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A study on Maximum Power Point Tracking techniques for Photovoltaic systems

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***Abstract*— There is an increase in global energy demand day by day. The best source of energy that can be chosen is renewable energy. Solar energy is available in abundance. Hence to meet the growing demand, solar energy is converted to electrical energy by using Photovoltaic (PV) systems. The PV systems have non-linear characteristics. Their energy conversion efficiency is very low. Hence Maximum Power Point Tracking (MPPT) is used to increase the efficiency of the system. It is used to ensure that maximum available energy is extracted under varying environmental conditions such as solar irradiation, temperature, load, etc. This further ensures that the available generating systems are used efficiently given the high cost of PV systems. Various algorithms have been implemented to design an MPPT based PV system. This paper gives a comparative study of the available algorithms to implement MPPT.**

The implementation of MPPT techniques began in 1970's. These techniques differ in efficiency, complexity, cost, power generated and so on. Before choosing an appropriate technique to design a PV system, it is necessary to study the characteristics of the available methods. This is important as the effective utilization of the available PV infrastructure is required. This paper presents the study of the available techniques on the basis of their characteristics. Major and common techniques namely, Perturb and Observe, Incremental Conductance, Fractional Open Circuit Voltage, Fractional Short Circuit Current and Particle Swarm Optimization have been studied. MATLAB simulations have also been presented. A concluding report has been presented to find out the most optimized technique.

***Index Terms*— Comparative study, Maximum Power Point Tracking, Photovoltaic systems, solar energy.**

I. INTRODUCTION

The global electrical energy consumption is steadily rising and therefore there is need to increase the power generation capacity. The required capacity increase can be based on renewable energy. Due to environmental issues such as pollution and global warming effect, photovoltaic (PV) systems are becoming a very attractive solution. Renewable energy sources play an important role. Various renewable sources such as solar energy, wind energy, geothermal etc. are harnessed for electric power generation. Solar energy is a good choice for electric power generation due to its availability and cleanliness.

The main applications of photovoltaic (PV) systems are in either stand-alone (water pumping, domestic and street lighting, electric vehicles, military and space applications) [1] or grid-connected configurations (hybrid systems, power plants) [2]. Unfortunately, PV systems have high fabrication cost and low energy conversion efficiency (generally less than 17%, especially under low irradiation conditions), and the amount of electric power generated by solar arrays changes continuously with weather conditions.

A. NONLINEAR CHARACTERISTICS

In addition, they have solar irradiation and temperature dependent nonlinear characteristics as shown in Fig.1 and Fig.2 [5].

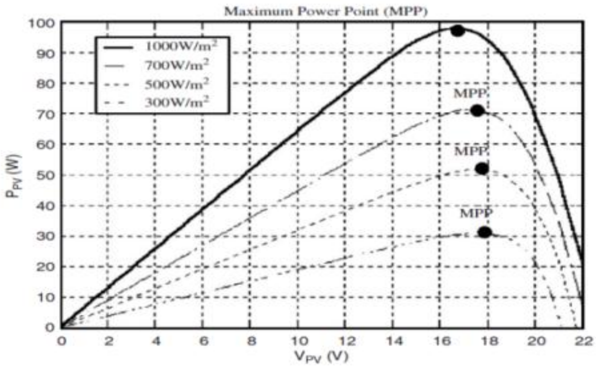

Fig.1. PV characteristics for different irradiation

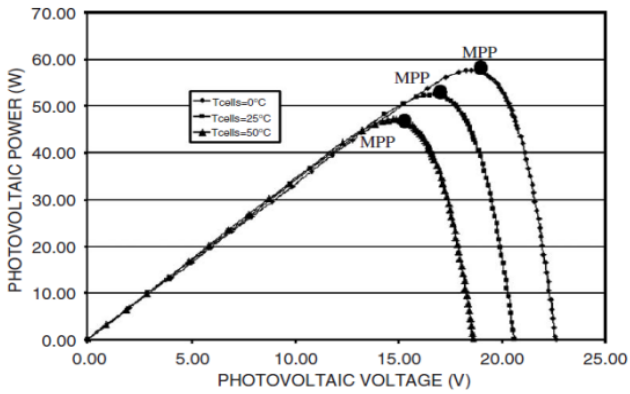

Fig.2. P-V Characteristics for different temperatures

Their operating point corresponding to maximum power changes nonlinearly with the environmental conditions such as solar irradiation, temperature and degradation levels. The main reason for the low electrical efficiency of PV systems is the nonlinear variation of output voltage and current with solar radiation levels, operating temperature, aging and load currents. Fig.3 and Fig.4 show the nonlinear variation of output voltage and current with varying sunlight [5]. In order to increase this efficiency, MPPT controllers are used. It can be observed that the temperature changes mainly affect the

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PV output voltage, while the irradiation changes mainly affect the PV output current.

