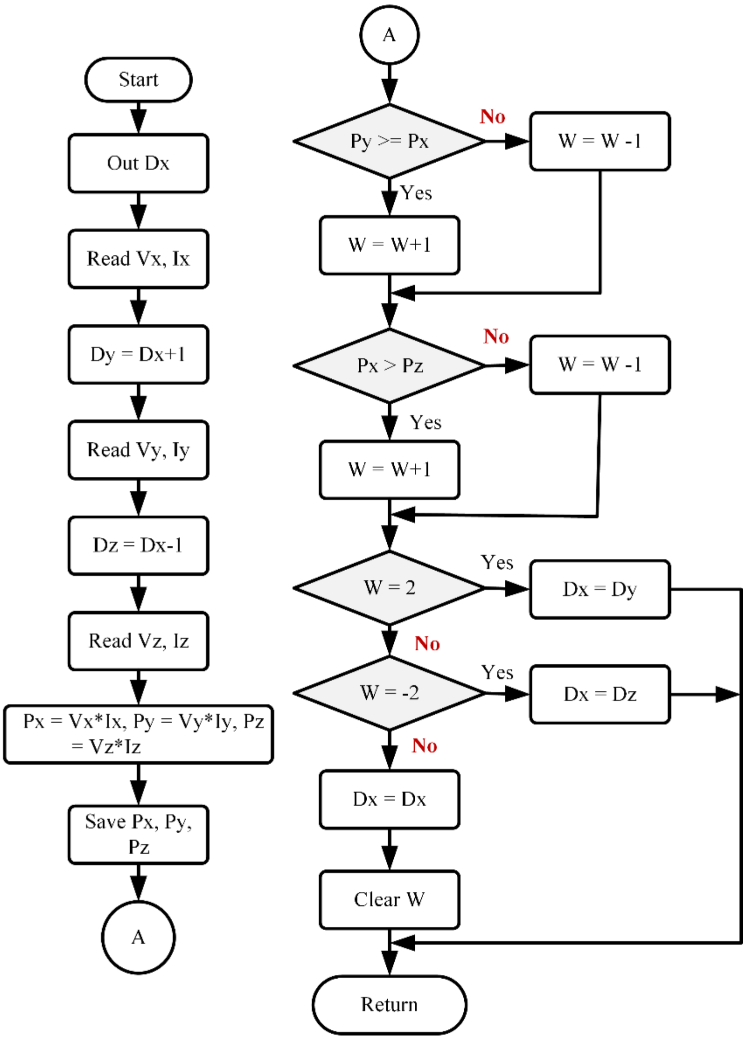

Figure 16. The three-point weight comparison algorithm.

Figure 17 shows the possible nine cases. The system works as; by taking the point X and Y if the point Y has more or equal wattage than the point X, then the status will be as positive weighting. If not, then the status shows the negative weighting. When taking the point X and Z if the Z has less wattage than point X, then the status is positive weight; otherwise, it will show negative weighting. Among the all measured points, if the two points are weighted positively, then the duty cycle D of the converter should increase. On the other hand, if the two points are weighted negatively, then the D of the converter should decrease. And in the case with one positive and one negative weighting, the point MPP is reached.

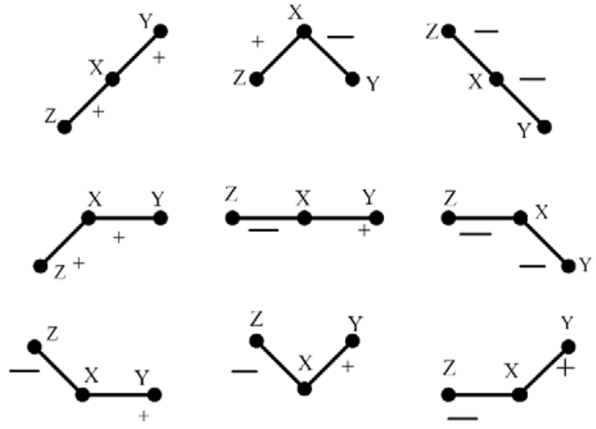

Figure 17. Possible causes for the three perturbing point.

4. Comparative analysis

This paper discussed extensively used conventional and selective advanced MPPT techniques. Comparative analysis for performance evaluation of the considered techniques based on the parameters such as the control variables used, control strategy types, circuitry, and implementation feasibility are discussed in the following section.

4.1. Based on the control variable used

Voltage, current, panel temperature, irradiation, etc. are the different control variables that are generally used to obtain the MPP. Measurement, implementation complexity and cost for the voltage sensor are less complicated and cheaper than that of the current sensor, which is complex bulk, and expensive in use. Above mentioned variables are required to be sensed by the MPP techniques. Therefore, according to the variable to be sensed, the MPP methods are classified as one variable-technique and two-variable method. Depending on the variable discussed techniques are compared, and the required variable is specified in the table below.

