Current Journal of Applied Science and Technology

21(6): 1-13, 2017; Article no.CJAST.34406
Previously known as British Journal of Applied Science & Technology
ISSN: 2231-0843, NLM ID: 101664541

Novel Classification for Tracking Techniques Maximum Power Point in Solar Photovoltaic Systems

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Authors' contributions

This work was carried out in collaboration between both authors. Author YS designed the study and structure of article, performed the finish editing. Author AJ performed the analysis, the first draft of the manuscript, managed the literature searches. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2017/34406
Editor(s):
(1) Giovanni Bucci, Department of Industrial Engineering and Information and economy, University of L'Aquila, Italy.
Reviewers:
(1) Halil Görgün, Dicle University, Turkey.
(2) A. Ayeshamariam, Khadir Mohideen College, Adirampattinam, India.
(3) Danladi Eli, Nigerian Defence Academy, Kaduna, Nigeria.
Complete Peer review History: http://www.sciencedomain.org/review-history/19664

Review Article

Received 26th May 2017
Accepted 15th June 2017
Published 22nd June 2017

ABSTRACT

This paper gives an overview and classification of methods maximum power point tracking (MPPT) controller is fundamental to acquire the maximum power from a solar array in the photovoltaic systems as the PV power module varies with the temperature and solar irradiation. Advantages and disadvantages of each method are described. These techniques vary in many aspects as: simplicity, speed of convergence, fast dynamic response, range of effectiveness. The MPPT methods can be classified into three broad categories: indirect, direct and hybrid methods. An assortment of MPPT methods have been proposed and implemented. This review paper introduces a classification scheme for MPPT methods based on three categories: indirect, direct and hybrid methods.

Keywords: MPPT; indirect; direct and hybrid methods.

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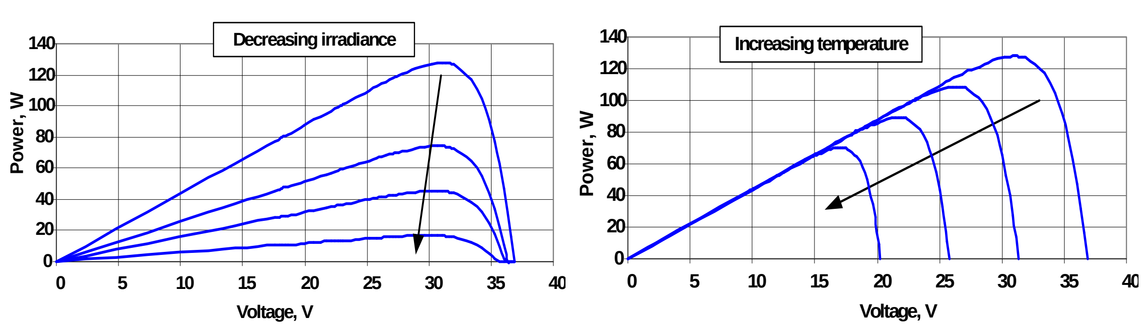
1. INTRODUCTION

Photovoltaic (PV) energy is one of the most important renewable energy sources [1]. As opposed to the conventional non renewable sources such as gasoline, coal, etc. Solar energy are clean, inexhaustible and free [2,3]. It constitutes a suitable choice for a variety of applications mainly due to the possibility of direct conversion of this form of energy to electrical energy using photovoltaic (PV) effect [4]. Although, photovoltaic systems are used as an alternative source requires considerable investment [5]. The output of a photovoltaic system depends depends on the radiation intensity, ambient temperature and load impedance [5-6]. These parameters in PV power system never remain constant, instead kept on changing at each instant [6]. The nonlinear behavior of PV systems as well as variations of the maximum power point with weather conditions, i.e. solar irradiance level and temperature complicates the tracking of the maximum power point (MPP), is the point at which system has the highest possible efficiency [6,7]. In variations weather conditions, there can only be single operating point in the system that can give the optimal maximum efficiency [8,9]. Therefore, to track this point in the system is very important in order to increase the system efficiency [9,10]. Particularly, the system having any kind of converter needs MPPT in order to make sure that it deliver maximum power to the other side [10]. Therefore, for understanding the concept of MPPT, it is sufficient to consider the I-V curve of a solar cell. The P-V curve is dependent on the module irradiance Fig. 1a and temperature Fig. 1b. In case, a decreasing irradiance leads to a decreased power and slightly decreased voltage, as illustrated in Fig. 1a and increase in temperature is accompanied by a decrease in the open circuit voltage value. Increase in temperature causes increase in the band gap of the material and thus more energy are required to cross this barrier. Thus the efficiency of the solar cell is reduced, Fig. 1b. Shows that an increasing temperature leads to a decreased power and has a detrimental effect on the decreased voltage [11-13].