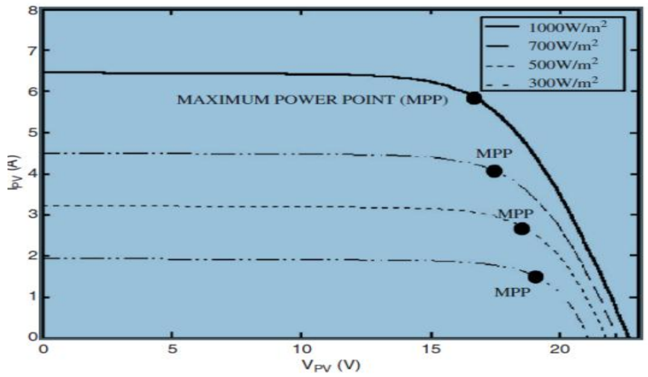

Fig.3. I-V Characteristics for different irradiation

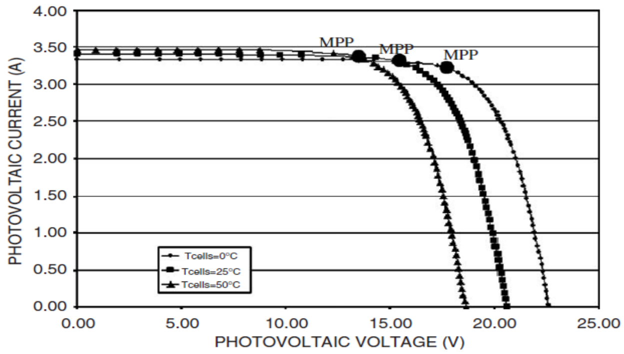

Fig.4. I-V Characteristics for different temperature

B. CONCEPT OF MAXIMUM POWER POINT TRACKING

MPPT or Maximum Power Point Tracking is the algorithm that is included in controllers used for extracting maximum available power from PV module under certain conditions. The voltage at which PV module can produce maximum power is called 'Maximum Power Point (MPP)'or 'peak power voltage'. Maximum Power Point Tracking is an electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. Fig 5 shows the general block diagram of MPPT based PV systems [3].

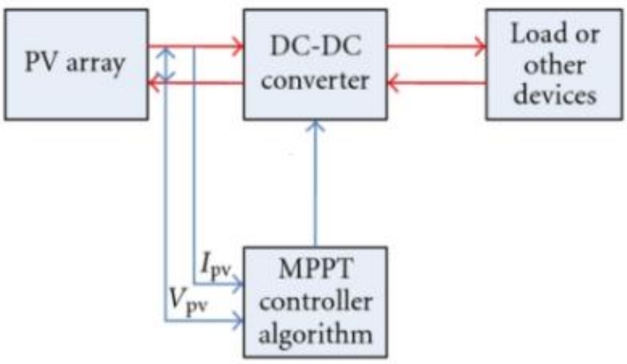

Fig.5. General Block diagram of MPPT based PV systems

C. COMPONENTS OF PV SYSTEMS

1. PV ARRAY

A PV array consists of several photovoltaic cells in series and parallel connections. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array. Typically a solar cell can be modeled by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistance. Series resistance is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance is due to the leakage current. Fig.6 shows the model of a solar cell [4].

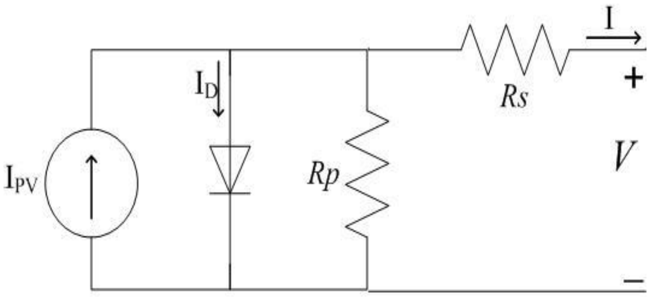

Fig.6. Equivalent circuit of a solar cell

$$I_D = I\,[exp\,(q\,(V + IR_S)/KT)) - 1] \qquad (1)$$

While, the solar cell output current:

$$I = I_L - I_D - I_{sh} \qquad (2)$$

$$I = I_L - I\,[exp\,(q(V + IR_S)/KT)) - 1] - (V + IR_S)/R_{sh} \qquad (3)$$

Where:

I: Solar cell current (A)

I_L: Light generated current (A) [Short circuit value assuming no series/ shunt resistance]

I_D: Diode saturation current (A)

q: Electron charge (1.6×10^{-19} C)

K: Boltzmann constant (1.38×10^{-23} J/K)

T: Cell temperature in Kelvin (K)

V: solar cell output voltage (V)

R_s: Solar cell series resistance (Ω)

R_p: Solar cell shunt resistance (Ω)

1. DC-DC CONVERTER

The maximum power point tracking is basically a load matching problem. In order to change the input resistance of the panel to match the load resistance (by varying the duty cycle), a DC to DC converter is required.