4.2. Based on the control strategy

Control strategies used in MPPT are broadly categorized into three types: indirect control, direct control, and probabilistic control. The indirect method utilizes data & parameter obtained indirectly such as take data from characteristics curve of PV array with different irradiation & temperature, or some mathematical or empirical formula is used to estimate MPP. The direct method involves direct tuning with PV array operating points, without knowledge of PV panel characteristics. The method is further divided into two types like sampling method and modulation method. In the sampling method, the comparison of the previous and latest information is made to track the MPP. In the modulation method, MPP is achieved by the generation of oscillation automatically with the use of feedback control. Based on the control strategy used, discussed techniques are classified as dependency on PV array and requirement on periodic tuning.

4.3. Based on circuitry

MPPT generally use two types of circuitry such as digital circuit and analogue circuit. Use of MPPT based on circuitry depends upon the users as some of the users feel convenient by using an analogue circuit based MPPT; on the other hand, some user needs a digital circuit. Sometimes both type of circuitry is required. Some methods can be easily implemented using both types of circuits such as P&O, Short circuit current, etc. Whereas some techniques can only be analyzed through a specific type of circuitry. Therefore, the feasibility of implementation of the discussed techniques using different circuit is examined and specified.

4.4. Based on tacking speed and implementation complexity

An important parameter to be considered in the comparative study of different tracking techniques is the time taken by the method to reach the MPP. That is the speed of convergence of the technique. Depending upon the speed of tracking, different techniques are broadly classified as fast speed, medium speed and slow speed techniques. In some methods, this speed may vary as the accuracy in tracking maximum power changes. Classifying different method on the bases of tracking speed will be very much helpful in selecting the techniques for a particular application.

Implementation complexity and cost are also very important parameters to be considered while comparing different MPPT techniques. The MPPT techniques are available at a different cost. In some complex applications such as large residential load, solar vehicle, big industry, the accuracy becomes an important parameter than the cost. But the area like small residential, water pumping (irrigation), etc.., the system requires cheap and simple MPPT. Similarly, implementation of MPPT techniques in some cases is a simple and easy task whereas in other cases implementation can be complex. Depending on the complexity in implementation and the speed of tracking presented techniques are studied and classified in Table 2.

Table 2. Comparison of different MPPT Techniques based on the selected parameter.

MPPT Techniques	PV array Dependency	Analog or Digital	Convergence Speed	Implementation Complexity	Sensor Parameters
P & O	Independent	Both	Varies	Easy to implement	V & I
Incremental Conductance	Independent	Digital	Varies	Medium	V & I
Open Circuit Voltage V_{oc}	Dependent	Both	Medium	Easy to implement	V
Short Circuit Current I_{sc}	Dependent	Both	Medium	Medium	I
Lookup Table	Dependent	Digital	Fast	Medium	V, I, irradiation, and Temp
Temperature Based	Independent	Digital	Medium	Complex	V, irradiation, and Temp.

Continued on next page

MPPT Techniques	PV array Dependency	Analog or Digital	Convergence Speed	Implementation Complexity	Sensor Parameters
Curve Fitting	Dependent	Digital	Medium	Easy to implement	V
OCC Method	Dependent	Both	Fast	Medium	I
Feedback Voltage or Current Tech.	Independent	Both	Medium	Easy to implement	V or I
Feedback of Power Variation with V/I Tech.	Independent	Digital	Fast	Complex	V or I
Fuzzy Logic Controller	Dependent	Digital	Fast	Complex	Varies
Artificial Neural Network	Dependent	Digital	Fast	Complex	Varies
Load Parameter Based	Independent	Digital	Medium	Medium	V & I
RCC Method	Independent	Analog	Fast	Easy to implement	V & I
Current Sweep	Dependent	Digital	Slow	Complex	I
Slide Mode	Independent	Digital	Fast	Medium	V & I
Three-Point Weight Comparison	Independent	Digital	Varies	Easy to implement	V & I

5. Conclusions

In this work, conventional and selected advanced MPPT techniques for solar PV application has been discussed. Techniques are explored focusing on different parameters. Comparative analysis based on different control strategies, control variables used, sensors used, response time, cost of implementation, complexity, and effectiveness are presented. A comprehensive study with proper comparative analysis of different techniques is presented in concise which will assist in selecting an appropriate technique for specific applications. This overview should serve as a useful reference for researcher and design engineers involved in MPPT designing and algorithm development for solar PV systems.

Conflict of interest

The authors declare that there is no conflict of interest in publishing this paper.

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