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Green Energy & Environment 2 (2017) 5−17

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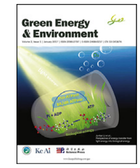

Review article

Comparative assessment of maximum power point tracking procedures for photovoltaic systems

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Received 29 August 2016; revised 24 September 2016; accepted 2 November 2016

Available online 9 November 2016

Abstract

The fast growing demands and increasing awareness for the environment, PV systems are being rapidly installed for numerous applications. However, one of the important challenges in utilizing a PV source is the maximum power harnessing using various maximum power point tracking techniques available. With the large number of MPPT techniques, each having some merits and demerits, confusion is always there for their proper selection. Discussion on various proposed procedures for maximum power point tracking of photovoltaic array has been done. Based on different parameters analysis of MPPT techniques is carried out. This assessment will serve as a suitable reference for selection, understanding different ways and means of MPPT.

Keywords: Maximum power point tracking (MPPT); Photovoltaic (PV); Solar; Perturb and observe; Optimization

1. Introduction

With the recent progress in technology, government schemes and the development of a healthy mind set, a shift towards use of renewable energy sources has been observed. Due to improvement in PV array manufacturing, efficiency and the fickle fuel costs, the use of PV system is gaining rapid momentum. And by the increase in the usage of renewable energy systems like solar PV and wind systems, development of technology for maximum power extraction from these systems is a must.

The maximum power point on highly nonlinear V−P characteristic of PV array depends on the atmospheric conditions [1−4]. Also the operating power point on the V−P characteristics depends on the impedance of connected load [1,5−7]. To extract maximum power from PV array various MPPT methods are used. These MPPT methods compel the PV array to operate at or very close to the maximum power point of the V−P or I−V characteristic [5−7]. The algorithms that are used in maximum power point trackers dynamically bring the current or voltage at or near the maximum power point.

Till date, a large number of MPPT methods have been proposed and developed. Some of these methods are for general purpose application and some deals with specific application. They may involve DC−DC converter or DC−AC converters with direct or hybrid algorithms. This script phases out through a wide range of approaches used for MPPT with a brief discussion and cataloguing of each method. Discussion about minor adaptation of original or existing methods has been avoided.

2. Basics of solar photovoltaic cell

Fig. 1 represents the simple equivalent circuit of a PV cell with load [10]. The elementary Equation defining the I−V

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http://dx.doi.org/10.1016/j.gee.2016.11.001

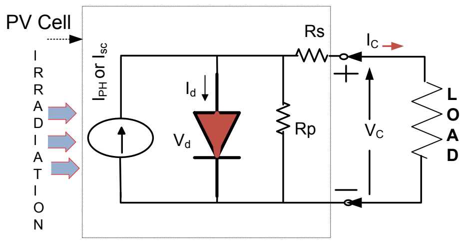

Fig. 1. Simple equivalent circuit of a PV cell.

characteristic of the ideal photovoltaic cell is given by Eq. (1) [8−12].

$$I_C = I_{PH} - I_0\left[e\left(\frac{qV_d}{kT_C}\right) - 1\right] \quad (1)$$

$I_{PH} = I_{SC}$ is the short circuit current whose magnitude depends on the area of the cell and is directly proportional to the solar insolation. V_d is the voltage across the diode, k is Boltzmann constant (1.38×10^{-23} J/°K), q is electron charge (1.602×10^{-19} C), I_o is reverse saturation current of diode (0.000025 A) and is calculated using Eq. (2), T_c is reference cell operating temperature (25 °C).

$$I_o = \frac{I_{sc,n} + K_I \Delta T}{\exp\left(\frac{V_{oc,n} + K_V \Delta T}{aVt}\right) - 1} \quad (2)$$

K_I is the current coefficient, K_V is the voltage coefficient, $V_{oc,n}$ is the open circuit voltage at the nominal condition (usually 25 °C and 1000 W/m^2), $\Delta T = T - T_n$ (being T and T_n the actual and nominal temperatures). In a practical PV cell, there is a series of resistance in the current path through the semiconductor material, the metal grid, contacts, and current collecting bus. These resistive losses are lumped together as a series resister (R_s). R_p takes into account the loss associated with a small leakage of current through a resistive path in parallel with the intrinsic device. I−V and P−V characteristic of a PV cell is shown in Fig. 2. The intersection of load line (i.e. I=V/R) and I−V plot of PV cell gives the operating point. R_1 and R_o are different load resistance. R_o corresponds to the load at which MPP coincides with the operating point.

The point at which I_{mp} and V_{mp} meets is the maximum power point [MPP] and this point varies with the change in atmospheric conditions. I_{mp} is the current corresponding to maximum power and V_{mp} is the voltage across cell at maximum power. The open circuit voltage (V_{oc}) decreases

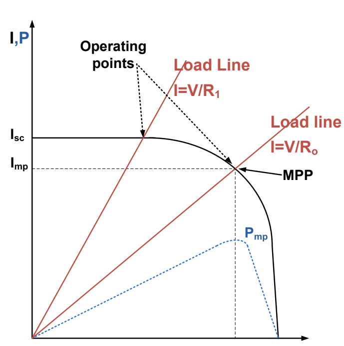

Fig. 2. I−V and P−V characteristics of PV cell.

linearly with the rise in the cell temperature and increases logarithmically with the ambient irradiation, while the short circuit current is a linear function of the ambient irradiation, this is clearly shown in Fig. 3.

To obtain maximum power from the PV array, the operating point should coincide with the MPP at different atmospheric conditions. The process of extracting maximum power from a PV array is done by the maximum power point tracker.

3. MPPT—Requirement

The purpose or role of various algorithms, proposed till date, is to control the duty ratio (D) of the converter used. This is done in such a manner that the actual load line as seen by the PV array coincides with that of a load at which maximum power in extracted from the panel. Four basic types of DC−DC converters are mainly used for this purpose and they are Buck, Boost, Buck-Boost and Cuk converter. For grid connected system or for AC loads generally an inverter is used after DC−DC converter but advancement in research has eliminated one stage by directly converting the panel DC output to AC [6]. Fig. 4 shows the schematic diagram of a PV system with DC−DC converter [2,3,5]. R_{in} is the input resistance of the converter and R_o is the output resistance or load resistance. In Fig. 5 the approximate range of R_{in} for different DC−DC converters has been shown, depending upon the value of R_o, the correct choice of converter can be made [5−7].

