Maximum Power Point Tracking Algorithms for Photovoltaic Applications: A Comparative Study

Parul Gaur*, Yajvender Pal Verma**, Preeti Singh***

UIET, PanjabUniversity, Chandigarh, India.

*parul34@gmail.com, **yajvender_verma@yahoo.com,***preets.singh.82@gmail.com

***Abstract*—With the increased demand of energy, renewable energy sources such as wind, solar, biomass and ocean are getting more attention as compared to conventional energy sources because of absence of fuel cost, lesser noise and low maintenance. Among the different renewable energy sources, photovoltaic generation is the most attractive research area during the past decades. Photovoltaic module results in the output power which keeps on changing with the environmental conditions. Thus, there is a need of control algorithms which can extract the maximum power from the photovoltaic modules irrespective of the environmental conditions such as temperature and irradiation. Numerous control algorithms have been proposed in the recent years. This paper presents a comparative study of various maximum power point tracking algorithms used for extracting maximum power from the photovoltaic modules.**

Keywords—Maximum Power Point Tracking (MPPT); Photovoltaic (PV); Open Circuit Voltage; Short Circuit Current; Perturb and Observe (P&O); Incremental Conductance (IC)

I. INTRODUCTION

In the recent years, deployment of renewable energy resources has been increasing rapidly. With the increasing concern about global environmental protection, widespread use of renewable sources such as photovoltaic (PV) or wind power systems for electric power generation has been taken place. According to Renewable Energy Network Policy 2014 report, renewable contributed to 19 percent to global energy consumption and 22 percent to electricity generation in 2012 and 2013, respectively. Rapid deployment of renewable energy such as solar and energy efficiency is resulting in significant climate change mitigation, energy security and economic benefits. To use solar energy more effectively, a great amount of research is going on the PV generation systems. The output power generated by a PV module depends upon the non linear current voltage (I-V) characteristics and the atmospheric conditions such as temperature, solar irradiation that falls over the PV modules and the connected load.

Due to non linear relationship between current and voltage, there exists a unique maximum power point (MPP) that keeps on changing with the atmospheric conditions, ambient temperature and irradiance levels. At the maximum operating point, a PV array operates at its highest efficiency. To obtain MPP under varying atmospheric conditions, maximum power point tracking (MPPT) control algorithms are generally used [1-5]. Extraction of maximum power from the PV module connected to each voltage level is done by the MPPT. To increase the efficiency of PV arrays, different MPPT controllers have been used. The use of these controllers has become imperative in PV systems. Various control strategies for tracking such as constant voltage, perturbation and observation, parasitic capacitance and fuzzy logic control have been reported for maximum power [6-8].

This paper is organized into six sections. Section I presents the brief introduction of emerging trends in renewable energy resources, grid connected PV systems and their MPPT control strategies. Section II enlists the photovoltaic systems. Various tracking control algorithms for maximum power are described in section III. Comparison of MPPT control algorithms are presented in section IV. Section V represents the conclusion and future scope.

II. PHOTOVOLTAIC SYSTEMS

A PV is a power system designed to supply a usable solar power by means of photovoltaics. PV systems consist of arrangement of several components, including solar panels to absorb and convert sunlight into electricity and a solar energy inversion and conditioning system to change electric current from DC to AC. Fig.1 shows a general PV system.

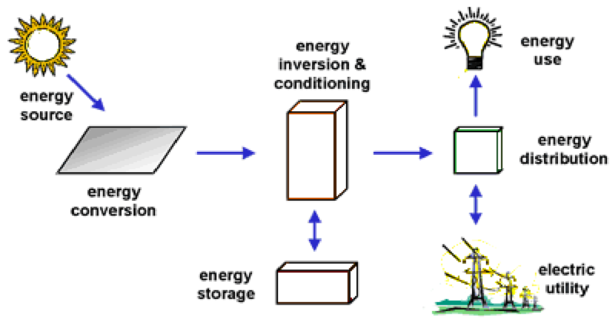

Fig.1. General PV System

The basic component of a PV system is PV cell. A PV cell is a semiconductor diode whose PN junction is exposed to light. Incidence of light generates the charge carriers in the PN junction, which results in the electric current. Large sets of PV cells can be connected together to form solar modules, arrays or panels. Equivalent circuit of PV cell is shown in fig.2.