2. MPPT CONTROLLER

MPPT controller is the block which provides the DC-DC converter the required pulse. This control circuit may be of any form. Various algorithms have been used to implement MPPT.

D. PROBLEM OVERVIEW

The problem considered by MPPT techniques is to automatically find the voltage VMPP or current IMPP at which a PV array should operate to obtain the maximum power output PMPP under a given temperature and irradiance. In some cases it is possible to have multiple local maxima, but overall there is still only one true MPP. The techniques that have been studied are as follows.

II. PERTURB & OBSERVE TECHNIQUE(P&O)

In this method the operating voltage of the PV array is perturbed by a small increment, and the resulting change of power, ΔP, is observed [6]. If the ΔP is positive, then the voltage perturbation is moving toward the MPP. This means that further perturbations in the same direction of voltage change will direct the operating point toward the MPP. If the ΔP is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to return back toward the MPP. The basic concept of the P&O algorithm is described in Fig .7 at constant Solar Radiation and temperature. The mathematical formulation of algorithm has 4 cases as follows:

- When ΔP <0 &V(j)>V(j-1), then Vref=V(j+1) = V (j) - ΔV
- When ΔP <0 &V(j)<V(j-1), then Vref=V(j+1) = V (j) +ΔV
- When ΔP >0 &V(j)<V(j-1), then Vref=V (j+1) = V (j) - ΔV
- When ΔP>0 &V(j)>V(j-1), then Vref=V (j+1) = V (j) +ΔV

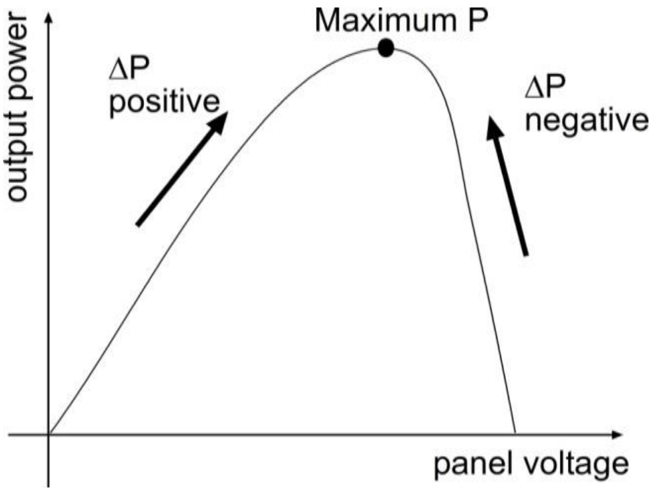

Fig.7. Power Vs Voltage for PV systems

The general flow chart P&O technique [7] has been given in Fig.8. The advantages of this method are that the circuitry used for the method is simple and requires only two sensors. The major drawbacks of P&O are occasional deviation from the maximum operating point in case of rapidly changing atmospheric conditions, such as broken clouds. Also, correct perturbation size is important in providing good performance in both dynamic and steady-state response [8]. Some P&O techniques have been mentioned commonly in the literatures [7],[8]: In the classic P&O technique (P&O1), the perturbations of the PV operating point have a fixed magnitude. The magnitude of perturbation is 0.37% of the PV array Voltage. In the optimized P&O technique (P&O2), an average of several samples of the array power is used to dynamically adjust the magnitude of the perturbation of the PV operating point.

In the three-point weight comparison method (P&O3), the perturbation direction is decided by comparing the PV output power on three points of the P-V curve. These three points are the current operation point (A), a point B perturbed from point A, and a point C doubly perturbed in the opposite direction from point B. All three algorithms require two measurements: a measurement of the voltage V_{PV} and a measurement of the current I_{PV}.

Adaptive P&O technique and Predictive and Adaptive MPPT P&O technique have been introduced. In the Adaptive P&O method, instead of V_{MPP}, the main emphasis has been given on the voltage perturbation. In Predictive and Adaptive MPPT P&O method, a constant duty cycle perturbation that linearly reduces with increase of power drawn from PV panel has been taken.

