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General Overview of Maximum Power Point Tracking Methods for Photovoltaic Power Generation Systems

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Abstract

Maximum power point tracking controller is essential to obtain the maximum power from a solar array in the photovoltaic systems as the PV power module varies with the temperature and solar irradiation. In this paper, several methods for the MPPT of the PV systems are discussed and it can to be used as a Helpful reference for the upcoming MPPT user in the PV applications.

Keywords: Photovoltaic system; Maximum power tracking; as perturb and observe; Neural Network.

1. Introduction

Nowadays, the renewable energies are growingly used. The photovoltaic (PV), fuel cell, wind farm and biomass are the most common sources [1]. Among these sources, the PV systems are dominant because of their availability and reliability. It is essential to track the maximum power point in order to capture the maximum solar energy from the PV system. There are many MPPT methods for tracking the maximum power with various cost, convergence speed, sensors, and complexity. However, it is hard to define the method that is most suitable for a certain PV system because of the above mentioned reasons. This paper reviews various methods with a categorization and brief discussion of each. It concludes with a summary of main characteristics of different methods in terms of complexity, the required sensors and their accuracy. In this paper, different MPPT methods are categorized as the hill climbing methods, intelligent methods and other methods.

1. Hill Climbing Methods

A) P&O Method

Perturb and observe (P&O) method has attracted more attention because of its simple algorithm in the previous research [2, 3]. In this method, the system current is disturbed by a perturbation in the duty cycle of the convertor and consequently it perturbs the PV system voltage.

As it can be seen from Fig.1, clearly when the power operating on the left side needs to increase the voltage, the one operating on the right side needs to decrease the voltage. Thus, where the power increases the next duty cycle should be maintained constant to obtain the maximum power point, while where the power is decreased the duty cycle should be reversed to reach the MPP. Then, this process is repeated periodically until the MPP is reached. Figure 2 depicts the algorithm of the P&O method. Owing to the ease of application and simplicity of the P&O technique, it is the most popular method in practice [4].

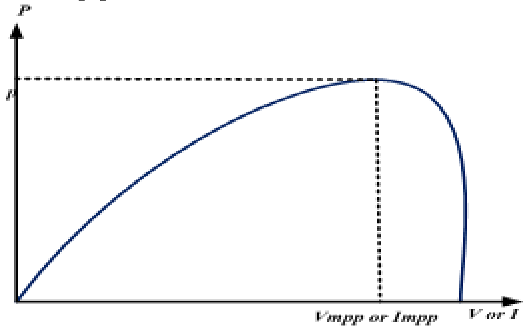

Fig. 1. Characteristic of PV panel power curve.

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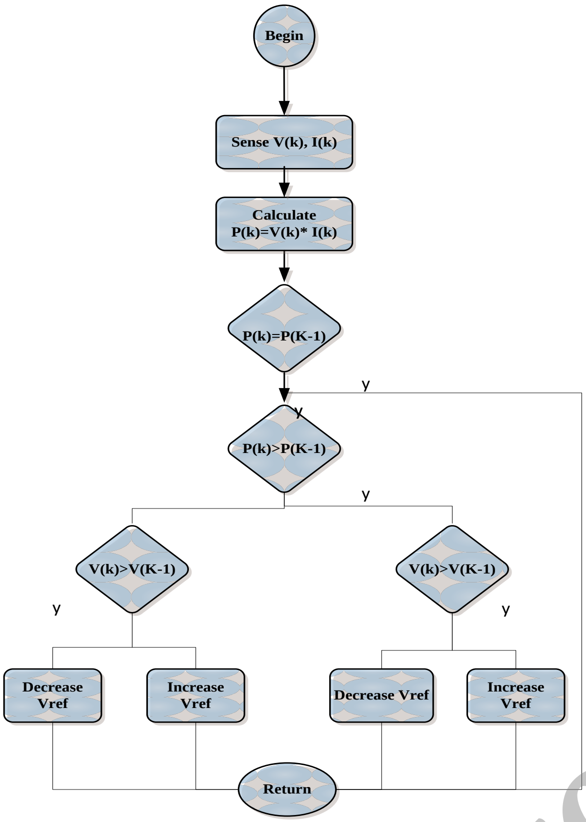

Fig. 2. Block diagram of P&O method

The two main problems in this method are determining the convergence rate of the tracking MPP as well as the oscillation amplitude. For instance, by larger perturbations, the MPP is tracked faster, but it will lead to higher oscillation amplitude. However, by smaller perturbations, the rate of convergence is reduced, but the oscillation around the MPP is decreased as well. In order to overcome these problems, a study [5] proposed a variable perturbation size to apply large perturbations, where the output power was far from the maximum power point. Smaller perturbations were applied, which were costly, complex and incapable of tracking the MPP where the operation point changed quickly [6].