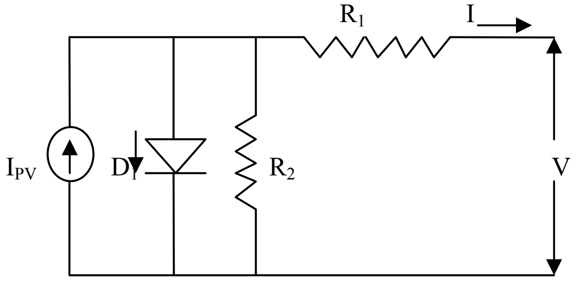

Fig.2. Equivalent Circuit of Photovoltaic Cell

PV cell is represented by a current source I_{PV} in parallel with a diode D_1. R_1 and R_2 represent the series and parallel resistances respectively. The net current I of the circuit is given by (1) as :

$$I = P_{PV}(n) - I_1[\exp(\frac{V + R_1 I}{V_T}) - 1] - \frac{V + R_1 I}{R_2} \tag{1}$$

Where I_{PV} is the PV current and V_T is the thermal voltage.

III. MAXIMUM POWER POINT TRACKING CONTROL ALGORITHMS

For maximum power extraction from a solar panel, MPPT is essential in PV systems because the MPP of a solar panel changes with temperature, shading and irradiation levels. A MPPT consists of a boost converter and a control circuitry for MPP control algorithms. Fig. 3 shows a PV system with MPPT. In normal situations, PV curve has only single maximum power point but in case of partial shading because of clouds and building shadows, PV curve has multiple maxima. The impact of partial shading appears significantly for large arrangement of arrays. Several factors are required to be considered while selecting and developing the algorithms for MPPT, such as capability of an algorithm to detect multiple maxima, convergence speed and cost etc. In order to improve performance of the PV system, numerous MPPT control algorithms are available for better tracking of MPP.

A. Differential Method

Differential method for MPP is based on solving the differential equation given by (2). $V_{PV}(n-1) = V_{PV}(n)$, P_{PV} represents the PV voltage and output power respectively. This method is cumbersome as it requires huge amount of calculations and measurements [9]. After calculating (2) parameters, sum ($I_{PV}\ dV_{PV} + V_{PV}\ dI_{PV}$) is calculated and a comparison is done between the sum and equal perturbation on the opposite side of the operating point.

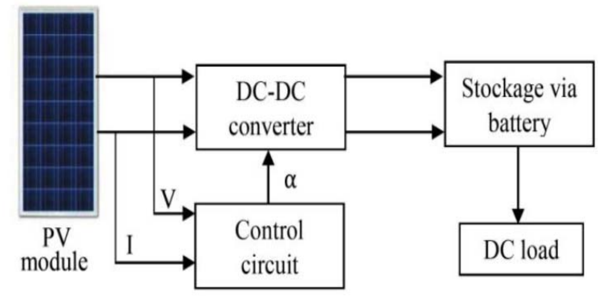

Fig.3. PV System with Maximum Power Point Tracker

This process is done till the final sum becomes zero. More calculations are required until the final sum becomes zero.

$$\frac{dP_{PV}}{dt} = V_{PV} , \frac{dI_{PV}}{dt} + I_{PV} \frac{dV_{PV}}{dt} = 0 \tag{2}$$

B. Curve Fitting Method

For curve fitting method, PV array characteristics, all the data and manufacturing details are required and also the mathematical model and equations specifying the output characteristics of the PV module are pre-assumed. It is basically an offline method, in which PV characteristics are mentioned by the (3), where a , b , c and d are coefficients, which are calculated by taking samples of voltage, current and power in the required interval.

$$P_{PV} = aV_{PV}^3 + bV_{PV}^2 + cV_{PV} + d \tag{3}$$

The voltage at which power attains the maximum value is given by the (4). This procedure should be repeated many times in order to achieve a good MPP. Curve fitting method requires the prerequisite of physical parameters related to cell material and manufacturing requirements. Number of calculations is more in this method and speed is low.

$$V_{MPP} = -b\sqrt{b^2 - 3ac} \,/\, 3a \tag{4}$$

C. Look-up Table Method

In this method, a comparison is done between the calculated values of PV's voltage and current and values which are stored in the control system that corresponds to the operation in the MPP. However, this method requires large amount of memory for storage of data and to store and record all the system conditions leads to complexity. Also algorithm must be adjusted for a specific PV array.