4. MPPT classification and details

4.1. Fractional Short Circuit Current method

Numerical methods have shown that there is a linear dependence between I_{mp} and I_{sc} [13]. This gives the Eq. (3) which portrays the main idea of Fractional Short Circuit Current technique for maximum power-point tracking. The MPPT makes the PV array to operate at a fixed percentage of I_{sc} and thus very close to the maximum power point. K_{sc} is a constant of proportionality and is called the "current factor". Its value depends on the type of cell used and it lies between 0.71 and 0.90 [13,14].

$$I_{mp} = K_{sc} I_{sc} \quad (3)$$

The main problem to implement this method is the difficulty of measuring I_{sc} while the PV system is in operation. For

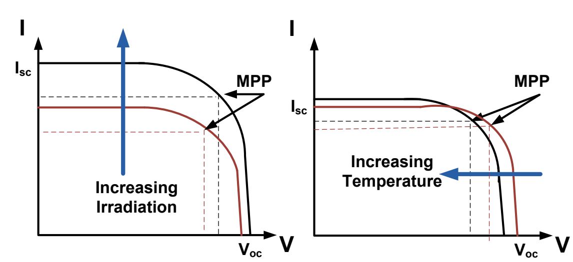

Fig. 3. I−V characteristics of PV cell with change in ambient irradiation & the cell temperature.

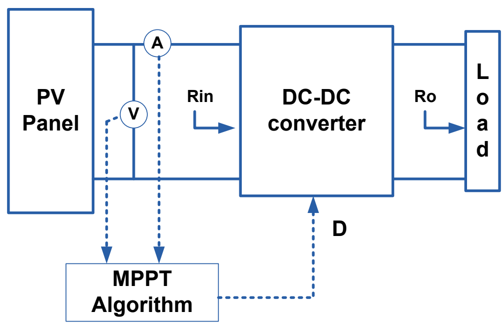

Fig. 4. Schematic diagram of complete PV system.

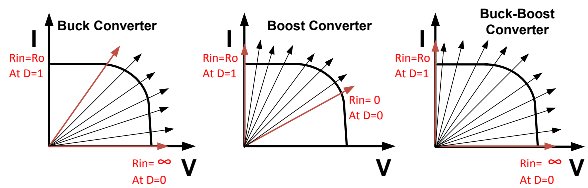

Fig. 5. Approximate range of R_{in} for different converters.

this the PV array has to be shorted, which is usually done using a supplementary switch with the power converter as shown in Fig. 6. This switch from time to time shortens the PV array and I_{sc} is measured by means of a current sensor. The use of switch, S, can be avoided by using a boost converter, whose switch itself may be used to shorten the PV array [14]. Fig. 6 represents the Schematic diagram for Fractional Short Circuit Current method. Due to periodic operation of S, the overall power output of the panel gets reduced and also since k_{sc} depends on the variation in atmospheric conditions, exact MPP tracking is not possible by this method and thus efficiency is low. To improve the MPP tracking by this method, K_{sc} has to be compensated as the atmospheric conditions changes [15,133]. In case of partial shading, to find global maxima, periodical sweep operation is required. The biggest advantage of this method is the fast tracking operation [16].

4.2. Fractional open circuit voltage method

Almost similar to the Fractional Short Circuit Current method, this method measures the open circuit voltage (V_{oc}) of the solar panel and the MPPT makes the panel to operate at a fixed percentage of V_{oc} which is very near to the maximum power point.

The logic behind this method is that the open circuit voltage (V_{oc}) has almost a linear relation with V_{mp} at varying insolation and temperature [17–20] and this is represented by Eq. (4); where K_{oc} depends on the type of PV cell used and has a value between 0.71 and 0.80 [28,133].

$$V_{mp} = K_{oc} I_{oc} \tag{4}$$

Similar to the Fractional Short Circuit Current method, here the measurement of V_{oc} creates problem. Generally V_{oc} is measured by disconnecting the DC–DC converter from the panel due to which momentarily power loss takes place. It is also possible to measure V_{oc} by having a pilot cell [18], but special care has to be taken to choose this pilot cell such that it has the same characteristics as the PV array. It is an approximate method and exact MPP tracking is not possible by this method but is easy, less costly and fast operation is achieved. In case of partial shading global maxima is achieved by periodical sweep operation.

4.3. Perturb-and-observe/hill climbing

The most commonly used, talked and simple MPPT algorithm is Perturb-and-Observe (P&O) method. Both Hill climbing (HC) [21–28] and P&O [29–36] methods have same logic and can be said to be two different means of visualizing the same method. In HC method duty ratio of the power converter used is perturbed and in P&O method the working voltage of the PV array is perturbed. Since a power converter is generally used with a PV array, so perturbing its duty ratio will automatically perturb the working voltage and thus both the methods are almost same. The logical flowchart of P&O method is shown in Fig. 7. V(k) and I(k) is the PV panel voltage and current at kth iteration. P(k) = V(k)·I(k), is the

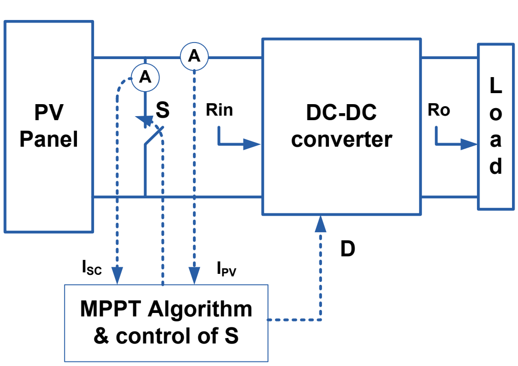

Fig. 6. Schematic diagram for Fractional Short Circuit Current method.