In general, the different tracking maximum power point methods can be categorized indirect methods [6.7,9,11,14], direct methods [6.7,9,11,14]. These two methods (indirect and direct) can not be classified as real searching MPP methods, be that as it may, the simplicity of these calculations and the simplicity with which they can be executed make them reasonable for use as part of novel hybrid methods [5], and hybrid methods [7,13-16] which are a combination of the above-mentioned methods.

The indirect methods are based on the use of a database of parameters that include data of typical I-V and P-V curves of PV systems that an increasing, or on the use of mathematical functions obtained from empirical data to estimate the MPP [6,7,9,11,14]. These methods, require to one or more of the solar panel values, such as short circuit current (I_{SC}), open circuit voltage (V_{OC}), temperature (T) and irradiation (E). The values of the solar cell parametrs are used to generate the control signal necessary for driving the solar cell to its maximum power point (MPP), I-V and P-V curves as showing in Fig. 2. [2,4,8-9,11-12,17].

The direct methods include those methods that use PV voltage and/or current measurements [6,7,9,11,14]. These direct methods have the advantage of being independent of the prior knowledge of the PV generator characteristics.



a b

Fig. 1. Impact of factors on power-voltage characteristics of a PV array: a - irradiation; b - temperature

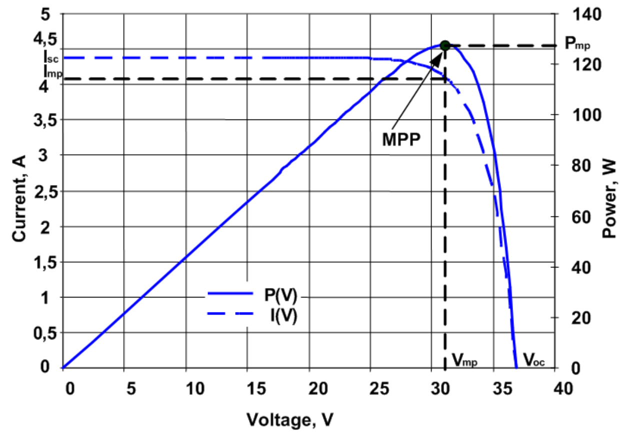


Fig. 2. Important points on the I–V and P–V characteristic curves of a solar cell

Thus, the operating point is independent of irradiation, temperature or degradation levels. In online methods, usually the instantaneous values of the PV output voltage or current are used to generate the control signals.

In hybrid methods [7,14.15,16], which are those that combine two different methods, each one by one of the above categories; the indirect and direct methods are used to get a quick approximation to the MPP whereas the direct method is used to improve the result.

The paper is organized organized as follows: modeling of pv panel are introduced in Section 2. In Section 3, MPPT algorithms are described under the three categories of indirect methods, direct methods and hybrid methods. Section 4 will include the conclusions.

2. MODELING OF PV PANEL

A photovoltaic cell can be modeled as a current source connected in parallel with a single diode for its simplicity [18]. Current source produces a constant current, this current is proportional to the intensity of the light falling upon the cell [7,16]. A general mathematical description of current-voltage output characteristics of a PV cell. The output obtained from the module is variable DC voltage, this voltage depends upon the solar radiation intensity and temperature. The leakage of the semiconductor junction is represented as the parallel resistance R_P of PV cell. Series resistance R_S represents the various contact resistance in the system [8-9,14,16,18-21]. According to the model of a solar cell, the relationship between the cell`s current and voltage, and by applying Kirchhoff's law, we can determine the voltage-ampere dependency of the photovoltaic cell. Can be expressed as equation (1) [5,7-9,11,14-17,20-25].

$$I = I_{ph} - I_s \cdot \left[exp\left(\frac{q\left(V + I \cdot R_s\right)}{AK_B T_c} \right) - 1 \right] - \frac{\left(V + I \cdot R_s\right)}{R_p} \tag{1}$$

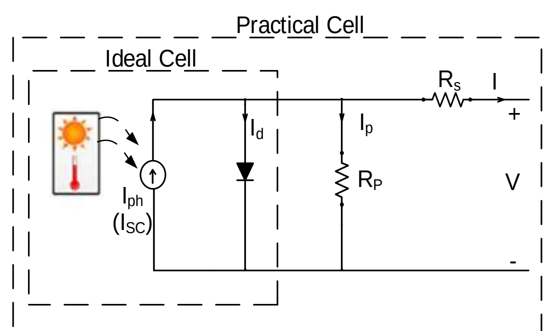


Fig. 3. Equivalent circuit of photovoltaic cell

Where is: The diode saturation current or cell saturation of dark current, (A), q: The electron charge ($1.602{\times}10^{-19}$), (C), K_B: The Boltzmann constant ($1.38{\times}10^{-23}$), (J/K), T_C: The cell working temperature, (K), A: The diode factor, (1…1.6), V: The PV module terminal voltage, (V).

