Modeling and Simulation of PV Array and its Performance Enhancement Using MPPT (P&O) Technique

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***Abstract* – The renewable energy will be an increasingly important part of power generation in the new millennium. Photovoltaic (PV) systems produce DC electricity when sunlight shines on the PV array, requiring little maintenance, and emitting no noise, among others. Day-by –day the energy demand is increasing and thus the need for a renewable source that will not harm the environment are of prime importance. The proposed model uses basic circuit equation of the photovoltaic solar cells including the effects of solar irradiation and temperature changes. The DC-DC converter is used for boosting a low voltage of the PV array up to the high dc bus voltage, which is not less than grid voltage level. A DC-DC converter performs the Maximum Power Point Tracking (MPPT). In photovoltaic systems for getting the maximum power we use MPPT techniques. In these methods open circuit voltage method is one, which is based on the observation that the voltage of the maximum power point is always close to a fixed percentage of the open circuit voltage. This technique uses only 76% of the open circuit voltage as the optimum operating voltage. The Perturb and Observe (P&O) method operates by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage or current and comparing the PV output power with that of the previous perturbation cycle. The proposed Perturb and Observe control algorithm is a software programme with a self-tuning function which adjusts the array reference voltage and step size of the voltage to achieve maximum power point. The validity of the photo voltaic module with P & O method allows better performance of MPPT due to variation of both power and voltage. This work is proposed to be carried out in MATLAB/SIMULINK environment.**

***Key Words:* Photovoltaic system, Boost converter, Maximum power point tracking, and modeling of PV arrays.**

I. INTRODUCTION

THE Renewable energy will be an increasingly important part of power generation in the new millennium. Distributed resources can provide benefits that bulk power generation can not. PV systems are ideally suited for distributed resource applications. Photovoltaic (PV) systems produce DC electricity when sunlight shines on the PV array, without any emissions. Photovoltaic (PV) generation is becoming increasingly important as a renewable source since it offers many advantages such as incurring no fuel costs, not being polluting, requiring little maintenance, and emitting no noise, among others. PV modules still have relatively low conversion efficiency therefore controlling maximum power Point tracking (MPPT) for the solar array is essential in a PV system. The amount of power generated by a PV depends on the operating voltage of the array. A PV's maximum power point (MPP) varies with solar insulation and temperature. As the energy demand and the environmental problems increase, the natural energy sources have become very important as an alternative to the conventional energy sources. Due to the capability of PV cells converting light directly to electricity has stimulated new research areas on PV cells so that the PV array applications have emerged as an important solution to the growing energy crisis since mid 1970's. Although the solar cell prices very expensive at the beginning, they have become cheaper during last decade due to developing manufacturing process, so that it is expected that the electricity from PV arrays will be able to compete with the conventional ones by the next decade.

Since a PV array is an expensive system to build, and the cost of electricity from the PV array systems is more expensive compared to the price of electricity from the utility grid, the user of such an expensive system naturally wants to use all of the available output power. Therefore, PV array systems should be designed to operate at their maximum output power levels for any temperature and solar irradiation level at all the time. The performance of a PV array system depends on the operating conditions as well as the solar cell and array design quality. The proposed MPPT Perturb and Observe (P&O) method is analyzed. Many techniques that are available mainly vary in many aspects including simplicity, convergence speed, hardware implementation, sensors required, and cost. In these methods open circuit voltage method is one, which is based on the observation that the voltage of the maximum power point is always close to a fixed percentage of the open circuit voltage. This technique uses only 76% of the open circuit voltage as the optimum operating voltage. The main drawbacks in this method are energy generated by PV system is less, additional power components are required and a static switch is needed in open circuit voltage method so the cost will increase.

These problems can be overcome by the Perturb and Observe method. This method operates by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage or current and comparing the PV output power with that of the previous perturbation cycle. If the PV array operating voltage changes and power increases, the control system moves the PV array operating point in that direction, otherwise the operating point is moved in opposite direction. In the next perturbation cycle the algorithm continuous in the same way. The advantages of P &O method are easy to implement, control scheme is simple, and the cost is less compare to other techniques and give high output power. The proposed Perturb and Observe control algorithm is a software program with a self-tuning function which adjusts the array reference voltage and step size of the voltage to achieve maximum power point. The validity of the photo voltaic module with P & O method allows better performance of MPPT due to variation of both power and voltage. This work is proposed to be carried out in MATLAB/SIMULINK environment.