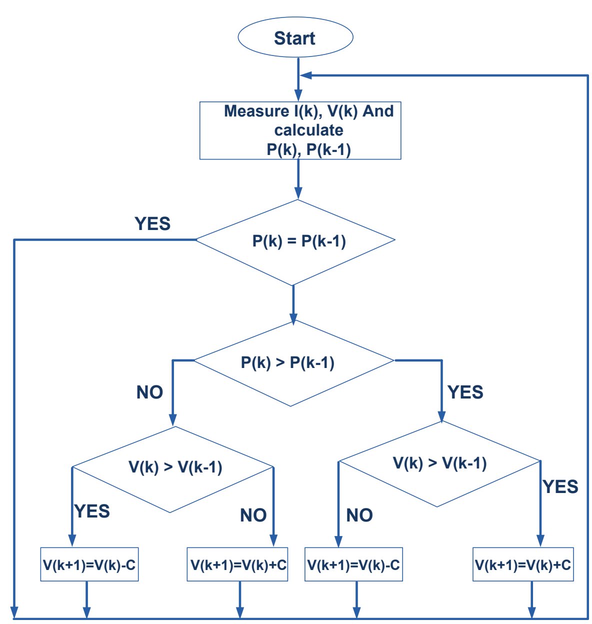

Fig. 7. Flowchart of P&O method.

output PV panel power at kth iteration. C is the length of voltage perturbation and choice of its value is very important. Small C results in slow tracking and large C gives fast tracking but the oscillation near the peak is large. The solution for this problem is the use of varying value of C, such that its value is large when the system is far from the MPP and its value approaches zero as the system reaches MPP [28,32,37,39−45]. In [46], it was shown that a fast convergence speed and almost no oscillation around the MPP can be achieved by taking the value of C at kth iteration i.e. C(k) according to Eq. (5).

$$C(k) = N\log_{10}(abs(\Delta P/\Delta V)) \tag{5}$$

Fuzzy logic can also be used to select the optimized value of C(k) [44]. Both Hill climbing and P&O method can track in the wrong direction, away from the MPP, and may fail under rapidly changing atmospheric conditions [47]. To avoid such problem, a solution is proposed in [38], where a three-point weighted comparison method in which comparison of the actual power point to two earlier ones has been done before taking a decision for the perturbation sign.

Generally two sensors are required and the method can be implemented using DSP or microcontroller although analog or digital circuit can also be used [24].

4.4. Incremental conductance

After P&O, IC method is very commonly used for solar PV MPPT. It is based on the fact that the derivative of power output of a PV panel with respect to voltage is zero at MPP, is negative on right of MPP and is positive left of MPP on P vs. V curve [48−59]. The derivative of power output (P) of a PV panel with respect to voltage (V) is given by Eq. (6).

$$\frac{dP}{dV} = \frac{d(IV)}{dV} \approx I + V\frac{\Delta I}{\Delta V} \tag{6}$$

The conditions used for tracking is given by Eqs. (7)−(9). ΔI/ΔV represents incremental conductance and I/V represents instantaneous conductance.

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V};\ \text{At MPP} \tag{7}$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V};\ \text{Left of MPP} \tag{8}$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V};\ \text{Right of MPP} \tag{9}$$

The flow chart of IC method is shown in Fig. 8. As the system reaches MPP, the PV array is operated at this point and perturbation stops till a change in ΔI/ΔV is observed [60]. The value of perturbation in voltage i.e. ΔV, plays a very important role and decides the speed of tracking [50,51,61,62]. Another way of implementing IC method is the logic of minimizing the error signal (e) given by Eq. (10).

$$e = \frac{\Delta I}{\Delta V} + \frac{I}{V} \tag{10}$$

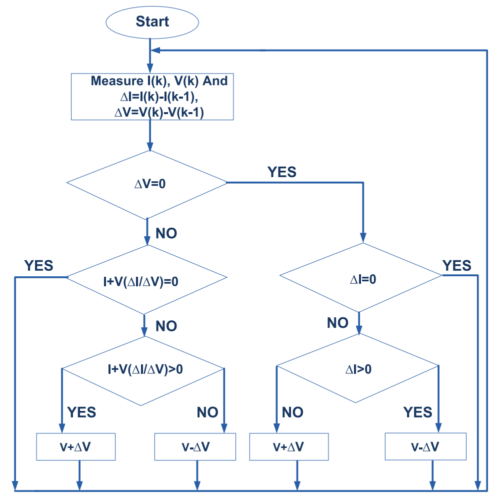

Fig. 8. Flowchart for incremental conductance method.

The IC method requires two sensors for the measurement of V, I and lends itself well to DSP and microcontroller control. Good performance is achieved by this method under fast changing atmospheric conditions. In [61] it has been thoroughly analysed that P&O and IC methods are two equivalent methods. In [63,66] the design principle of the partially variable step-size IC MPPT was developed on the uniform insolation for the PV array and not only the steady-state performance but also the dynamic response was improved.

4.5. Computational/lookup table

In Lookup Table method a table is formulated based on the experimental data available [52,63,64] while the computational MPPT method uses a predefined equation to find the MPP [15,64,65]. One of the equations that is used in computational MPPT method is given by Eq. (11). Where N is the number of cells, I_{MPP} is the current at MPP, V_T is the temperature voltage, and VD_o is the differential voltage [15].

$$T_L = (\eta \cdot V_T \cdot I_{MPP} - N \cdot R_S) \cdot I_{MPP} + \{V_{oc} - \eta[VD_0 + V_T]\} \tag{11}$$

Very fast tracking is achieved from these methods and no forced biasing is required for tracking. In lookup table with only condition of varying insolation, a 2 dimensional array for each possible value of voltage and current is required, but if there is another one condition of varying temperature, then a 3 dimensional array is required. Thus in this method, tracking is independent of the number of conditions however the number of sensors required increases with the number of conditions. While in computational method, the complexity of the predefined equation just gets more as the number of variables increases. These methods are not exact maximum power point trackers but tracking is almost very near to the exact MPP.

4.6. Switching Ripple correlation control method

Due to switching of the DC−DC converter, there are ripples in current and voltage of the PV array, the Switching

Ripple correlation control (SRCC) method uses this ripple for maximum power tracking [67]. The logic is that (dp/dt)*(dv/dt) or (dp/dt)*(di/dt) are positive to the left side of the MPP, negative to right side of the MPP, and zero at the MPP. From Fig. 2, it is clear that on left side of MPP, if we move such that voltage (v) increases or the current (i) decreases, the power (p) increases, we get dv/dt positive or di/dt positive, the value of dp/dt is positive, i.e. (dp/dt * dv/dt) is positive or (dp/dt * di/dt) is positive on left side of MPP. Thus we are below MPP. While if we are on the right side of MPP and moving such that voltage (v) increases or the current (i) increases, the power (p) decreases, we get dv/dt positive or di/dt positive but dp/dt is negative, i.e. (dp/dt * dv/dt) is negative or (dp/dt * di/dt) is negative on right side of MPP. Thus we are below MPP. Finally the value of (dp/dt * dv/dt) or (dp/dt * di/dt) is zero at MPP. Also, in place of derivatives, the ripple components can be used directly [67–70].