D. Sampling Method

In sampling method, initially a sample of PV's voltage and current is taken. Next with the aid of diverse strategies, PV output power is calculated. Afterwards, PV output power with a certain time interval of ($t + \Delta t$), is again computed. Knowing the past and present values of PV output power, depending on the location of the MPP controller makes a

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decision. This tracking procedure is repeated several times until the MPP is achieved.

E. Open Circuit Voltage Method

One of the simplest MPPT control algorithm is open circuit voltage method, sometimes also called as constant voltage method [10-12]. This method is based upon the non-linear relationship between the maximum power voltage (V_{MPP}) and the open circuit voltage (V_{oc}) under the changing irradiance and temperature levels, as mentioned in (5). Generally used value of V_{MPP}/V_{oc} is 76%.

$$V_{MPP} = k_1 V_{oc} \tag{5}$$

Here k_1 represents the proportionality constant and it has been reported to be between 0.71 to 0.78. As k_1 depends upon the characteristics of the PV array being used, it generally has to be estimated beforehand by empirically determining V_{oc} and V_{MPP} for the particular PV array at different irradiance and temperature levels. Once k_1 is estimated, V_{MPP} can be calculated with V_{oc} computed periodically by momentarily shutting down the power converter. Fig. 4 shows the flowchart for this method. Open circuit voltage method does not need any input. It is simple and cheap method. This method is found to be effective when the PV array is in low insulation conditions. However, this method suffers the disadvantage of temporary loss of power and sometimes it becomes difficult to select an optimal value of proportionality constant.

F. Short Circuit Current Method

Short circuit current or constant current method is similar to open circuit voltage method. In this method, MPP current

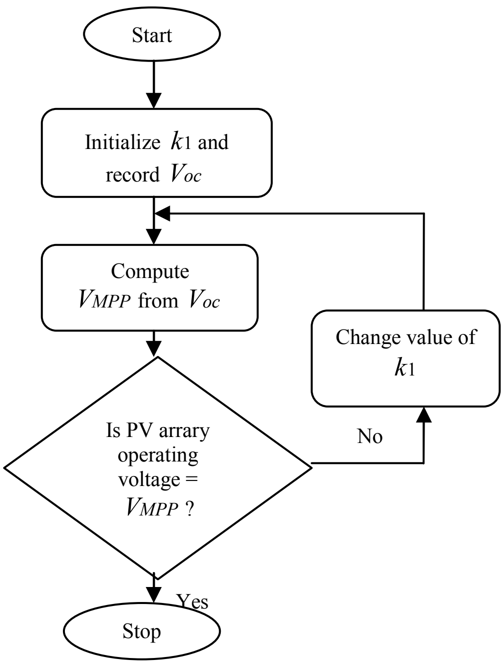

Fig.4. Flowchart of Open Circuit Voltage Method

(I_{MPP}) is linearly proportional to short circuit current (I_{SC}), given by (6) as:

$$MPP = k_2 I_{SC} \tag{6}$$

Here k_2 is the proportionality constant; its value is generally reported between 0.78 to 0.92. During operation another problem associated is measurement of I_{SC} . An additional switch has to be inserted to the power converter to periodically short the PV modules so that measurement of I_{SC} can be done using current sensor [13-15].

G. Feedback Voltage or Current Method

To adjust the duty cycle of the boost converter and to operate the PV module at a particular operating point; that is close to MPP, the feedback of PV voltage or current and a comparison with a constant voltage or current is used. This method is simple and economical and makes use of only one feedback loop control, but the system fails to adapt according to changeable atmospheric conditions such as temperature levels and irradiance.

H. Methods by Modulation

An appropriate adjustment of the maximum voltage point results in a point close to and oscillating around the maximum power point. With the aid of feedback control systems, oscillations are generated automatically. Another technique that adds an oscillation is known as forced oscillation method. In the forced oscillation method, a small voltage is added to the operating voltage of the PV module. This results in a ripple power, whose phase and amplitude is dependent on the relative location of the operating point to the MPP. Depending upon the relationship between ripple power and voltage, location of the MPP is determined. The output power is either in phase or 180^{o} out of phase with respect to voltage. The major advantage of this technique is that amplitude and phase analysis provides the knowledge of the location of the MPP. Also, when the point of operation approaches towards the maximum value of power the exit signal converges slowly towards the zero value. This results in the adjustment of the operating voltage towards the MPP voltage. Therefore, no continuous oscillation will be there around the MPP. The only disadvantage of this technique is that the great amount of complexity involved in the implementation of this method.