The paper is organized in the following way. Section II presents the entire system configuration, the components that are used. Section III presents the Mathematical modeling of PV array, the Maximum Power Point Tracker and the Perturb and Observe (P&O) Control Technique, and analyzing the boost converter is discussed in Section IV. Finally, conclusions are made in SectionV.

II .SYSTEM CONFIGURATION

The PV array develops the power from the solar energy directly and its output changes depending upon the temperature and irradiance. So we are controlling this to maintain maximum power at the output side. We are boosting the voltage by controlling the current of the array with the use of a PI controller. By depending on the boost converter the output AC voltage changes and it finally connects the utility grid for various applications. The system configuration is shown in fig.1

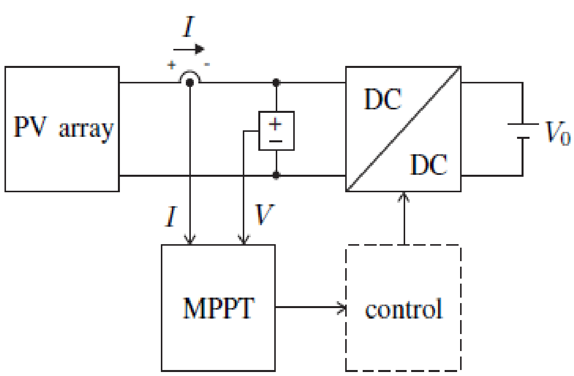

Fig.1 System Configuration

The fig 1 shows a PV system where the PV array feeds the DC-DC converter.The output of the converter is represented by a constant DC voltage source. This kind of converter with constant output voltage may be used in battery charging systems or in systems with a second cascaded conversion stage (DC-AC). The output power of the PV array is regulated by the converter. The MPPT block observes the power at the terminals of the array and controls the input voltage or the input current of the converter forcing the PV array to operate at the maximum power point.

III. MATHEMATICAL MODELING OF PHOTOVOLTAIC ARRAY

The PV receives energy from sun and converts the sun light into DC power. The PV array consists of a number of solar cells, which are connected in series and parallel to achieve the required voltage and current. We can substitute PV cell by equivalent electric circuit where is included a power supply and a diode. If we connect a resistive load R to cell then working point of cell will be on crossing point volt-ampere characteristic of cell and load characteristic. The simplified equivalent circuit model is as shown in fig.1. The PV cell output voltage is a function of mathematical equation of the photocurrent that mainly determined by load current depending on the solar irradiation level during the operation. The equation is:

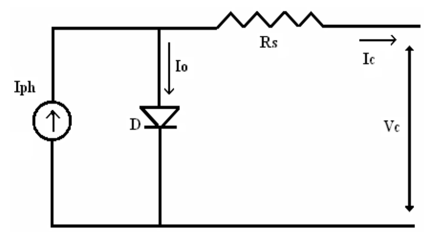

Fig.2. Simplified – equivalent Circuit of Photovoltaic Cell

$$V_{c}=(AKT_C/e) * \ln((I_{ph}+I_o-I_c)/I_O)-R_s I_c \qquad (1)$$

Where the symbols are defined as follows:

e: electron charge (1.602 × 10-19 C).
k: Boltzmann constant (1.38 × 10-23 J/^{0}K).
Ic: cell output current, A.
Iph: photocurrent, function of irradiation level and junction temperature (5 A).
I0: reverse saturation current of diode (0.0002 A).
Rs: series resistance of cell (0.001 Ω).
Tc: reference cell operating temperature (20 °C).
Vc: cell output voltage, V.