B) Incremental Conductance Method

Some studies [7, 8 and 9] applied the incremental conductance (IC) based on the characteristic PV system power curve as shown in Fig.1. If the slope of power curve (dp/dv) is zero, the system's power is at the left side and its negative value indicates that the system's power is at the right side. Therefore, the MPP can be tracked by comparing the incremental and the instantaneous conductance. Figure 3 below shows this process as presented in [7, 8, 9]. The main disadvantage of this method is that the control system is complex, while it is capable of tracking the MPP under the changing atmospheric conditions [6, 41, 42, 43 and 44].

Comparison of the most widely used MPPT methods: the incremental conductance (IC) as well as perturb and observe (P&O) both operate under the same conditions (temperature and irradiation) [10]. The comparison was based on the power losses, energy efficiency and response time. Theoretically, the IC method has a better MPP tracking than the P&O method, but it was experimentally found that the P&O technique had the same MPPT efficiency as the IC method when it was properly optimized. In addition, it is highly competitive against other MPPT methods owing to the ease of implementation [10].

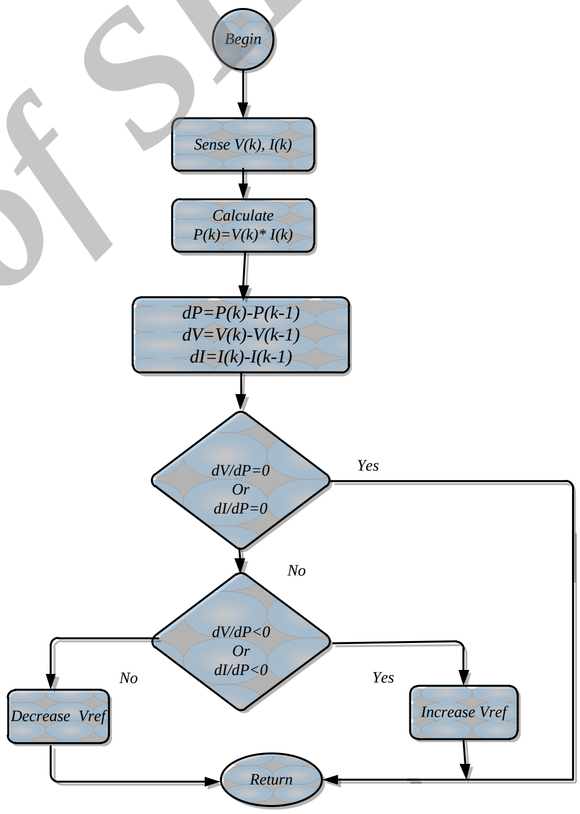

Fig. 3. Block diagram of incremental conductance method

2. Intelligent Methods

In this section, intelligent methods, such as the Genetic algorithm, Fuzzy logic and neural network are discussed. The main advantages of these methods are that they do not require prior knowledge of the PV system, they can work with variable inputs nonlinearity as well as their robustness [11].

A) Genetic Algorithm

The searching process of the GA algorithm is included by selection, crossover and mutation [12]. The steps of a GA algorithm to maximum power point tracking are under the following equations. The initial position of the population is given as below:

$$[parent\ (1)\ ,\ parent\ (2)\ ,\ parent\ (3)\ ,\ parent\ (4)] = [0.8\ ,0.6\ ,0.4\ ,0.2] \times 2 \times V_{oc} \quad (1)$$

In the crossover step, two parent chromosomes were combined to produce a child under the following equations:

$$Child\ [k] = r \times parent\ (k) + (1 - r) \times parent\ (k + 1) \quad (2)$$

$$\text{Child}\ [k + 1] = (1 - r) \times \text{parent}\ (k) + r \times \text{parent}\ (k + 1) \quad (3)$$

And, the duty cycle is defined as below:

$$D_{(k)} = (1\text{-}\ child\ [k]) / (2 \times V_{oc}) \quad (4)$$

The objectives were to satisfy the two following equations:

$$|V_{(k+1)} - V_{(k)}| < \Delta V \quad (5)$$

$$|(P_{(k+1)} - P_{(k)}) / P_{(k)}| > \Delta P \quad (6)$$

The results showed that the proposed GA designed by [12] could track the MPP.