In this method the ripple itself is used to obtain maximum power tracking without extra perturbation and thus optimizing the converter operation. The behaviour of PV cell gets reflected in both the shapes and phase relationships between p, and either v, or i, and this gets changed while passing through the MPP. The correlation between power and either the voltage or current ripple waveform is used to track MPP. The duty ratio of the used converter is given by Eq. (12), where K is a positive constant [66–68].

$$D(t) = -k \int \dot{p} \cdot \dot{v} dt \tag{12}$$

In this method the global stability depends on two suppositions i.e. power vs. voltage characteristic do not have any local maxima and second, input voltage is always a nonzero ripple quantity. Due to local maxima, false tracking can take place.

Easy analog circuits of low cost can be used to implement SRCC and quick, accurate tracking is achieved. Due to the high switching frequency of the converter used, the time taken to achieve MPP is less. Also no prior information of the PV array characteristics is needed for MPPT.

4.7. Fuzzy logic based MPPT

The biggest advantage of fuzzy logic is the capability of functioning with inaccurate inputs without the need of a precise mathematical model and capable of dealing with nonlinearity [71]. Three basic stages in Fuzzy logic control are: fuzzification, rule base table, and defuzzification [71–78]. During first stage of fuzzification, numerical input variables are transformed into linguistic variables based on a membership function as shown in Fig. 9.

In case of MPPT based on Fuzzy logic, generally five fuzzy levels are used as shown in Fig. 9. Where *P* is positive, *B* is big, *S* is small, *N* is negative and *ZE* is zero. Also *a* and *b* are based on the range of values of the numerical variable. Greater fuzzy levels ensure greater accuracy [73,76,132]. The inputs to a MPPT fuzzy logic controller are usually an error *E* and a change in CE and its output is change in duty cycle (dD). In a

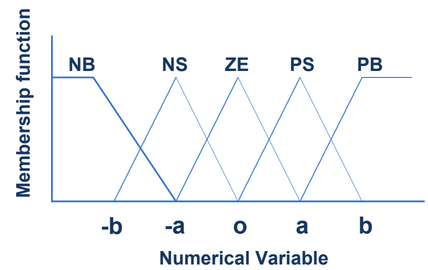

Fig. 9. Membership function for inputs and outputs of Fuzzy logic controller.

fuzzy logic MPPT, the step size and direction depends on how much E and CE is measured. Eqs. (13) and (14) show how the error and change in error are determined.

$$E(k) = \frac{P_{ph}(k) - P_{ph}(k-1)}{i_{ph}(k) - i_{ph}(k-1)} \tag{13}$$

$$CE(k) = E(k) - E(k-1) \tag{14}$$

Second stage is the formation of rule based table. A set of these rules is shown in Table 1. To understand the table, consider the following statement. *IF (E is PS) AND (CE is ZE) THEN (dD is PS).* Thus using Table 3 the size and direction of the change in duty cycle can be determined.

In the last stage of defuzzification, conversion of controller output from a linguistic variable to a numerical variable is done by using a membership function. Finally the analog signal generated is given to the power converter for MPPT.

The performance of MPPT fuzzy logic controllers is very good under varying atmospheric conditions. However, good result depends greatly on right error computation and development of correct rule base table. Constantly tuning of membership functions and the rule base table is shown in [73], and optimum performance was achieved. Two different membership functions will result in different tracking performance [76] and hence choice of membership function is also very important.

4.8. Neural network based MPPT

Neural network (NN) and fuzzy logic are almost same age technologies. Excellent performance can be achieved by combining NN and fuzzy technique for solar PV MPPT but the high computational load has limited the use of this hybrid technique [79].

The logic of neural network is motivated by the sophisticated functionality of human brain where hundreds of billions of interconnected neurons process information in parallel

Table 1
Rule based table for Fuzzy logic MPPT.

E＼CE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

[80,81]. Thus neural networks based MPPT are generally presented as systems of interconnected "neurons" which send messages to each other. Solar PV array parameters like V_{OC}, I_{SC}, irradiance, temperature or any combination of these can be taken as the input variables for the neural network. Generally three layers are used in neural networks and they are: input, hidden, and output layers as shown in Fig. 10. Faster operation can be achieved by using two stage ANN with Incremental Conductance MPPT but this requires system great understanding to govern when to switch between the two stages [82,83]. Varying, user-dependent number of nodes can be there in each layer. A duty cycle signal is the output which is used to control the power converter to operate the PV system very near or at the MPP. The perfectness of NN based MPPT depends on its training and on the algorithm used in hidden layer. The number of training sets can be reduced by using two cascaded NNs [82]. In ANN2 proposed Extension NN MPPT algorithm needs less constructed data and simple learning procedure [84]. In Fig. 10 W_{ij} is the weight of the link between node i and j. Similarly each link is given a weight which is carefully obtained by training process. To obtain these weights PV arrays are tested for months or years and the pattern between inputs and outputs is recorded. These patterns differ with PV arrays as most of PV arrays have different characteristics, thus the neural network has to be specially trained for each PV array with which it has to be used. Also with passage of time, the PV array characteristics get changed, requiring periodic training of the neural network used. The use of NN based MPPT is gaining more responsiveness because of its robust, fast and precise performance.

4.9. Sweep MPPT method

In this method first the MPP is computed from the I–V characteristic of the PV array used. To plot the I–V characteristic, a sweep waveform for the array is used. The sweep waveform can be a function of voltage or current. The voltage or current is varied periodically from open circuit to short circuit value to obtain the I–V characteristic [85–88]. Fast determination of MPP by fast acquisition of I–V characteristic can be done by using a switched impedance circuit, based on either capacitor or inductor [86].