Both k and T_C should have the same temperature unit, either Kelvin or Celsius. The curve fitting factor A is used to adjust the I-V characteristics of the cell obtained from the actual characteristics obtained by testing. Hence, the effects of the changes in temperature and solar irradiation levels should also be included in the final PV array model. When the ambient temperature and irradiation levels change, the cell operating temperature also changes, resulting in a new output voltage and a new photocurrent value. The solar cell operating temperature varies as a function of solar irradiation level and ambient temperature. The variable ambient temperature Ta affects the cell output voltage and cell photocurrent. These effects are represented in the model by the temperature coefficients C_{TV} and C_{TI} for cell output voltage and cell photocurrent, respectively, as

$$C_{TV} = 1 + \beta_T (Ta - T_X) \quad (2)$$

$$C_{TI} = 1 + \gamma_T / S_C \ (T_X - T_a) \quad (3)$$

Where, β_T=0.004 and γ_T=0.06 for the cell used and T_a=20°C is the ambient temperature during the cell testing. This is used to obtain the modified model of the cell for another ambient temperature T_X. Even if the ambient temperature does not change significantly during the daytime, the solar irradiation level changes depending on the amount of sunlight and clouds. If the solar irradiation level increases from S_{X1} to S_{X2}, the cell operating temperature and the photocurrent will also increase from T_{X1} to T_{X2} and from I_{Ph1} to Iph2, respectively. Thus the change in the operating temperature and in the photocurrent due to variation in the solar irradiation level can be expressed via two constants, C_{SV} and C_{SI}, which are the correction factors for changes in cell output voltage V_C and photocurrent Iph, respectively,

$$C_{SV} = 1 + \beta_T \alpha_S (S_X - S_C) \quad (4)$$

$$C_{SI} = 1 + 1/S_C \ (S_X - S_C) \quad (5)$$

Where S_C is the benchmark reference solar irradiation level during the cell testing to obtain the modified cell model. The temperature change, ΔT_C occurs due to the change in the solar irradiation level and is obtained using

$$\Delta T_C = \alpha_S (S_X - S_C) \quad (6)$$

The constant α_S represents the slope of the change in the cell operating temperature due to a change in the solar irradiation level and is equal to 0.2 for the solar cells used. Using correction factors C_{TV}, C_{TI}, C_{SV} and C_{SI}, the new values of the cell output voltage V_{CX} and photocurrent I_{PHX} are obtained for the new temperature T_X and solar irradiation S_X as follows**,**

$$Vcx = C_{TV} C_{SV} V_C \quad (7)$$

$$I_{phx} = C_{TI}\ C_{SI}\ I_{ph} \quad (8)$$

V_C and I_{PH} are the benchmark reference cell output voltage and reference cell photocurrent, respectively. The resulting I-V and P-V curves for various temperature and solar irradiation levels were discussed The effects of the temperature and solar irradiation levels are represented by two variables gains. They can be changed by dragging the slider gain adjustments of these blocks named as variable temperature and variable solar irradiation. The effects of the changing temperature and solar irradiation level are modeled inside the block called Effect of Temperature & Solar Irradiation. The output power from PV is the result from multiplying PV terminal voltage and PV output current. The power output from PV modules is shown in equation (9).

$$P_C = V_C[I_{ph} - I_o * e\text{^}((q/KT)*V_C - I_o)] \quad (9)$$

$$I_C = I_{ph} - I_o * e\text{^}((q/KT)*V_C - I_o)) \quad (10)$$

IV. Maximum Power Point Tracking Control

A. *Maximum Power Point Tracker (MPPT)*

The proposed integrated Maximum Power Point Tracker (MPPT) has been used to force the PV array to work around the maximum power point. For this reason, the MPPT is required to track the maximum power available in the PV array.
The need for Maximum Power Point tracking is the power output of the Solar PV module changes with the change in solar insolation level and the atmospheric temperature. There is a single maxima of power, that is there exists a peak power corresponding to particular voltage and current. As the module operates at low efficiency, it is desirable to operate the module at its peak power point so that the maximum power can be delivered to the load under varying irradiance and temperature conditions. Hence, maximization of power improves the utilization of the solar PV module.

The tracking algorithm works based on the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point as shown in fig.3