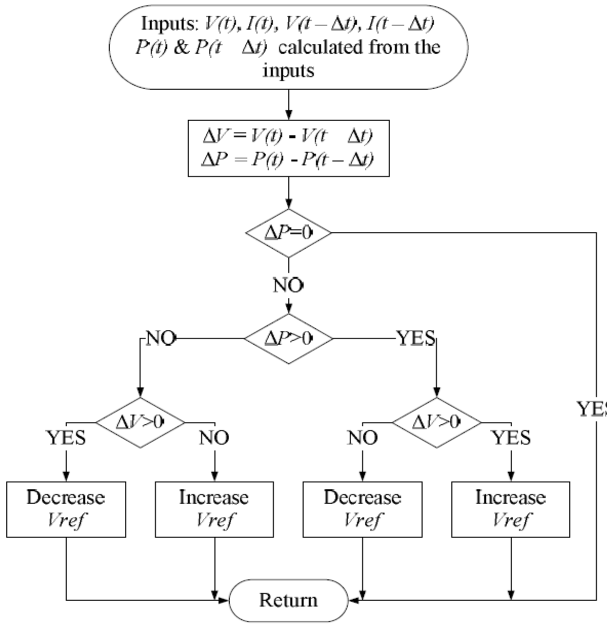

Fig.8. P&O Flow Chart

The *problem* of tracking the true Maximum Power Point is shown in Fig 9 [5]. The case is considered in which the irradiance is such that it generates the P–V curve characteristics, curve 1. In this way, the operating voltage initially oscillates around the maximum point, from A to A1. Now, an increase in the power will be measured because the solar irradiation has increased from curve 1 to curve 2. Then, if one assumes that being in point A, that it comes from a diminution of the voltage, and before the following disturbance takes place, the irradiance is increased, with the curve characteristic being now curve 2, and the operation point will occur at B1. Indeed, since there has been a positive increase in power, the disturbance will continue in the same direction. In other words, the voltage will diminish and go to point B. Furthermore, if the irradiance is increased again quickly to curve 3, there will be another increase in positive power, with which the operation point will now be C. That is, due to two increases of irradiance, the operation point has been transferred from A to C, moving away from the maximum point. This process remains until the increase of the irradiance slows or stops.

Results:

According to [4], Results from MATLAB simulation using simple programs with P&O algorithms have been shown in the Fig.10 (a, b). In Fig 10.a, the maximum power point to as coordinates (V= 174 V, P= 760 W) to provide illumination sets (1000 W/m^2). Fig 10.b shows results for variable illumination. According to [9], the oscillations around MPP are shown in Fig.11.

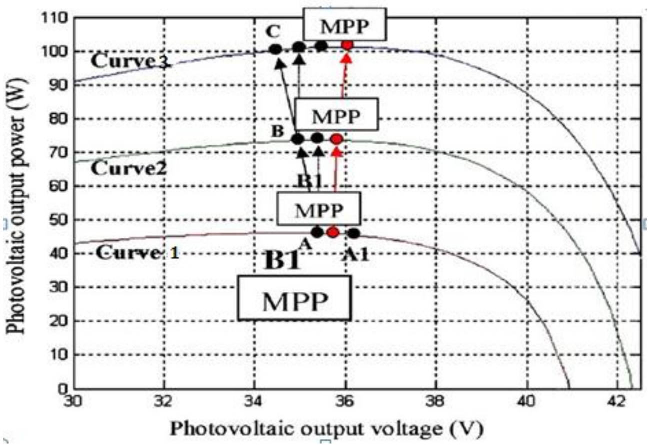

Fig.9. Deviation from MPP under varying irradiation

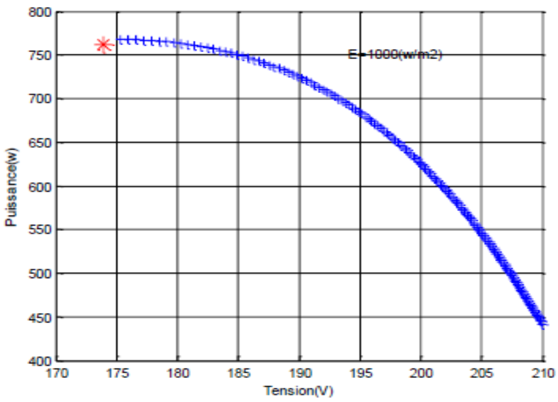

Fig.10(a). The Variation in Power Depending on the Voltage

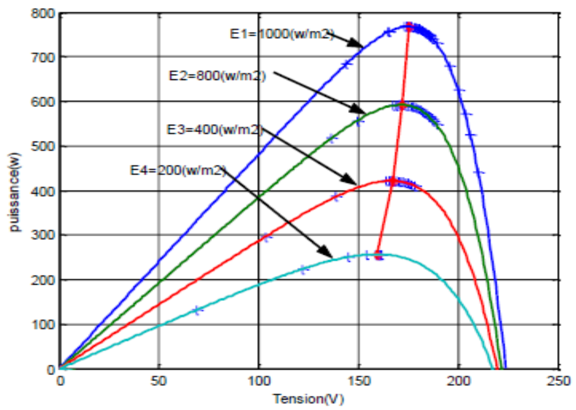

Fig.10(b). Tracking of the Power Point Maximum by (P & O) Algorithm to the Variable Illumination