3. MPPT ALGORITHMS

MPPT function is to regulate the DC (Direct Current) output voltage or current in such a way that the maximum possible power can be obtained, with respect to any changes in weather conditions. The behavior of an illuminated solar cell can be characterized by an current-voltage

I-V curve. Interconnecting several solar cells in series or in parallel merely increases the overall voltage and/or current, but does not change the shape of the I-V curve Fig. 4 [11,12].

In order to achieve MPPT awide variety of algorithms have been proposed and implemented. In this these methods have been classified into three broad categories: indirect methods, direct methods, and hybrid methods.

3.1 Indirect Methods

In indirect methods usually the physical values of the PV panel are used to generate the control signals [6.7,9,11,14]. These methods are based on the calculation of the position of MPP with the help of the current-voltage characteristics database of photovoltaic panels, or on the use of mathematical functions on the basis of the previously obtained empirical data. These methods that only are used for PV systems are include: open circuit voltage coefficient (K_V), short circuit current coefficient (K_I) and new method maximum power coefficient (K_P) method.

3.1.1 Open circuit voltage coefficient (K_V) method

This method is one of the simplest indirect methods which uses the approximately linear relationship between the open circuit voltage (V_{oc}) and the voltage of PV generator at the maximum power point voltage (V_{mp}) under different environmental conditions[1,4,6-7,9,11]. The coefficient of the open circuit voltage is not constant, it varies according to the PV parameters, which relies on the material and the fabrication know-hows of the solar cells technology, fill factor and the climatic conditions. can be described by the following equation [13-14,26-27]:

$$K_V = V_{mp} / V_{oc} \quad (2)$$

Where K_V is coefficient of the open circuit voltage, this coefficient is empirically derived based on measurement of the V_{oc} and V_{mp} under different environmental conditions. In each successive stage as M_{PP} is tracked, this value of V_{mp} which is chosen as the set point is assumed to remain relatively constant over a wide range of temperature and irradiance values. The K_V flowchart is shown below in Fig. 5 [7,9,14]. In spite of the relative ease of implementation and low costs, this method suffers from two major disadvantages [9]. First, the MPP may not be tracked accurately. Second, measurement of V_{oc} requires periodic shedding of the load, which may interfere with circuit operation and will cause more power losses. The open circuit voltage (V_{oc}), at the power generated is equal zero. The cefficient reference of the open circuit voltage K_{Vref} at which PV array is to be operated when the MPP is achieved at that instant K_{Vref} must be equal to K_V at maximum power point [11].