B) *Fuzzy Logic Control*

The fuzzy logic controllers are robust with nonlinearity and imprecise inputs. In addition, by using these controllers, no mathematical model of the used system is needed [13]. These advantages caused these controllers become popular for controlling the MPP in the last few years [13, 14]. The fuzzy logic method consists of three parts: fuzzification, inference system and deffuzification as shown in Fig.4.

The numerical input values, which are usually an error (E) and a changing error (ΔE) are given as:

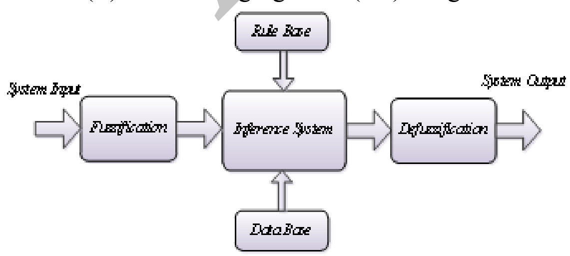

Fig. 4. Block diagram of fuzzy logic controller.

$$E_{(n)} = (P_{(n)} - P_{(n-1)}) / (V_{(n)} - V_{(n-1)}) \quad (7)$$

$$\Delta E_{(n)} = E_{(n)} - E_{(n-1)} \quad (8)$$

They were converted to linguistic variables based on the defined membership function by the researcher. Then, by the defined rules (which are usually determined by an expert or a look-up table provided by the researcher), the output of the controller duty ratio (ΔD) was determined. These controllers could track the MPP, especially under the changing atmospheric conditions. However, their effectiveness depends on the designer's knowledge of choosing the appropriate look-up table, especially considering the appropriate type of membership function, which is very effective to track the performance [15].

A modified fuzzy logic MPPT controller was developed in [16]. This method located the maximum power point quickly by scanning and storing procedures. During the scanning procedure, to ensure storage of the maximum power, the initial tracking speed was set high [17]. This method exhibited good performance, even under partial shading conditions. Furthermore, smoother signal was resulted in a steady state with less fluctuation and oscillations around the MPP.

The advantages of using the fuzzy system are its capability to handle nonlinear systems, fast convergence, and independence from the systems' mathematical model, while its accuracy is dependent on the designer's knowledge to determine the fuzzy rules and form of the membership functions [6].

C) *Neural Network Method*

Among the intelligent controllers, the neural network shows good performance with nonlinear systems [18]. The neural network method consists of three parts: input, hidden layers and output as shown in Fig.5.

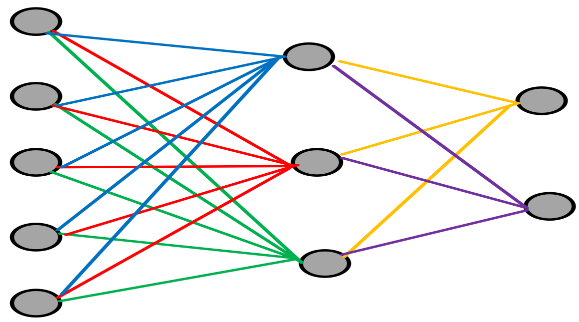

Fig. 5. Neural network model

By using the NN in the PV system to track the MPP, the NN input can be parameters, such as temperature, irradiance, Voc and Isc among others. The output also can be the duty ratio to drive the system to perform as close as possible to the MPP. This goal is achieved where the defined algorithm is trained well by testing the PV system over months or years to find the best pattern between the inputs and outputs of the NN controller. The NN should be trained and learned by the input and output data, which are obtained from the simulation or experimental results to find the relation (weight) of inputs (temperature and irradiance) with output (V_{mpp}); then, it can find the MPP accurately [19, 20, 21 and 22]. The number of nodes in each layer depends on the designer. In addition, its efficiency to reach the MPP depends on the hidden layer, algorithm and good training of the neural network controller [17].