III. INCREMENTAL CONDUCTANCE(IC)

The incremental conductance method (IC) is based on the fact that the derivative of the output power Ppv with respect to the array voltage Vpv is equal to zero at MPP. The PV array characteristic shows that this derivative is positive to the left of the maximum power point and negative to the right of maximum power point. That is, differentiating the power with respect to voltage and setting the result to zero [5].The equations governing the concept of IC are given below. Fig 13 shows the flow chart.

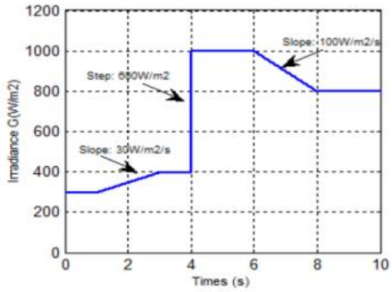

Figure11: Irradiation variation

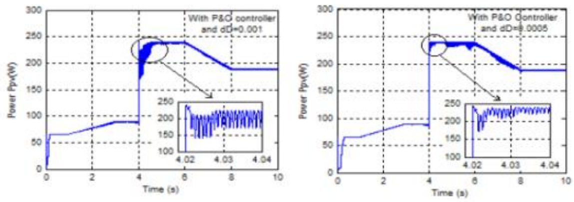

Fig.11. Oscillations around MPP

$$\frac{dP_{fv}}{dV_{fv}} = I_{fv}\frac{dV_{fv}}{dV_{fv}} + V_{fv}\frac{dI_{fv}}{dV_{fv}} = I_{fv} + V_{fv}\frac{dI_{fv}}{dV_{fv}} = 0$$

$$-\frac{I_{fv}}{V_{fv}} = \frac{dI_{fv}}{dV_{fv}}.$$

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \quad \text{at MPP}$$

$$\frac{dI_{pv}}{dV_{pv}} > -\frac{I_{pv}}{V_{pv}} \quad \text{to the left of MPP}$$

$$\frac{dI_{pv}}{dV_{pv}} < -\frac{I_{pv}}{V_{pv}} \quad \text{to the right of MPP} \tag{4}$$

There are two main different IC methods available in the literature. The classic IC algorithm (ICa) requires the same measurements in order to determine the perturbation direction: a measurement of the voltage *VPV* and a measurement of the current *IPV*. The Two-Model MPPT Control (ICb) algorithm combines the Constant Voltage method (CV) and the ICa methods: if the irradiation is lower than 30% of the nominal irradiance level, the CV method is used, other way the ICa method is adopted. This method requires the solar irradiation as *additional* measurement.

The main *advantage* of IC is that it gives good yield in rapidly varying environmental conditions. It also achieves lower oscillation around MPP that P&O. The *disadvantage* is that the control circuit required is more complicated.

Results:

According to [4],[10]: the algorithm shown in the flow chart was converted to a program and the MATLAB simulation results are shown. Fig.12 (a, b) shows the performance of IC based on illumination and absolute error. The performance is better under higher illumination. Compared to P&O, the time response is lesser and average power is more. Ripple amplitude is also lesser [10].