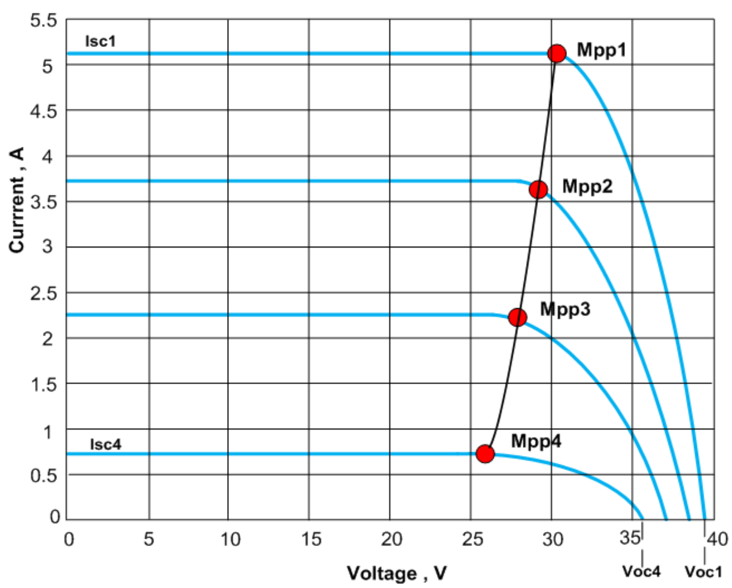


Fig. 4. The I–V characteristics of solar cells under varying sunlight

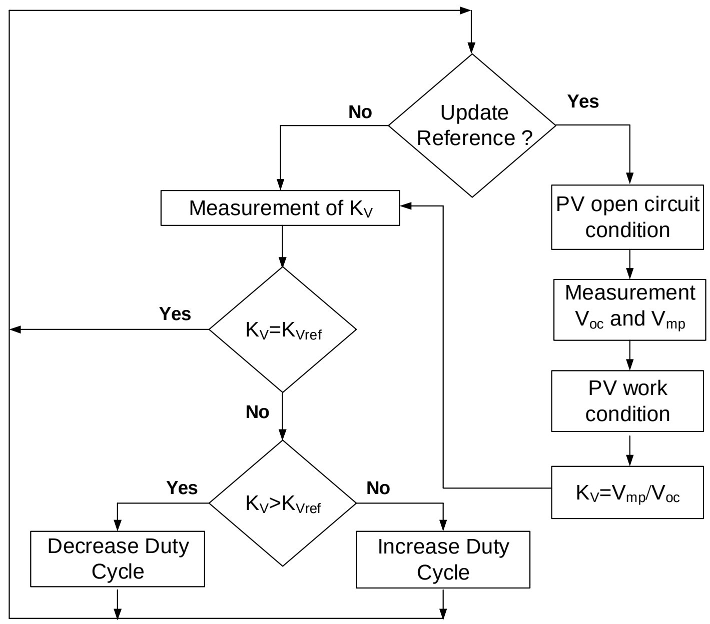


Fig. 5. Flow chart of the K_V

3.1.2 Short circuit current coefficient (K_I) method

To track the power, this MPPT technique requires the value of short circuit current by isolating the PV array. This method represents an indirect approach, which is relatively similar to the K_v method [1,6-7,9,11]. The K_I flowchart is shown below in Fig. 6. The cefficient reference of the short circuit current K_{Iref} at which PV array is to be operated when the MPP is achieved at that instant K_{Iref} must be equal to K_I at maximum power point [11].

The short circuit current (I_{sc}) is based on the measurement of the PV module short circuit current when its output voltage is equal to zero, and the PV module maximum output current at MPP (I_{mp}), is linearly proportional to (I_{sc}), which can be described by the following equation [13-14,26-28].

$$K_I = I_{mp} / I_{sc} \tag{3}$$

Where K_I is a coefficient of the open circuit voltage that can be calculated from the PV curve. While the K_I method is more accurate and efficient than the K_v method [9,25]. With a boost converter is used, where the switch in the converter itself can be used to apply a short circuit to the PV array. An improvement similar to that proposed above for the K_v method can be applied to the K_I method. In particular, the short circuit current (I_{sc}), at the power generated is equal zero.

3.1.3 Maximum power coefficient (K_P) method

The maximum power coefficient is a new method, which it multiplication of the open circuit voltage coefficient K_V [1,4,6-7,9,11] (the ratio of actual voltage to open circuit voltage V_{OC}) and the short circuit current coefficient of K_I [1,6-7,9,11] (the ratio of the actual current to short circuit current I_{SC}). The K_P flowchart is shown in Fig. 7.

$$K_P = K_V \cdot K_I = \frac{V_{PV} \cdot I_{PV}}{V_{OC} \cdot I_{SC}} \tag{4}$$

3.2 Direct Methods

The direct methods are based on the instantaneous measurements of voltage and current values and the use of these measurements for calculation of the MPP position [6.7,9,11,14]. The methods of this group include: the differentiation methods, perturbation and observation (P&O) method, incremental conductance (IC) method and hill climbing (HC) method.