In [86], a circuit as shown in Fig. 11 is used to determine the MPP by the I–V characteristic. Switch S1 is kept on and switch S2 is turned off such that initially short circuit current flows through the previously discharged capacitor, C. C is then charged and during charging process (i.e. during sweep operation for time T_{sweep}), PV array current and voltage are measured, sampled with a sample interval T_s and are used to find the absolute MPP. In [88] the function *f(t)*, selected for the sweep waveform is directly proportional to its derivative i.e. for current sweep *f(t)* is given by Eq. (15).

$$f(t) = i(t) = kdf(t)/dt \tag{15}$$

The current can be obtained by using the circuit as shown in Fig. 11. Once the sweep operation is over, an analog circuit can be used to operate the PV array at its MPP [88]. The advantage of this method is the capability to let the PV source work around the absolute MPP with less complexity in computation. It is to be noted here that there is always a power loss associated with sweep operation which takes around 45–55 ms [88]. The use of an extra power switches and capacitor increases the cost but this limitation is not particularly critical for low power ratings realizations [86].

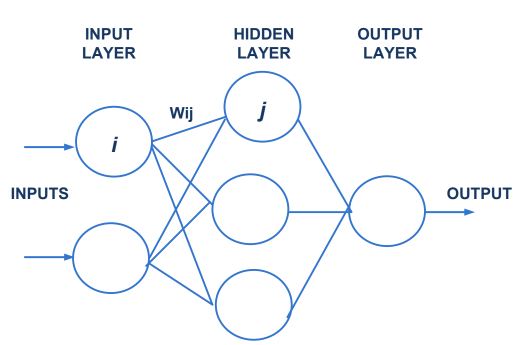

Fig. 10. Layers of NN based MPPT.

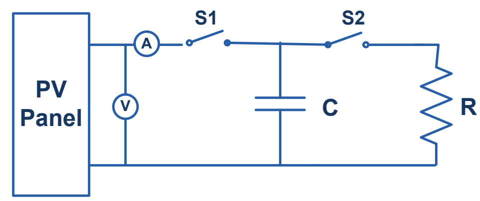

Fig. 11. Circuit used for sweep operation.

4.10. Droop method

MPPT of a PV system connected to an a.c. system can be achieved by specifically designed method known as DC-link capacitor droop control [14,89–91]. The schematic diagram of DC link capacitor droop method is shown in Fig. 12.

The DC link voltage starts drooping as soon as the power requirement by the inverter surpasses the maximum power accessible from the PV array. This logic is used in this method for MPPT. The DC link voltage is kept constant before the drooping of capacitor voltage starts and thus as the current going in the inverter increases, the power coming out of the DC/DC converter increases and accordingly increases the power coming out of the PV array and thus d is adjusted and MPPT is achieved. The drooping of DC link voltage is prevented by giving a feedback signal of AC line current [89–93]. This

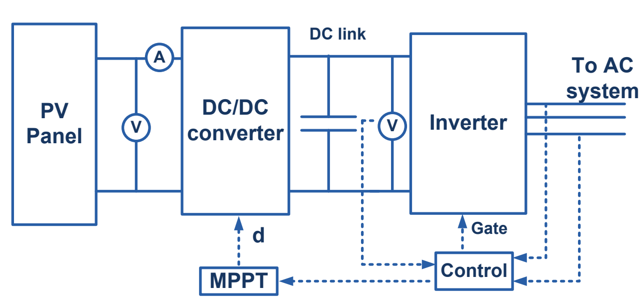

Fig. 12. DC-link capacitor droop method.

MPPT method is limited to PV system connected with an AC system line. Response of this method weakens as compared to a method that detects the power; this is because it depends on the response of the DC-voltage control loop of the inverter. Easy implementation of this scheme can be done using analog OPAMS and decision-making logic units.

4.11. Particle Swarm Optimization MPPT

Particle Swarm Optimization [PSO] technique is one of the highly potential technique among various evolutionary algorithms. Due to its simple structure, fast computation ability and easy implementation, PSO has gained a lot of attraction [94–99]. PSO is based on the behaviour of bird flocks and is a population based stochastic search method [97]. The PSO algorithm maintains a swarm (flock/group) of individuals (called particles), where each particle represents a candidate solution. Each particle tries to compete with the success of neighbouring particles and its own attained success. Thus the position of each particle depends on the best particle in a neighbourhood (P_b) and on the best solution (G_b) established by all the particles in the complete population. The position of a particle (X_i) is adjusted by using Eq. (16) [98].

$$x_i^{k+1} = x_i^k + \varnothing_i^{k+1} \quad (16)$$

Where $\varnothing i$ represents the step size of velocity component. Generally the position is defined as the actual duty cycle (d_i^{k+1}); velocity represents the perturbation in present duty cycle and thus Eq. (16) can be rewritten as Eq. (17).

$$d_i^{k+1} = d_i^k + \varnothing_i^{k+1} \quad (17)$$

$\varnothing_i^{k+1}$ is calculated using Eq. (18), where k_1 and k_2 are the acceleration coefficients, w is the inertia weight,, r_1, r_2 lies between 0 and 1, P_b is the best position of particle i, and G_b is the best position of the particles in the complete population.

$$\varnothing_i^{k+1} = w\varnothing_i^k + k_1 r_1 \{P_{bi} - x_i^k\} + k_2 r_2 \{G_b - x_i^k\} \quad (18)$$

Fig. 13 shows the representative movement of particles in the PSO process. From Eqs. (17) and (18), it is clear that if the present duty cycle is far from P_b and G_b, the subsequent change in the duty cycle will also be large, and vice versa and thus MPPT is achieved.

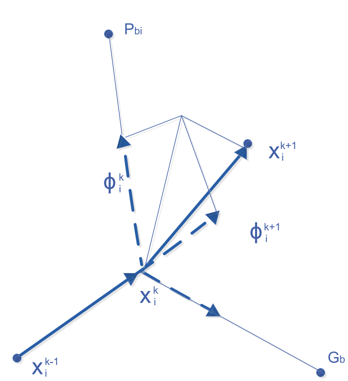

Fig. 13. Particle movement in the PSO Process.