The main drawback of the controller is that it is dependent on the PV system being used. In addition, to guarantee accurate MPP tracking, this controller has to be trained over time because of periodical change in the characteristics of the PV systems [20]. The main advantage of the NN technique is that it can track the MPP accurately without the knowledge of the PV systems.

The NN controller developed in [23] consists of three layers; the PV cell temperature and irradiation are considered as the inputs layer, the optimum duty cycle as the output and the hidden layer composed of seven neurons. The method used in this paper is the retro-propagation to minimize the total error E defined below [137]:

$$E = 0.5 \times \sum (O_n - t_n)^2 \tag{9}$$

, where On is the nth measured output and tn is the nth target. The E (error) is calculated by the retro-propagation and in order to reduce the error, the weights between the neurons were adjusted by the following equation [23]:

$$\Delta W_n = (\delta \times \Delta W_{n-1}) - \eta \times (\sigma E / \sigma W) \tag{10}$$

, where ΔWn and ΔWn-1 are the changes of these weights for n and n-1 iterations, η is the training rate and δ is the speed term [23]. The advantages of this method are independence from the knowledge of system parameters as the optimum duty cycle is obtained by the NN controller [23].

The intelligent methods in the MPPT were compared in [23]. The inputs of these controllers were obtained from the cell temperature and solar irradiation. The optimum duty cycle was determined by the controller output to track the maximum power in the PV system [23]. Depending on the load voltage and current, the duty cycle continually was adjusted to control the dc-dc converter [23]. These controllers were built based on a variable resistor, an irradiation sensor, a temperature sensor and practice data. The results showed that these methods could accurately estimate the MPP at any irradiation and temperature, but the fuzzy method yielded power with the minimum total error and more efficiency compared to the NN.

The advantages of using the fuzzy system are its capability to handle nonlinear systems, fast convergence, and independence from the systems' mathematical model, while its accuracy is dependent on the designer's knowledge to determine the fuzzy rules and form of the membership functions [6].

3. Other Techniques

A) Fractional Open Circuit Voltage (Voc)

Some studies [24, 25] used a linear function of Vmpp (voltage at MPP) as given below:

$$V_{mpp} = K \times V_{oc} \tag{11}$$

Where k is the constant value and depends on the characteristics of the PV system used. In addition, this value should be computed at different irradiance and temperature levels by determining the V_{oc} and V_{mpp}. As it can be seen, to find the V_{mpp}, first k and Voc should be determined. The suggested value of the factor k is between 0.71 and 0.78. Then, where the k is known, the power converter should be shut down momentary to measure the V_{oc}. This is a drawback of this method because of temporary power loss. To deal with this problem, [24] suggested that nearly 75 percent of the Voc can be generated by diodes; thus, it is not required to measure the V_{oc} and V_{mpp}. The above-mentioned methods are approximation values of the V_{mpp} and the value of k is not valid in the changing atmospheric conditions (partial shading and temperature). An optimal value of K is difficult to determine. In order to measure the V_{oc}, the PV output must be shaded periodically, which will cause more power loss [6]. To overcome the power loss, an approximate approach can be used by measuring the irradiance and temperature to estimate an approximate value of the V_{oc} based on the equation below:

$$V_{oc} = V_{oc1} + a_2 \times (T - T_1) - (I_{sc} - I_{sc1}) \times R_s \tag{12}$$

Comparing with the other methods, this method has the higher power loss [6].

B) Fractional Short-Circuit Current (Isc)

The Some studies [26, 27] used a linear function of the Impp (the current at MPP) as:

$$I_{mpp} = K \times I_{sc} \tag{13}$$

, where K is a constant value (generally suggested to be between 0.78 and 0.92) . The value of factor K should be determined by the used PV system. To measure the Isc, a switch should be added to the converter, the PV system should be periodically shortened and the Isc measured by a current sensor. This method, similar to the Voc method, can never track the MPP because of the approximation value of K, especially in the changing