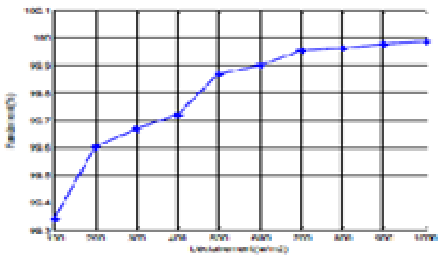

Fig. The Variation of Performance Based on Illumination

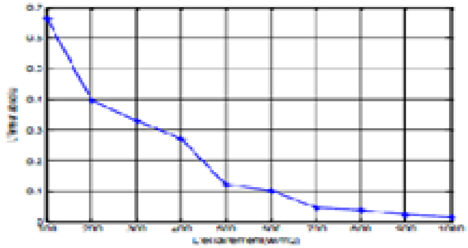

Fig. The Variation In the Absolute Error Depending on The Illumination

Fig.12(a). Performance of IC

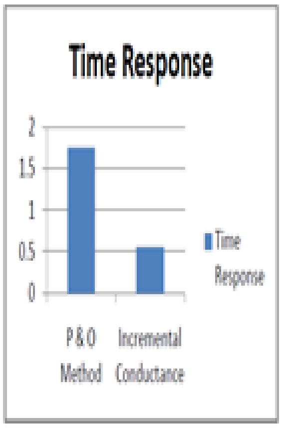

Figure : Comparison of Time Response of different MPPT techniques

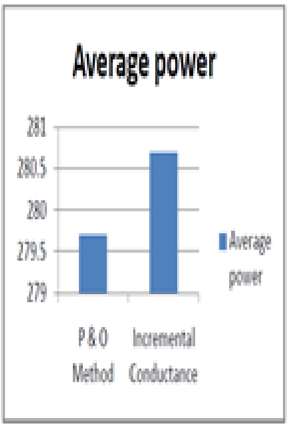

Figure : Comparison of Average Power of different MPPT techniques

Fig.12(b). Performance of IC

IV. FRACTIONAL OPEN CIRCUIT VOLTAGE METHOD(FOCV)/ CONSTANT VOLTAGE METHOD (CV)

This method uses the approximately linear relationship between the MPP voltage (*VMPP*) and the open circuit voltage (*VOC*), which varies with the irradiance and temperature:

$$V_{MPP} \approx k_1 V_{OC} \quad (5)$$

Where *k*1 is a constant depending on the characteristics of the PV array, fabrication technologies and it has to be determined beforehand by determining the *VMPP* and *VOC* for different levels of irradiation and different temperatures. According to [11], the constant *k*1 has been reported to be between 0.71 and 0.78. The range between 0.78 and 0.92 is also reported [8].

This method is recommended when the solar insolation and temperature variations are insignificant. The MPP voltage at different irradiance is assumed approximately constant. The *disadvantage* is, to measure *VOC* the power converter has to be shut down momentarily so in each measurement a loss of power occurs. It is incapable of tracking the MPP under irradiation slopes, because the determination of *VMPP* is not continuous. MPP reached is not the real one because the relationship is only an approximation.

To overcome this, pilot cells can be used to obtain *VOC*. They are only used for obtaining parameters. But, the cost of the system is increased. This method is not suitable for partial shading conditions [7]. The *advantage* is that the circuit is simple and inexpensive. According to [12], Fig.14 shows the flow chart.

Results:

As per MATLAB analysis in [4], the comparison between the methods illustrated so far is shown in Fig 15. The average values of performance are also 98.2273%, 99.193%, and 99.7981% for FOCV, P&O and IC methods respectively. Blue, red and black curves represent FOCV, P&O, and IC methods respectively. FOCV can be used under constant irradiation and temperature conditions. IC method is reported to be better than FOCV and P&O [4].

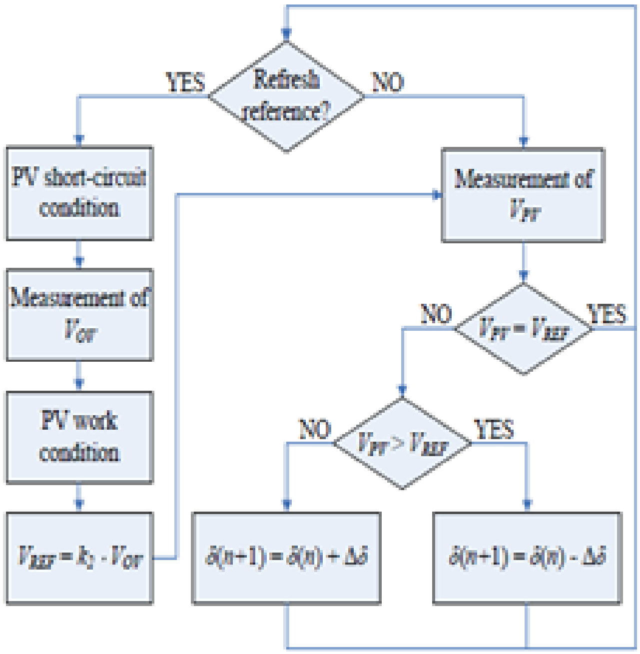

Fig.14. Flow chart for Open voltage method

V. FRACTIONAL SHORT CIRCUIT CURRENT METHOD(SC)

Fractional short circuit current results from the fact that, under varying atmospheric conditions, *Impp* is approximately linearly related to the *Isc* of a PV array thus,