PSO method works efficiently for non-uniform irradiance conditions but the initial position of the particles plays a great role in the convergence of this method. It has been observed that once the particles reach the MPP, the velocity associated with the particles becomes very low or practically zero, this property was used in [98], by combining direct duty control with PSO. This resulted in reduction of the steady-state oscillations to almost zero that normally exists in other MPPT methods and thereby increasing the efficiency. This methods work well during large variations of insolation and partial shading conditions. To further improve the performance of PSO method, DEPSO (Differential Evolutionary Particle Swarm Optimization) technique is used which is more reliable and accurate [98,131].

4.12. Ant colony optimization based MPPT

Ant colony Optimization (ACO) is based on probabilistic study used to find the universal optimal solution for a nonlinear problem. The logic of ACO comes from the searching behaviour of ants and their indirect communication based on pheromones [100]. To find a shortest path, ants start their initial search randomly and lay down pheromone in their path already covered; this pheromone is used by other ants to follow. The density of pheromone increases as the number of ants that travel a path increases, and thus increasing the probability that subsequent ant will choose that path. Finally, most of the ants follow the track until the shortest path is found by sharing the information. In this process the user defines the parameters such as the number of ants, convergence speed, solution archive and locality of search process [80]. In order to illustrate the use of ACO in solar PV MPPT, a control vector has to be defined and is generally given by Eq. (19).

$$C^t = \left[I_1^t, I_2^t, \ldots .. I_n^t\right] \quad (19)$$

Where C^t is the vector of current at step t, I_n^t is the current control value for nth PV string at step t. The objective function of chosen for this optimization problem $P(C^t)$ is the sum of the power output from each PV sub-string after giving current variable to each PV string. $P(C^t)$ described by Eq. (20).

$$P(C^t) = \sum_{j=1}^{n_{pp}} \left(I_j^t X V_j^t\right) \quad (20)$$

where V_j^t is the voltage value for jth PV string at the step t. The power of each current vector, $P(C^t)$, is calculated and assessed at each stage concurrently. While searching is going on, the solution obtained at each stage is stored and updated iteratively with the newly generated solutions and thus forming a solution matrix. This process continues unless the global MPP is attained for a particular shading pattern. With change in atmospheric condition, shading pattern the global maxima changes and thus the ACO-based searching is very useful in case of MPPT during partial shading condition [80,100–102].

This method of MPPT promises to find the global MPP at a fast convergence speed under various partially shaded conditions without the knowledge of PV array characteristic. The cost of this method is also low because it requires only one pair of current and voltage sensors.

4.13. GA based MPPT

GA is an evolutionary algorithm used for solving problems using the principles of biological evolution. In this method recombination or mutation of inputs which are considered as chromosomes is done, and the result is then tested to satisfy an already defined fitness function. This method follows the objective of evolution i.e. to make or to improve the new species than its predecessor and thus GA finds the best solution by a random combination of different genes [99,103–105]. The flowchart of this algorithm is shown in Fig. 14.

In case of solar PV MPPT, the initial set of chromosomes, which are taken as the searching parameters for the optimization problem, can be either voltage or duty cycle. The power equation of PV array is considered as the fitness function. Next step is to utilize the crossover and mutation phenomena which change the DNA of the chromosomes and new generations of chromosomes are created. Now this new generation is assessed through fitness function and new fitness value is assigned. This process is repeated and after several iterations, highest fitness value chromosome is chosen as the optimized parameter for MPP. In [103] short-circuit current generator algorithm is considered, in which I_{SC} is not measured but is estimated using GA and thus increases the efficiency of Fractional Short Circuit Current method. In [99], parent's chromosomes were altered by embedding PO MPPT feature in GA optimization problem between mutation stage and replacement of the old by new chromosomes, this resulted in faster optimization.

4.14. Colony of firefly algorithm (CFA) based MPPT

This algorithm is motivated by the flashing actions of fireflies. Flashing serves three functions, first one is to attract mating partners, second is to attract potential prey and the third purposes is to give protective warning. While using this algorithm following assumptions are made: 1) One firefly is attracted by other fireflies irrespective of their sex, because they are of unisex; 2) greater the brightness greater will be the attraction; 3) the landscape of objective function determines the brightness of a firefly [106–108].

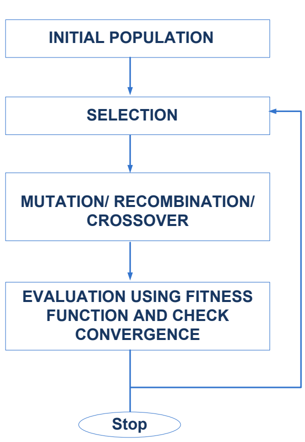

Fig. 14. Flowchart of genetic algorithm.

If X_r and X_s are the positions of two fireflies' r and s, respectively, then the distance (Z_{rs}) between them is given by Eq. (21). Z_{rs} is the Cartesian or Euclidean distance.

$$Z_{rs} = \|Xr - Xs\| \tag{21}$$

The extent of attraction between fireflies, ζ depends on the distance between two fireflies and is given by Eq. (22). Where n is greater than one, absorption coefficient (τ) controls the reduction of light intensity and lies between 0 and 10 and n = 2 [108]. The symbol ζ_o is one and called as initial attraction [106–108].

$$\zeta(Z) = \zeta_o e^{-\tau(Z_{rs})^n} \tag{22}$$

The new position of r is determined using Eq. (23). Where it is assumed that brightness of r is less than s, β is the random movement factor which is constant during the program and has a value in the range (0, 1) and for each movement of firefly rand (a random number) is evenly distributed between 0 and 1.

$$X_r^{t+1} = X_r^t + \zeta(Z)\cdot(Xr - Xs) + \beta(rand - 0.5) \tag{23}$$

For applying this algorithm to solar PV MPPT, following stages has to be followed.

Stage 1: Fix the constants ζ_o, τ, β, n, population size N, and the end criterion. Take the position of the firefly as a duty cycle d of the dc–dc converter. The power P_{pv} of the PV system is equal to the brightness of each firefly corresponding to the position of this firefly.

Stage 2: positioning of the fireflies in the allowable solution space between d_{min} to d_{max} is done. d_{min} and d_{max} represent the minimum and maximum values of the duty ratio.

Stage 3: Corresponding to each duty ratio (i.e. corresponding to the position of each firefly) PV output power, P_{pv} is taken as the brightness or light intensity of the respective firefly by operating the DC–DC converter.