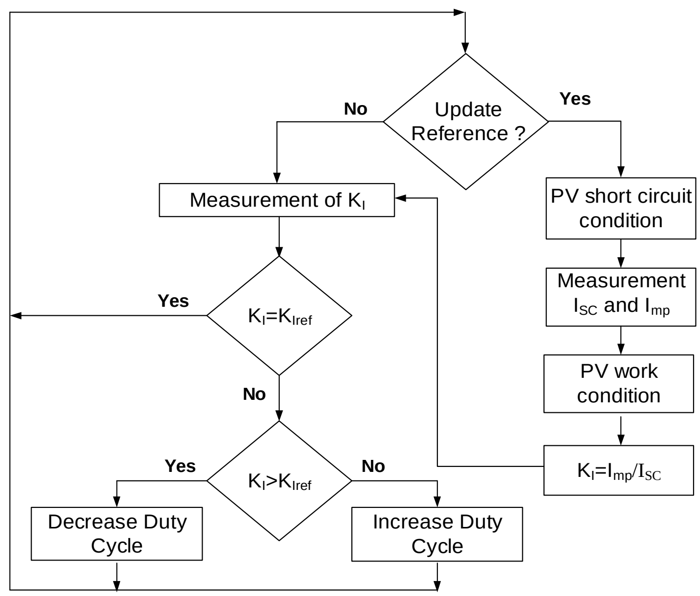


Fig. 6. Flow chart of the K_I

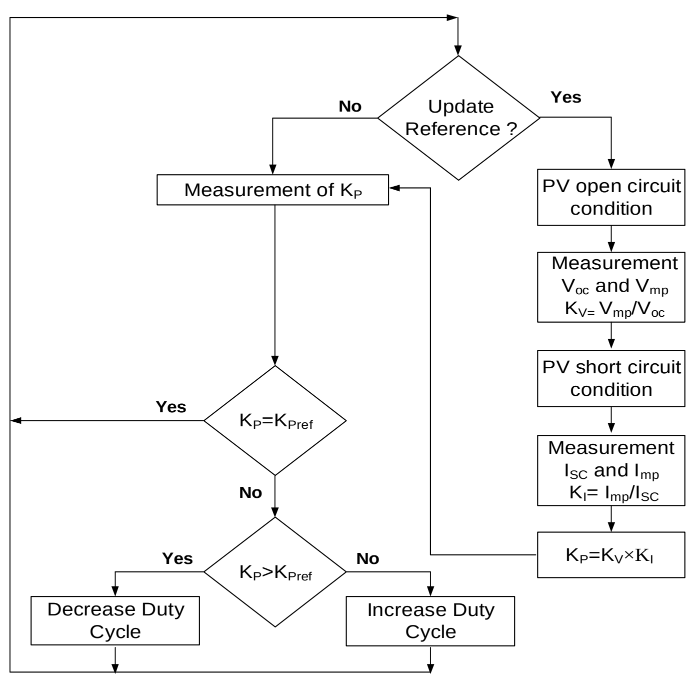


Fig. 7. Flow chart of the K_P

3.2.1 Perturbation and observation (P&O) method

P&O method is one of the most frequently used algorithms to track the maximum power due to its simple structure and fewer required parameters. This method finds the maximum power point of PV modules by means of iteratively perturbing, observing and comparing the power generated by the PV modules [4,5,6,8,9,14,26]. It is widely applied to the maximum power point tracker of the photovoltaic system for its features of simplicity and convenience [5,6,9,11]. Shown in Fig. 8 is the Perturb and Observe (P&O), which described the relationship between the terminal voltage and output power generated by a PV module. It can be observed that regardless of the magnitude of sun irradiance and the terminal voltage of PV modules, the maximum power point is obtained while the condition $dP/dV = 0$ is accomplished [4,5,6,9,11-14,22]. The slope (dP/dV) of the power can be calculated by the consecutive output voltages and output currents, and can be expressed as follows.

$$\frac{dP}{dV}(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \quad (5)$$

$$P(k) = V(k) \cdot I(k) \quad (6)$$

It can also be seen from Fig. 8. That voltage corresponding to M_{PP} called V_{mp} and current I called I_{mp}. These values at STC are available in the data sheet of every PV module. The difference among the selected three MPPT algorithms is the method used to meet the condition.

$$\begin{aligned} &dP/dV > 0 \textit{ (Left hand side of } M_{PP}); \\ &dP/dV < 0 \textit{ (Right hand side of } M_{PP}); \\ &dP/dV = 0 \textit{ (At } M_{PP}). \end{aligned} \quad (7)$$

The variations of the output voltage and power before and after changes are then observed and compared to be the reference for increasing or decreasing the load in the next step.

If the perturbation in this time results in greater output power of PV modules than that before the variation, the output voltage of PV modules will be varied toward the same direction. Otherwise, if the output power of PV modules is less than that before variation, it indicates that the varying direction in the next step should be changed [4,5] The algorithm is illustrated in the flowchart shown in Fig. 9. The maximum output power point of a PV system can be obtained by using these iterative Perturbation, Observation and comparison steps. The advantages of the P&O method are simple structure, easy implementation and less required parameters. The shortcomings of the P&O method can be summarized [8-9,12-14,22,28-30]:

(a) The power tracked by the P&O method will oscillate and perturb up and down near the maximum power point. The magnitude of the oscillations is determined by the magnitude of variations of the output voltage.

(b) There is a misjudgment phenomenon for the P&O method when weather conditions change rapidly.

The PV-output voltage (V_k) and PV output current (I_k) are sensed. The power is calculated (P_k) and compared with the power vale calculated from the Previous sample (P_{k-1}) in order to get ΔP_k. If the results of ΔP_k is zero the system is working at M_{PP}. Otherwise and according to the sign of ΔP_k and to the sign of ΔV_k the command voltage to control the duty cycle D of the converter (let's say the perturbation), will be decreased or increased in order to force the working point of the PV module towards the MPP [13].