$$\partial P / \partial V = 0 \text{ for } V = V_{mp} \quad (11)$$

$$\partial P / \partial V > 0 \text{ for } V < V_{mp} \quad (12)$$

$$\partial P / \partial V < 0 \text{ for } V > V_{mp} \quad (13)$$

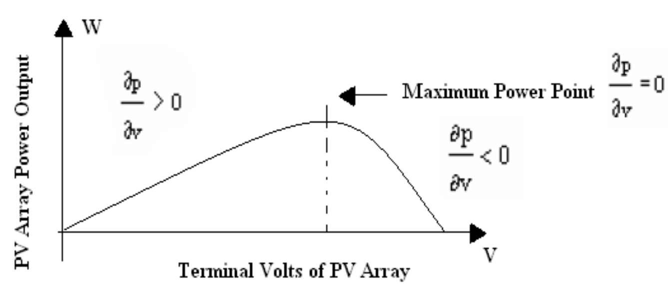

Fig.3 P-V Characteristics of a module

The module P-V characteristics are shown on fig.3 shows the derivative greater than zero to the left of the peak point and is less than zero to the right. The peak power is reached with the help of a dc/dc converter by adjusting its duty cycle. An automatic tracking can be performed by utilizing various algorithms such as Perturb and Observe (P&O), Incremental Conductance, Open Circuit Voltage, Short Circuit Current. We mainly concentrate on the P&O algorithm.

B. Perturb and Observe (P&O) Control Technique

The perturb and observe(P&O), as the name itself states that the algorithm is based on the observation of the array output power and on the perturbation (increment or decrement) of the power based on increments of the array voltage or current. The algorithm continuously increments or decrements the reference current or voltage based on the value of the previous power sample. The P&O is the simplest method which senses the PV array voltage and the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't step at the MPP and keeps on perturbing in both the directions.

The P&O algorithm states that when the operating voltage of the PV panel is perturbed by a small increment, if the resulting changes in power ΔP is positive, then we are going in the direction of MPP and we keep on perturbing in the same direction. If ΔP is negative, we are going away from the direction of MPP and the sign of perturbation supplied has to be changed

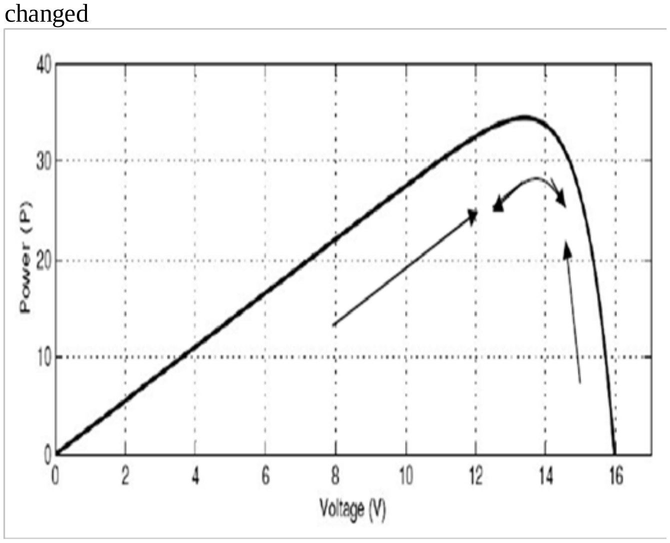

Fig.4 Perturb and Observe Algorithm

The operation of the P&O technique is shown in fig 4 analyses the plot of module output power versus voltage for a solar panel. The P&O algorithm operates by periodically perturbing the array terminal voltage or current and comparing the PV output power with that of the previous perturbation cycle. First a slight perturbation is introduced in the system, due to which the power of the module changes. If the power increases due to perturbation then the perturbation is continued in that direction. After the peak power is reached, the power at the next instant decreases and hence after that the perturbation is reversed.

The P&O method has slow dynamic response, when there is a small increment in the value and low sampling rate is employed. Low increments are necessary to decrease the steady state error because the P&O always makes the operating point oscillate near the MPP. The lower the increment, the closer the system will be to the array MPP. The greater the increment, the faster the algorithm will work, but the steady state error will be increased. Considering that a low increment is necessary to achieve a satisfactory steady state error, the algorithm speed may be increased with a higher sampling rate. So there is always a compromise between the increment and the sampling rate in the P&O method.

The common problem in P&O algorithms id the array terminal voltage is perturbed every MPPT cycle: therefore when the MPP is reached, the output power oscillates around the maximum, resulting in power loss in the PV system. This is especially true in constant or slow-varying atmospheric conditions.