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atmospheric conditions [28]. In addition, in this method, one more switch is required in order to measure the Isc; therefore, its cost is higher than the Voc method. To overcome the power loss, an approximate approach can be used by the measurement of the irradiance and temperature to estimate an approximate value of the Isc based on the equation below:

$$I_{sc} = I_{sc1} \times (G / G_1) + a_1 \times (T - T_1) \qquad (14)$$

C) Dc Link Capacitor Droop Control

This method was designed to track the MPP, where the PV system is linked to an AC system line and the duty ratio of a boost converter is as:

$$d = 1 - (V / V_{link}) \qquad (15)$$

, where V_{link} is voltage of the DC link as shown in Fig.6 and V is voltage of PV system [29, 30]. This control method is executed by an analog circuit and power computation of the PV system is not required. It was suggested [31] that the MPP can be tracked in voltage source application, where the I_{out} (current load) is maximized and in the current source application, this point can achieved, where the V_{out} (voltage load) is maximized. Consequently, by this method only one sensor is needed. However, the MPP never can be tracked by this method on the basis of the hypothesis that the power converter is not lost.

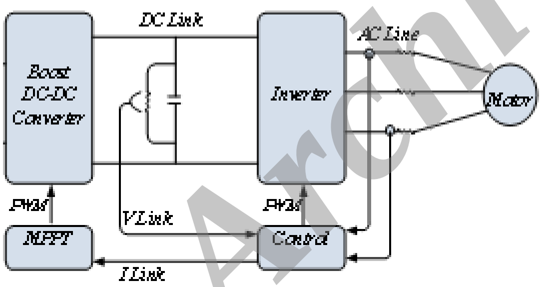

Fig. 6. Block diagram of dc link capacitor droop method

D) Extremum Seeking Control Method (ESC)

This method includes a nonlinear dynamic system with adaptive feedback to track the MPP in the PV system [32, 33]. The complexity of its implementation is its main disadvantage, while the MPP is guaranteed by this method.

E) Temperature Method

This method uses the temperature sensors and temperature function to track MPP [34, 35]. This is a simple method with good tracking, low cost and simple implementation [36].

F) Feedback Voltage Method

This method maximizes the power at the output (load) or the input (panel) power. By the feedback from the output power, the duty cycle is adjusted to drive the (dp/dv) to zero [38].

G) Curve Fitting Method

This method uses the mathematical model and equation to calculate the V_{mpp} and track the MPP. The disadvantage of this method is that it needs large memory, low speed and prior knowledge of the PV system, while its advantage is its simplicity [40, 11].

4. Comparison and Discussion

The main factors of complexity, convergence speed, PV module dependency and number of sensors in different MPPT techniques for the PV applications are summarized in Table 1. Various MPPT methods were reviewed in this paper [2-44]. Each method has pros and cons and it is quite challenging to choose the best method. The choice of best method is dependent on specific application. For example, fast convergence to the MPP is needed similar to the solar vehicles. In this case, the intelligent methods are suitable options. In the case of space satellites, where the reliability and performance of the MPPT are essential, appropriate methods are the Hill-climbing methods, because the right MPP must be tracked in the least possible time, without intermittent time tunes.

Table.1.
Appearance properties of accepted

MPPT methods	PV dependent	Analog /digital	True MPPT	Convergence speed	Sensed parameters	Periodic tuning	complexity
P&O	N	Both	Y	Varies	V and I	N	L.
IC	N	Digital	Y	Varies	V and I	N	M.
Fuzzy	Y	Digital	Y	Fast	Varies	Y	H.
NN	Y	Digital	Y	Fast	Varies	Y	H.
GA	Y	Digital	Y	Fast	Varies	Y	M.
Voc	Y	Both	N	Medium	V	Y	L.
Isc	Y	Both	N	Medium	I	Y	M.
DC-link	N	Both	N	Medium	V	N	L.
ESC	Y	Both	Y	Fast	V and I	Y	H.
Temp	N	Digital	Y	Medium	Irr, Temp	N	H.
V-fb	Y	Digital	N	Medium	V	Y	L.
P-fb	Y	Digital	N	Medium	V and I	Y	M.
Curve-fit	Y	Digital	N	Medium	V and I	Y	L.

5. Conclusion

In this paper, various MPPT methods were reviewed and discussed with their pros and cons. These methods can be easily understood and compared according to their complexity, sensors, cost and PV module dependency. The discussion and comparison in this paper can be considered as useful criteria for selecting the right MPPT controller for particular PV applications.

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