$$Impp \approx K2 \times Isc \quad (6)$$

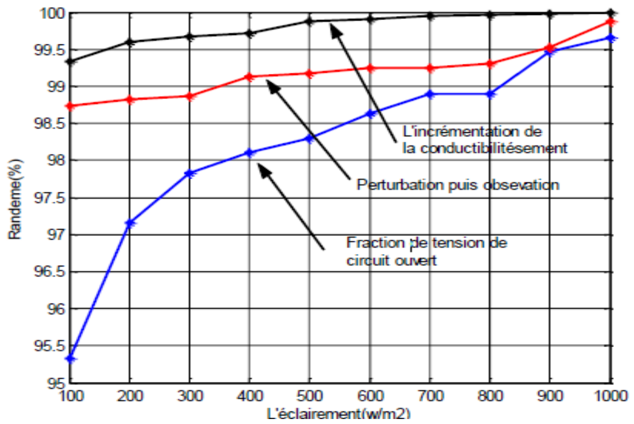

Fig.15. Comparison of PO, IC & CV methods

Where K2 is proportionality constant, just like in the fractional *Voc* technique, K2 has to be determined according to the PV array in use. The value of K2 is found to be 0.78 and 0.92 [13]. It is also reported to vary between 0.64 and 0.85 [8]. Fig.16 shows the flow chart. Measuring the short circuit current is a problem. The PV array has to be shorted periodically by using a switch across the terminals. This leads to loss of power. Further K2 also changes under partial shading. The control used for tuning K2 under such conditions makes the circuit complex [7]. This method has not been chosen frequently as the earlier methods for analysis and simulation, hence less significant.

Result:

According to [12], it has been reported as one of the poorly performing techniques for MPPT.

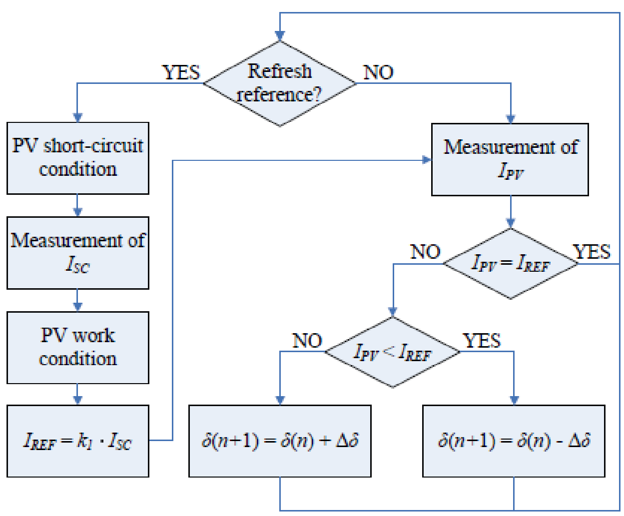

Fig.16. Flow chart of SC method

VI. PARTICLE SWARM OPTIMIZATION(PSO)

The PSO method is a simple and effective meta-heuristic approach that can be applied to a multivariable function optimization having many local optimal points. The PSO uses several cooperative agents and each agent shares the information attained by each individual during the search process. Here PSO initializes the variables randomly in a given space. The number of decision variables determines the dimension of space. Each optimization problem is to search the solution space of a particle, each particle runs at a certain speed in the search space, the speed of particles is in accordance with its own flight experience and flight experience of other examples with dynamic adjustments. In the optimization space, each particle has decided to adapt the objective function value, and recorded their own best position Pi found so far, and the entire group of all particles found in the best position Pg [14].

Velocity and position update formula are as follows.

$$x_{k+1}^{i} = x_{k}^{i} + v_{k+1}^{i}$$

$$v_{k+1}^{i} = v_{k}^{i} + c_1 r_1 (p_k^i - x_k^i) + c_2 r_2 (p_k^g - x_k^i) \qquad (7)$$

Where

x_k^i - Particle position

v_k^i - Particle velocity

p_k^i - Best "remembered" individual particle position

p_k^g - Best "remembered" swarm position

c_1, c_2 - Cognitive and social parameters

r_1, r_2 - Random numbers between 0 and 1

Algorithm for PSO:

Step 1- Set the number of particles and searching parameters along with the limit for position and velocity

Step 2- Randomly initialize Position and velocity of each particle.

Step 3- Compute the fitness value of each particle.

Step 4- The particle having the best fitness value is set as Gbest (Global Best).

Step 5- Update the position and velocity of each particle with respect to the Gbest.

Step 6- Repeat Step 3 & 4 till the optimum solution is reached.

Step 7- Gbest at the end of the last iteration gives the optimized value.

Step 8- Compute the Duty-cycle.