I. Hill Climbing Techniques

Perturb and Observe (P&O) method and Incremental Conductance (Inc Con) method work on Hill Climbing principle, in which operating point of PV array shifts in the increasing direction of output power.

(*1) Perturb and Observe (P&O) Method*

P&O is basically an iterative method, which senses the PV voltage periodically with a voltage sensor and PV output

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power is computed [16]. A comparison is made between the present and previous value of PV output power and the resulting change i.e. ΔP_{PV} is measured. Positive value of ΔP_{PV} indicates the perturbation of operating voltage in the same direction of increment. However, negative value denotes the perturbation of operating voltage in the opposite direction of increment. In this method, PV voltage and current are sensed, PV output power is computed and a comparison is made between the present and previous sample of output power and voltage. Based upon the comparison, MPP is tracked.

(2) Incremental Conductance (Inc Con) Method

P&O method does not consider the rapid change of irradiation level and this ultimately leads to wrong computation of MPP. This limitation is overcome in Inc Con method. This method is based on the differentiating the PV output power with respect to PV voltage, given in (7) and setting the result equal to zero. At MPP, (7) is set equal to zero, while value less than or greater than zero shows the deviation of operating point from the MPP.

$$\frac{dP_{PV}}{dV_{PV}} = I_{PV} + V_{PV}\frac{dI_{PV}}{dV_{PV}} \quad (7)$$

Main advantage of this method is that it yields good result under rapidly varying environmental conditions.

J. Neural Networks and Fuzzy Logic Method

Another technique for implementing MPPT, that is also well adapted for microcontrollers, is neural networks and fuzzy logic control. Neural networks commonly have three layers: input, hidden and output layers. The number nodes in each layer vary and are user dependent. The input variables can be PV array parameters such as V_{oc} , I_{sc} , atmospheric data like irradiance and temperature or combination of these. The output is usually one or several reference signals used to drive the power converters to operate at or close to the MPP.

IV. COMPARISON OF MPPT ALGORITHMS

The MPP of PV array changes with temperature and radiation. Under changing environmental conditions, the variation of MPP demands an optimized algorithm, which further controls the power converter's operation for better efficiency of PV array. Table I presents a detailed comparison of the various MPPT algorithms. In view of changing atmospheric conditions, each MPPT algorithm has its own advantages and limitations. Open circuit voltage and short circuit current methods are easy to implement but it is very tedious to find the optimal value of k factor under changing environmental conditions. Short circuit method operates better according to changing atmospheric conditions and is more accurate than open circuit voltage method.

Table I. Comparison of Maximum Power Point Tracking Algorithms

MPPT Technique	**Sensed Parameters**	**Convergence Speed**	**Microcontroller Computation**	**Periodic Tuning**	**Realization**	**Complexity**	**Reliability**	**Overall Cost**
Open Circuit Voltage	Voltage	Medium	Absent/Low	Yes	Easy to implement	Very simple but difficult to get optimal k1	Not accurate	Low
Short Circuit Current	Current	Medium	Absent/Low	Yes	Easy to implement	Very simple but difficult to get optimal k2	Accurate	Medium
Perturb and Observe	Voltage	Varies	Low	No	Takes time to implement	Medium	Not so much accurate	Low/ Medium
Incremental conductance	Voltage, Current	Varies	Medium	No	Takes time to implement	Medium	Accurate and operate at MPP	Low/ Medium
Neural Networks and Fuzzy Logic	Varies	Fast	Medium	Yes	Depends upon the input and output variables	Medium	Accurate	Medium

V. CONCLUSION

The role of the MPPT is to match the load power required with maximum of the available power that can be generated from a PV array. Various MPPT control algorithms and their comparison in terms of convergence speed, reliability, complexity and overall cost has been presented in this paper. In particular, ten MPPT control algorithms were considered. Taking into account the detailed comparison, the P&O and IC algorithms receive the best rankings. P&O and IC methods are in general the most efficient of the analysed MPPT control algorithms. Moreover, P&O and IC techniques do not require additional static switches in comparison to open circuit and short circuit method, thus the relative costs are not too high. P&O and IC both algorithms have almost same efficiency. Another MPPT control algorithm i.e. neural networks and fuzzy logic method is fast and accurate but the cost of implementation is slightly higher in comparison to P&O and IC methods. As a future scope, research will be carried out for drawing the maximum power from the PV modules with the aid of MPPT algorithms and further applications in multilevel inverters based grid connected PV systems. Furthermore, research should focus on experimental comparisons between the MPPT control algorithms especially under shadow conditions.

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