As shown in fig.5 the P&O algorithm operates by periodically perturbing the operating voltage and comparing it with the previous instant. If the power difference ΔP and the voltage difference ΔV, both in the positive direction then there is an increase in the array voltage. If either the voltage difference or the power difference is in the negative direction then there is a decrease in the array voltage. If both the voltage and power difference are in the negative direction then there is a increase in the array voltage. Similarly the next cycle is repeated until the Maximum Power Point is tracked

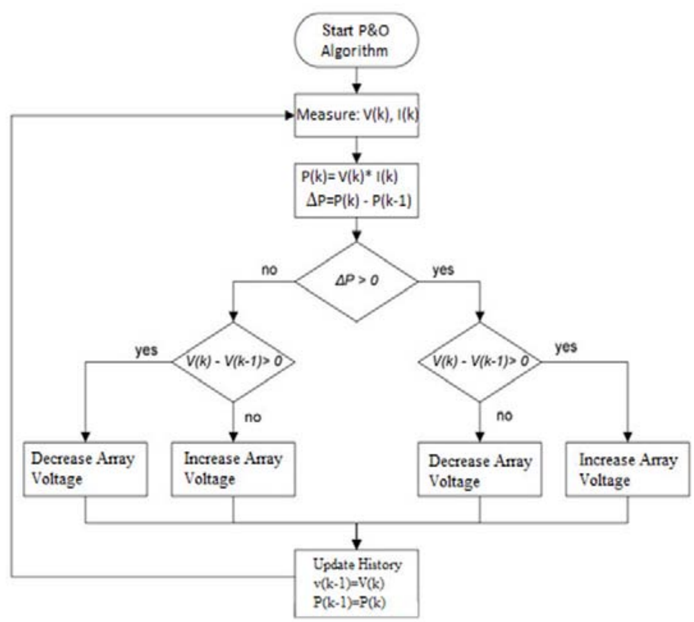

Fig.5 Flowchart of Perturb and Observe (P&O) Control Technique

The Fig.6 shows that the PV array has been interfaced with the boost converter using a controlled voltage source. The inductor current which is same as the load current of the PV system is used as feedback for designing the PV array. The output of the filter which is the control signal is compared with the saw-tooth waveform to generate the PWM signal which is fed as gate signal to the switch S.

The output current of the PV array and the converter inductor current are same, so the MPPT algorithm can observe the array output power and optionally use the converter inductor current as the control variable. A comparison between actual and reference values for PV terminal voltage and maximum power available from PV array will control the duty ratio of boost converter.

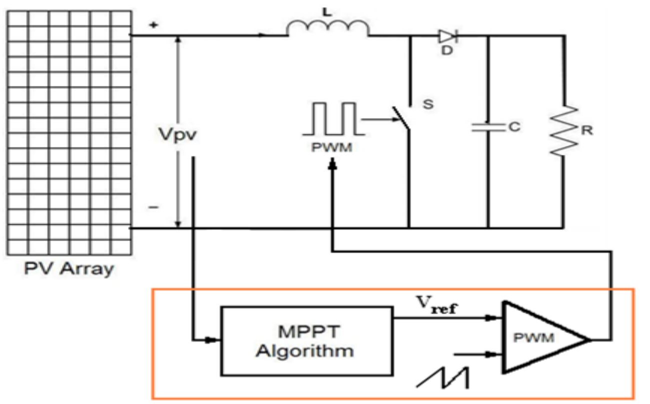

Fig.6 Perturb and Observe (P&O) MPPT

The MPPT of photovoltaic power generation systems changes with changing atmospheric conditions, an important consideration in the design of efficient PV systems is to track the MPP correctly. The dependence of power generated by a PV array and its MPPT on atmospheric conditions can readily be seen in the current-voltage and the power-voltage characteristics of PV arrays. Moreover, the MPPT changes with changing radiation and temperature, implying continuous adjustment of the array terminal voltage if maximum power is to be transferred.

C. Boost Converter

DC-DC Converters are used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage. The regulation is normally achieved by a PWM at a fixed frequency and the switching device used is a MOSFET. As 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-DC Converter is required.

The boost converter is which boosts the voltage to maintain the maximum output voltage constant for all the conditions of temperature and solar irradiance variations. A simple boost converter is as shown in fig.7.