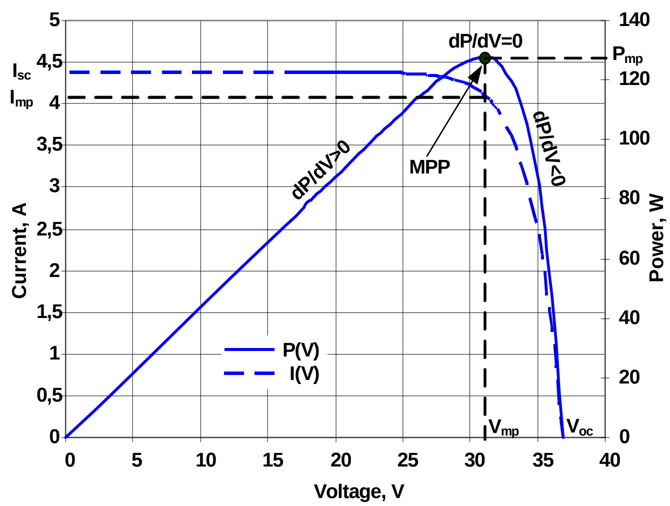


Fig. 8. Perturb and observe (P & O) method

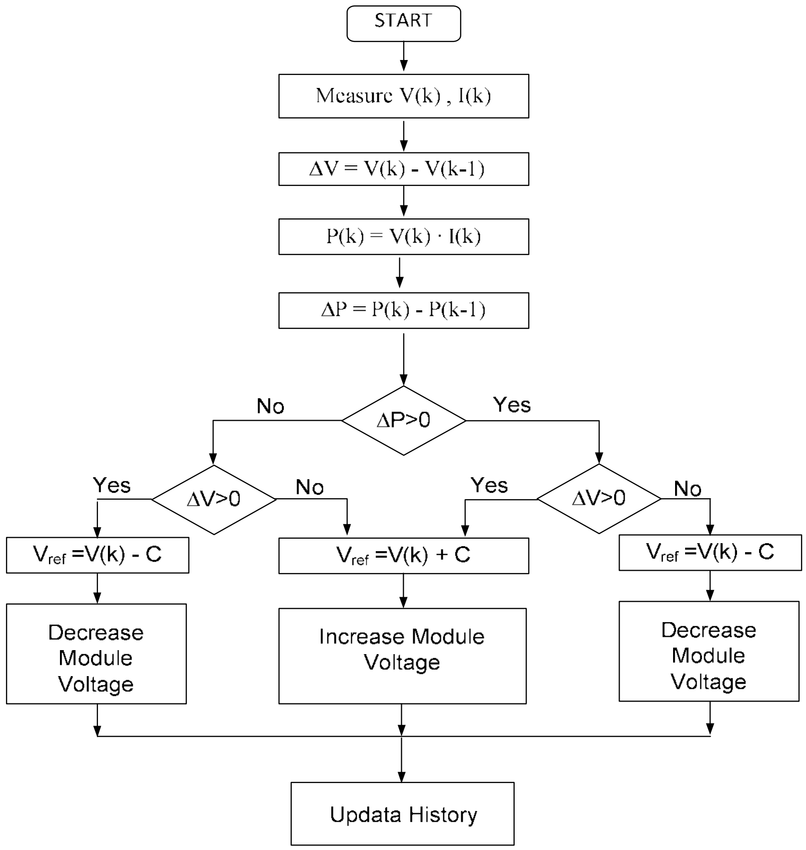


Fig. 9. Flowchart of Perturb and Observe (P & O)

3.2.2 Incremental conductance (IC) method

This method is considered cheap, and easy to implement for (MPPT). The theory of the incremental conductance method is to determine the variation direction of the terminal voltage for PV modules by measuring and comparing the incremental conductance and instantaneous conductance of PV modules. If the value of incremental conductance (dI/dV) is equal to that of instantaneous conductance (-I/V), it represents that the maximum power point is found. The basic theory is illustrated by Fig. 9. When the operating behavior of PV modules is within the constant current area, the output power is proportional to the terminal voltage. That means the output power increases linearly with the increasing terminal voltage of PV modules (slope of the power curve is positive, $dP/dV > 0$).When the operating point of PV modules passes through the maximum power point, its operating behavior is similar to constant voltage. Therefore, the output power decreases linearly with the increasing terminal voltage of PV modules (slope of the power curve is negative, $dP/dV < 0$). When the operating point of PV modules is exactly on the maximum power point, the slope of the power curve is zero ($dP/dV = 0$) and can be further expressed as [4-9,12,22,27,29-30].

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} \cdot \quad (8)$$

By the relationship of $dP/dV = 0$, Eq. (8) can be rearranged as follows Eq. (9),

$$\frac{dI}{dV} = -\frac{I}{V} \cdot \quad (9)$$

dI and *dV* represent the current error and voltage error before and after the increment respectively. The maximum power point (operating voltage is V_m) can be found when

$$\left(\frac{dI}{dV}\bigg| V = V_m\right) = \left(-\frac{I}{V}\bigg| V = V_m\right) \cdot \quad (10)$$

When the equation in Eq. (10) comes into existence, the maximum power point is tracked by MPPT system. However, the following situations will happen while the operating point is not on the maximum power point:

$$\frac{dI}{dV} > -\frac{I}{V};(\frac{dP}{dV} > 0)\cdot \quad (11)$$

$$\frac{dI}{dV} < -\frac{I}{V};(\frac{dP}{dV} < 0)\cdot \quad (12)$$

Equations (11) and (12) are used to determine the direction of voltage perturbation when the operating point moves toward the maximum power point [10]. In the process of tracking, the terminal voltage of PV modules will continuously perturb until the condition of Eq. (8) Comes into existence. Fig. 10 is the operating flow diagram of the incremental conductance algorithm. From the flow diagram shown in Fig. 11, it can be observed that the weather conditions don't change and the operating point is located on the maximum power point when $dV = 0$ and $dI = 0$. If $dV = 0$ but $dI > 0$, it represents that the sun irradiance increases and the voltage of the maximum power point rises. Meanwhile, the maximum power point tracker has to raise the operating voltage of PV modules in order to track the maximum power point. On the contrary, the sun irradiance decreases and the voltage of the maximum power point reduces if $dI < 0$. At this time the maximum power point tracker needs to reduce the operating voltage of PV modules. Furthermore, when the voltage and current of PV modules change during a voltage perturbation and $dI/dV > -I/V$ ($dP/dV > 0$), the operating voltage of PV modules is located on the left side of the maximum power point in the P-V diagram, and has to be raised in order to track the maximum power point. If $dI/dV < -I/V$ ($dP/dV < 0$), the operating voltage of PV modules will be located on the right side of the maximum power point in the P-V diagram, and has to be reduced in order to track the maximum power point [4-9,12,22,27,29-30].

3.2.3 Hill climbing (HC) method

The most common MPPT method in space applications is the hill climbing method owing to its high precision, simple structure, direct investigation of power, high reliability, and independence from sensors such as radiation and temperature sensors [13,22,24,29,31]. This method has three major disadvantages: Firstly tracking local peaks of the solar array voltage-power curve, secondly oscillations around the MPP and thirdly low speed.

The difference among the selected three MPPT algorithms is the method used to meet the condition.

$$\begin{aligned} &dP/dD > 0 \text{ (Left hand side of } M_{PP}); \\ &dP/dD < 0 \text{ (Right hand side of } M_{PP}); \\ &dP/dD = 0 \text{ (At } M_{PP}). \end{aligned} \quad (13)$$