Stage 4: The position of brightest firefly remains same while remaining fireflies update/change their position based on Eq. (23).

Stage 5: Go to stage 3 if the end criterion is not reached; else terminated the program. Once the program is terminated, optimum duty cycle corresponding to global MPP is achieved.

Stage 6: Check if the insolation changes, if yes reinitiate the algorithm.

In [107] it is shown that CFA is capable of jumping out of the current MPPT point and moves towards new global MPP under rapidly changing partial shading conditions. The method can be implemented using low-cost microcontroller [107].

4.15. Bayesian network

Based on conditional probabilistic graphical modelling, Bayesian network is used for the modelling of a joint probability distribution of multiple random variables [104]. For solar PV multidimensional MPPT problems, this method is useful when hybrid methods involving two or more soft computing techniques are used for tracking. In [109] a hybrid PSO-IC method in conjunction with BN is used for MPPT. Bayesian network used in [109] is shown in Fig. 15.

A1, A2,…, A20 represent nodes. The network used has 20 nodes i.e N = 20 nodes [109]. These nodes are divided into two sections as shown in Fig. 15. The left observation nodes represent 10 points of the I−V curve that has to be estimated by the PSO method. The remaining 10 nodes have to be estimated by the IC method. After fusion process the final location is estimated and is shown by L. A state value of 1 is assigned to nodes that match from both sides and otherwise a state value of 0 is assigned. A formerly trained output vector in offline mode is assigned to all selected nodes. Best value is given to the input nodes using conditional probability. After successive iteration, final output comes to be the best possible value, i.e. MPP. The MPP tracking using this method is fast and efficient under both normal and partial shading condition [105−109]. This method is very effective but, the complexity associated with this method is the major limitation for realizing it using a low-cost microprocessor.

4.16. Array reconfiguration

Depending on the specific load requirements, a technique known as array reconfiguration is used [110,134,136]; here arrangement of the PV arrays in various diverse series and parallel permutations/combinations is done, this method is time-consuming.

4.17. Steepest descent method

Originally an optimisation technique, steepest descent or gradient descent method [111] finds the MPPT by computing the function given in Eq. (24).

$$v(n+1) = v(n)\ \frac{dp/_{dv}|_{v=v(n)}}{k_e} \tag{24}$$

Where, k_e is step-size corrector and decides the steepness of each step in the gradient direction. $dp/_{dv}$ is the deviation and is calculated by using Eqs. (25) and (26).

$$dp/_{dv} = f(v(n), p(n)) \tag{25}$$

$$f(v(n), p(n)) = \frac{p(n+1) - p(n-1)}{2\Delta V} + O(\Delta V)^3 \tag{26}$$

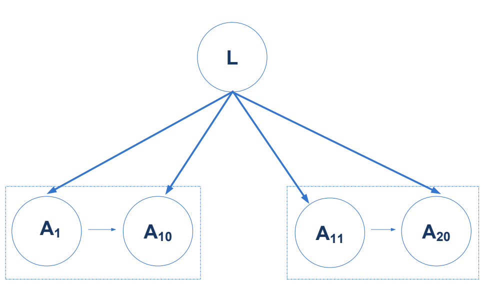

Fig. 15. Bayesian network.

Where, $O(\Delta V)^3$ is the local truncation error for the centred differentiation and is of second-order accuracy.

This method is applied to find the nearest local MPP by computing the gradient of the function. According to the theorem, the extremum, which is maximum or minimum, occurs at the critical point. The local MPP can be continuously tracked and updated to satisfy a mathematical equation: $\frac{dp}{dv} = 0$, where p represents the photovoltaic power and v represents the control variable chosen as the photovoltaic voltage.

4.18. Hybrid methods

A hybrid MPPT will have a combination of two or more MPPT techniques resulting in a better tracking performance. A great number of papers have been written on Hybrid techniques but the most common are PO based hybrid MPPT. In [112] ANN optimization is used with P&O MPPT controller and improved performance in dealing with the array power fluctuations was achieved. In [113] duty cycle is varied using ANN optimization in conjunction with IC/P&O MPPT and fast tracking with smaller steady-state error is attained. In [76] Fuzzy logic with ANN is used in hybrid MPPT. In [114] Fuzzy P&O hybrid MPPT with offline tracking function to avoid local maxima is studied. Various other Hybrid techniques have been proposed but it is not possible to cover all techniques here [114,135,137].

4.19. Other MPPT methods

In [115,116] Load Current or Load Voltage Maximization MPPT is used based on the logic that maximizing the converter output power would maximize the PV array power. In [117] it is shown that for a voltage-source type load, the load current has to be maximized to reach the maximum output power and for a current-source type load, the load voltage has to be maximized while for the other load types, either load current or load voltage can be used. In [118,119], different Distributed MPPT (DMPPT) methods have been stated. Each module in DMPPT uses a single MPPT. In [120], MPP is tracked using a nonlinear time varying dynamic feedback controller by representing the system with state space model, and the method is called state-based MPPT. In [121], MPPT techniques directly track the MPP by calculating the solar cell voltage and current from the irradiation and temperature. In [122] a Cuckoo Search (CS) method for MPPT has been proposed. In [123], a method is represented in which MPP is achieved by collecting statistical data of irradiance and temperature levels over a period of one year and the control sets to the best fixed voltage representative of the MPP. In [124], linear-reoriented coordinates MPPT method in which approximate solution of the PV array equation is obtained iteratively. Here the linear relation between I_{mp} and the irradiance level is used to find MPP using a PI controller. Irradiance is sensed and corresponding I_{mp} is found. In [125] one more MPPT technique (TEODI) has been suggested, here corresponding to the forced displacement of the input operating points of two identical PV systems equalization of the output operating points is achieved and every panel of the

PV array has its individual DC/DC converter with a single centralized control block.

5. Comparative assessment

With large number of MPPT techniques available, it is very necessary to have a comparison of them so that best possible MPPT is selected for a particular application. In this article best possible comparative assessment of different MPPT methods has been done on the following parameters: convergence speed, sensors used, analog or digital implementation, multiple peaks, algorithm complexity, accuracy, efficiency, availability etc. comparison of MPPT methods according to these parameters has been tabulated in Tables 2—5.