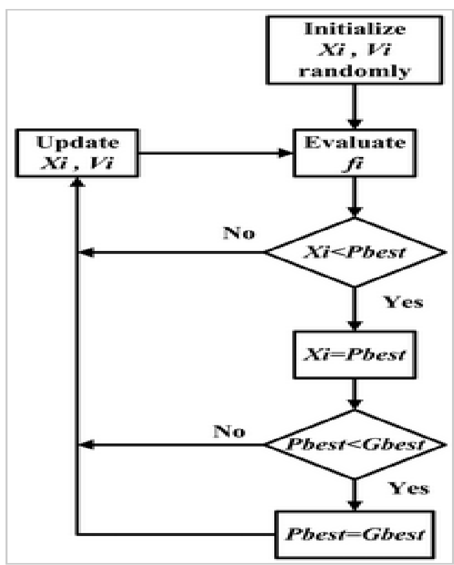

Fig.17. Simple PSO flow chart

This method is modeled after the behavior of bird flocks. The PSO algorithm maintains a swarm of individuals (called particles), where each particle represents a candidate solution. Many local maxima may exist under partial shading conditions. The advantage of PSO is that it helps to track the global maximum and escapes from the many existing local maximums. Thus all the particles attain the global best solution. It also tracks without oscillations around MPP.

Results:

According to [15], MATLAB simulation has been done for P&O, IC and PSO methods. The theoretical maximum power is 60W. The power tracked by PSO is 60.7W, by IC is 59.89W, and by P&O is 59.7W, the lowest. PSO method is faster than other methods in tracking. The efficiency of PSO is higher than P&O and IC at lower irradiation (200KW/m^2). The results highlight that the tracking efficiencies of the systems with PSO in all conditions is higher than 99.8%. The tracking of P&O is poorer than IC. The Fig.18 & Fig.19 show performance of PSO under low and varying irradiation.

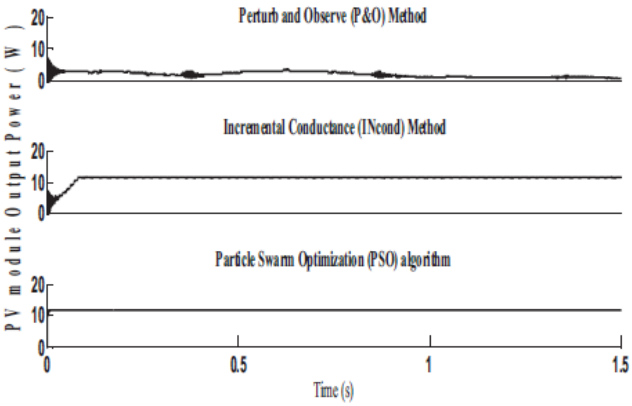

Fig.18. MATLAB simulation under low irradiation (200KW/m^2, 25°C)

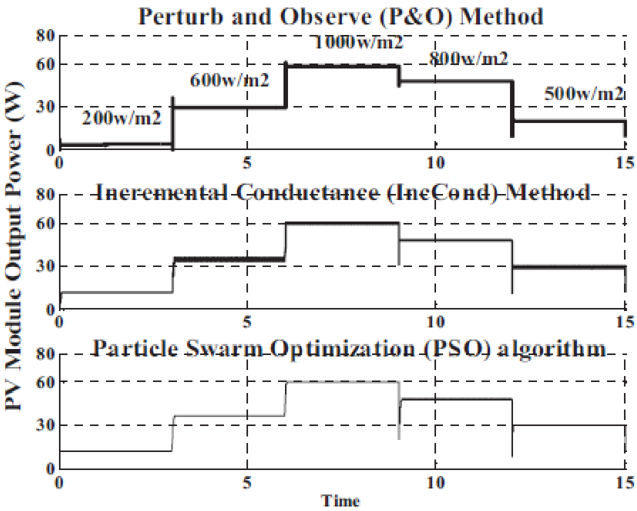

Fig.19. Simulation under varying irradiation, 25°C

VII. CONCLUSION

The techniques that have been presented in this paper are P&O, IC, FOCV, SC and PSO methods. Conclusions regarding these techniques are given in Table I. PSO, an intelligent control technique, has turned out to be the most optimized technique which helps to utilize the PV array effectively, given the cost of the panel is high. Though the complexity and cost are high, this technique can be used under partial shading conditions. Over 26 methods have been specified in [8]. In [7], it has been reported that over 30 methods have already been studied. Many other techniques like Fuzzy logic, Neural networks, exist in literature. Their study is beyond the scope of this paper.

Table I. Comparison of MPPT techniques

Technique	Efficiency	Convergence speed	Oscillations	Cost	Implementation complexity	Comments
Perturb and Observe	Medium	Varies	Present	Lesser than IC	Low	Voltage, current sensed
Incremental conductance	Better than P&O	Varies	Lesser than P&O	Expensive	Medium	Voltage, current sensed
Fractional open circuit voltage	Poor	Medium	Depends on conditions	Inexpensive	Low	Voltage sensed. Efficient under constant atmospheric conditions
Fractional short circuit current method	Poor	Medium	Depends on conditions	Inexpensive	Medium	Current sensed. Power loss.
Particle Swarm optimization	Maximum (99.8%)	Fast	No Oscillations	Expensive	Medium	Multivariable. Effective for Partial shading.

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