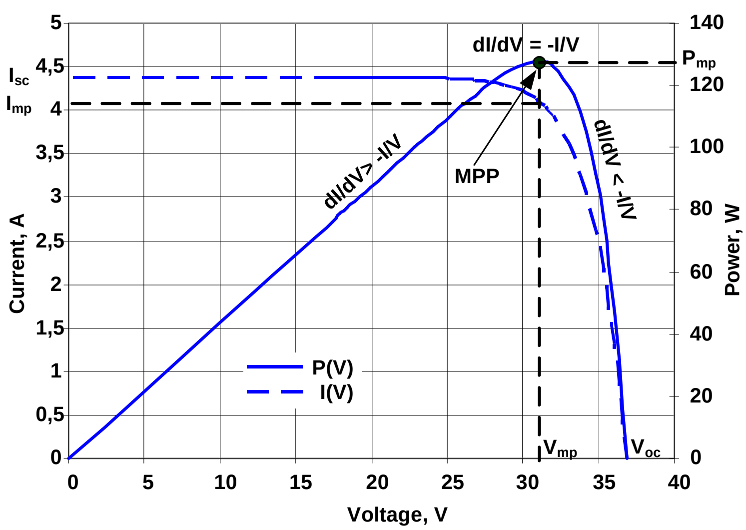


Fig. 10. Incremental conductance (IncCond) method

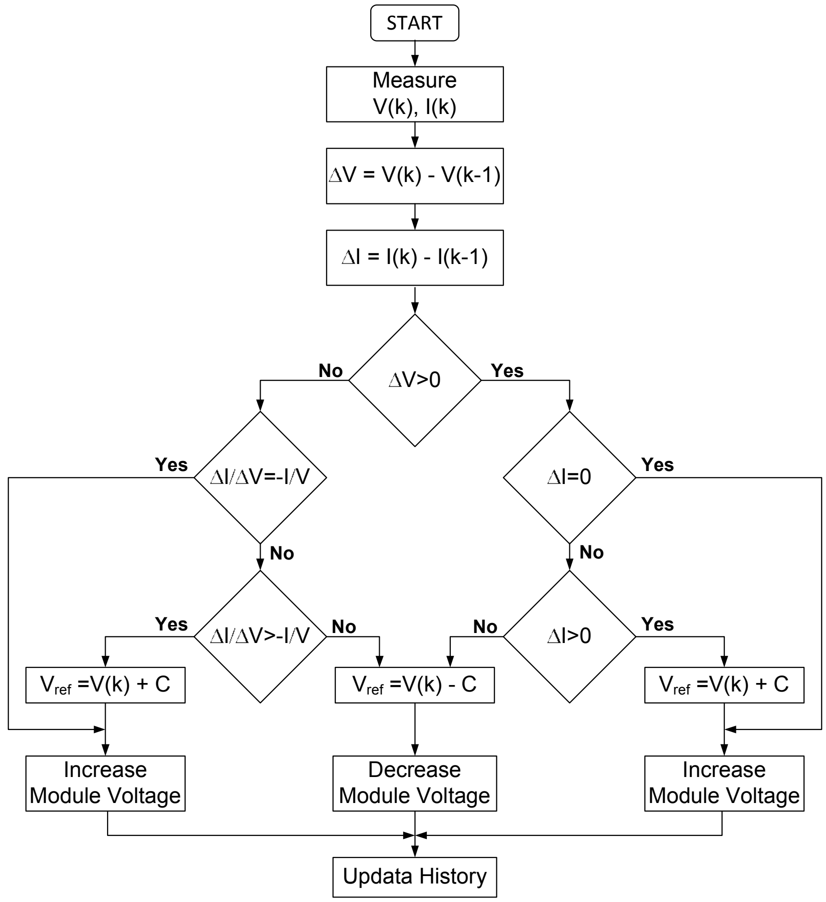


Fig. 11. Flowchart of incremental conductance (IncCond) method

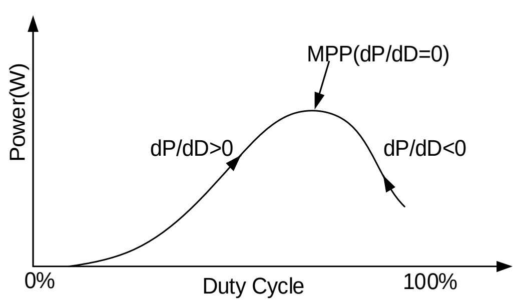


Fig. 12. P-D curve diagram of the hill climbing method

The hill climbing method uses the duty cycle (*D*) of these switching mode power interface devices as the judging parameter when the task of the maximum power point tracking is implemented. When the condition $dP/dD = 0$ is accomplished, it represents that the maximum power point has been tracked. The flow diagram of the hill climbing algorithm is shown in Fig. 13.

The duty cycle in every sampling period is determined by the comparison of the power at the present time and previous time. If the incremental power $dP > 0$, the duty cycle should be increased in order to make $dD > 0$. If $dP < 0$, the duty cycle is then reduced to make $dD < 0$.

3.3 Hybrid Method

The Hybrid methods, which are those that [7,13-16,29].

1. Combination of indirect and direct methods.
2. Estimates a value by indirect method
3. Tracks using perturbations towards MPP using direct methods.
4. Faster convergence rate.
5. Variable amplitudes of perturbation.

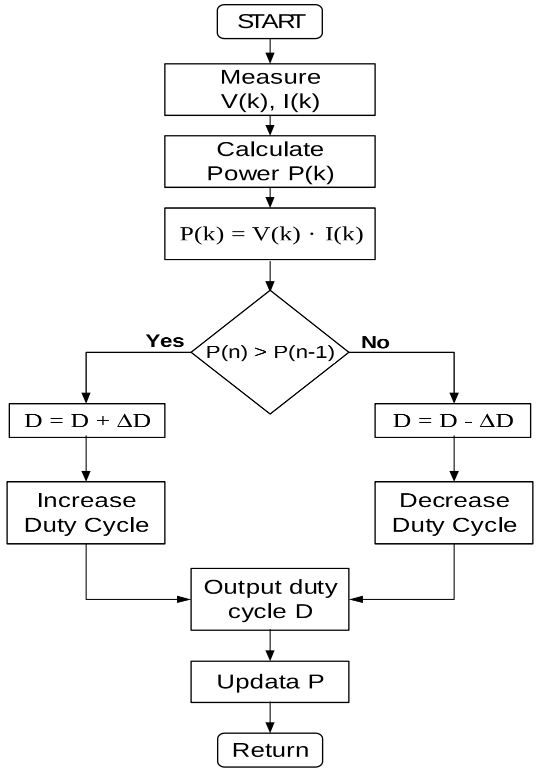


Fig. 13. Flowchart of the hill climbing method

4. CONCLUSION

The purpose of this paper is to study and compare advantages, disadvantages and execution of several MPPT methods. These methods have been classified into three categories: indirect, direct and hybrid methods. It is important to observe that when the PV panel is in low insulation conditions. IC has a feature over P&O as it can determine when the output has reached the MPP, whereas P&O keeps oscillating around the MPP. The P&O algorithm has well regulated PV output voltage than a hill climbing algorithm. However, the perturbation magnitude of the hill climbing method will be getting smaller under the condition of having similar oscillations of PV output voltage. This causes a longer simulation elapsed time for the hill climbing method to track the maximum power point. Therefore, P&O algorithm possesses faster dynamic response than a hill climbing algorithm. The incremental conductance method has advantages of exact perturbing and tracking direction and steady maximum power operating voltage. However, the other two methods have the possibility of misjudgment of determining the perturbing and tracking direction. Therefore, the incremental conductance method is more competitive than the other two methods in the PV system which uses.

The indirect methods, including open circuit voltage coefficient (K_V) method, short circuit current coefficient (K_I) method. The K_I method is more accurate and efficient than the K_V. Proposed a new method maximum power coefficient K_P, which is multiplication K_V and K_I.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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