5.1. Control strategy and complexity

Direct control, indirect control, and probabilistic control are the three main control strategies used in MPPT. Direct control strategies directly seeks MPP by sensing the variations of the PV panel operating points without any prior information of the PV panel characteristics and is further divided in two categories and they are sampling methods [126—128] and modulation methods. Indirect control is established on records that consist of statistics such as the PV panel I—V characteristic for different insolation and temperature. In case of probabilistic control, information based on the results obtained by applying rules of probability is used.

Complexity here refers to the algorithm and hardware implementation/circuit complexity and it plays a very important role in the selection of MPPT technique.

5.2. Multiple peaks/environmental conditions and type of circuitry

An environmental condition like partial shading leads to multiple peaks and thus affects the choice of MPPT technique to be used. True MPP should be tracked otherwise considerable power loss takes place. Analog or digital circuit is used to implement MPPT techniques. This choice depends on the type of user, as some are more comfortable with analog and some may prefer digital circuit. Though, it is not easy to accomplish division functions, and in this case, the digital execution is preferred.

Table 2
Comparison of MPPT methods according to their control strategy and complexity.

MPPT	Control strategy	Complexity
Fractional Short Circuit Current	Indirect	Medium
Fractional open circuit voltage	Indirect	Simple
Perturbation and observation method/hill climbing method	Sampling	Simple
Incremental conductance method	Sampling	Medium
Computational/lookup table	Indirect	Medium
Switching Ripple correlation control	Modulation	Complex
Fuzzy logic	Probabilistic	Complex
Neural network	Probabilistic	Complex
Sweep MPPT method	Modulation	Complex
Droop control	Modulation	Simple
PSO based MPPT	Probabilistic	Medium
ASO based MPPT	Probabilistic	Complex
Genetic algorithm based MPPT	Probabilistic	Complex
CFA based MPPT	Probabilistic	Medium
Array Reconfiguration	Indirect	Complex
Steepest descent method	Sampling	Medium

Table 3
Comparison of MPPT methods according to their circuit and true peak searching.

MPPT	Circuit used	True MPPT
Fractional Short Circuit Current	Both	No
Fractional open circuit voltage	Both	No
Perturbation and observation method/hill climbing method	Both	Yes
Incremental conductance method	Digital	Yes
Computational/lookup table	Digital	No
Switching Ripple correlation control	Analog	Yes
Fuzzy logic	Digital	Yes
Neural network	Digital	Yes
Sweep MPPT method	Digital	Yes
Droop control	Both	No
PSO based MPPT	Digital	Yes
ASO based MPPT	Digital	Yes
Genetic algorithm based MPPT	Digital	Yes
CFA based MPPT	Digital	Yes
Array reconfiguration	Digital	Yes
Steepest descent method	Digital	Yes

Table 4
Comparison of MPPT methods according to their cost and type of sensors used.

MPPT	Sensors	Cost
Fractional Short Circuit Current	Current	Cheap
Fractional open circuit voltage	Voltage	Cheap
Perturbation and observation method/hill climbing method	Current, Voltage	Expensive
Incremental conductance method	Current, Voltage	Expensive
Computational/lookup table	Irradiation, Temp.	Cheap
Switching Ripple correlation control method	Current, Voltage	Expensive
Fuzzy logic	Varies	Expensive
Neural Network	Varies	Expensive
Sweep MPPT method	Irradiation	Expensive
Droop control	Voltage	Expensive
PSO based MPPT	Varies	Expensive
ACO based MPPT	Varies	Expensive
Genetic algorithm based MPPT	Varies	Expensive
CFA based MPPT	Varies	Expensive
Array reconfiguration	Current, Voltage	Expensive
Steepest descent method	Voltage or current	Expensive

5.3. Number and type of sensors used

Generally voltage and current sensors are used in most of the cases as these two are the controlled variables, but it is good to use MPPT methods that require only one sensor when the system consists of several PV arrays with separate MPP trackers [80,127]. In some cases Temperature and irradiation may also be the sensed parameters. If possible, the use of

Table 5
Omparison of MPPT methods according to their efficiency and speed.

MPPT	Accuracy/efficiency	Speed
Fractional Short Circuit Current	Low	Medium
Fractional open circuit voltage	Low	Medium
Perturbation and observation method/hill climbing method	Medium	Varies
Incremental conductance method	Medium	Varies
Computational/lookup table	Varies	Fast
Switching Ripple correlation control method	High	Fast
Fuzzy logic	Very high	Fast
Neural network	Very high	Fast
Sweep MPPT method	High	Slow
Droop control	Medium	Medium
PSO based MPPT	High	Fast
ASO based MPPT	High	Fast
Genetic algorithm based MPPT	High	Fast
CFA based MPPT	High	Fast
Array reconfiguration	Varies	Slow
Steepest descent method	High	Medium

current sensors should be avoided as they are bulky and expensive.

5.4. Accuracy and speed of tracking

Accuracy of a MPPT technique is judged by the fact that how close it takes the system to true MPP. Greater the accuracy greater is the efficiency of the MPPT technique. Efficiency [129,130] of a MPPT is given by Eq. (27)

$$\eta = \frac{Tracked\ Power}{V_{mp}I_{mp}} \tag{27}$$

Speed of tracking is a very important factor in case of continuously and fast changing atmospheric conditions. Also for the charging of batteries in case of solar vehicles, an extremely fast MPP tracking is required.

6. Conclusion

The daily increase in the number of PV systems in different areas has resulted in extensive research for finding answers to energy and environmental problems. In this perspective, the MPPT methods play a very vital role to extract the maximum power available from PV system. This article offers an insight into various MPPT used in PV system. An effort has been made to point out the advantages and shortcomings of various MPPT methods. This paper provides acumen to select a MPPT technique depending upon various constraints. The tables provide a wide-range guide for the operational choice of a MPPT technique based on all major factors like cost, efficiency, complexity etc. It is remarkable to point out that there are very slight variances in performances among the best studied MPPTs. This review has also encompassed recent hybrid MPPT methods along with original methods. Further, this assessment is expected to be very useful for not only the MPPT end users but also for the engineers, researchers and commercial producers of PV systems.

Conflict of interest

There is no conflict of interest.

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