For steady state operation, the average voltage across the inductor over a full period is zero. The input voltage Vd=Vin

$$V_{in}*t_{on} - (V_o-V_{in})t_{off} = 0 \quad (14)$$

Therefore,

$$V_{in}*D*T = (V_o-V_{in})\ (1\text{-}D)\ T \quad (15)$$

$$V_o/V_{in}=1/1\text{-}D \quad (16)$$

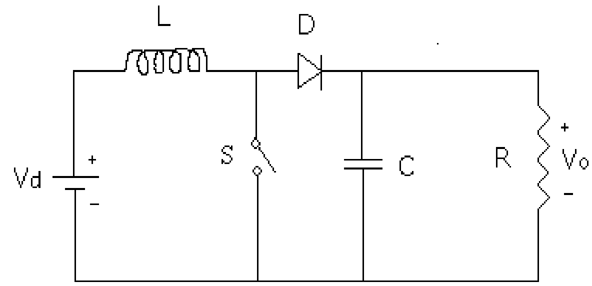

Fig.7. Boost Converter Topology

By designing this circuit we can also investigate performance of converters which have input from solar energy. A boost regulator can step up the voltage without a transformer. Due to a single switch, it has a high efficiency. The input current is continuous. The output voltage is very sensitive to changes in duty cycle D in equation (16). The average output current is less than the average inductor current by a factor of (1-D), and a much higher rms current would flow through the filter capacitor.

If the boost converter operates in continuous conduction mode (CCM), then the value of inductance L from the inductor current ripple analysis is given by equation (17)

$$L_{min}=(1\text{-}D)^2 *D*R/2*f \quad (17)$$

The current supplied to the output RC circuit is discontinuous. Thus a large filter capacitor is used to limit the output voltage ripple. The filter capacitor must provide the output dc current to the load when the diode D is off.

The minimum value of filter capacitance that results in voltage ripple V_r=deltaV_O/V_O is given by equation (18)

$$C_{min}=D/\ R*f*V_r \quad (18)$$

The working of the boost converter when the switch S is in ON state the current in the boost inductor increases linearly and the diode is off. The inductor is charged from the input voltage source V_{in} and the capacitor discharges across the load. When the switch S is in OFF state the energy stored in the inductor is released through the diode to the output RC circuit. The sum of input voltage and inductor voltage appears as the load voltage V_o.

V. SIMULATION RESULTS

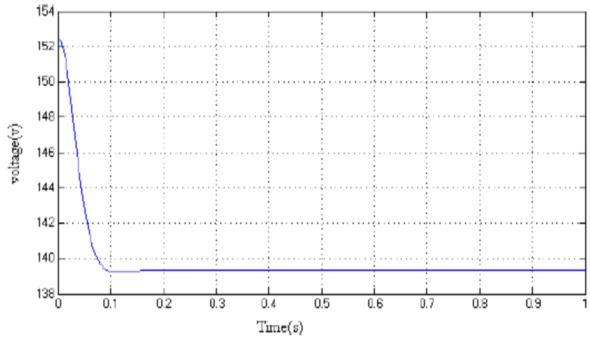

Fig.8 Output Voltage of the PV array

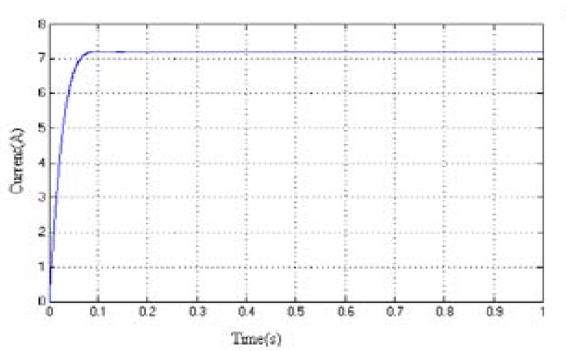

Fig.9 Output Current response of PV array

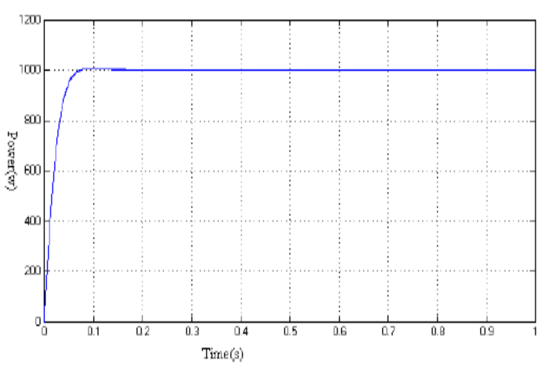

Fig.10 Output Power response of the PV array

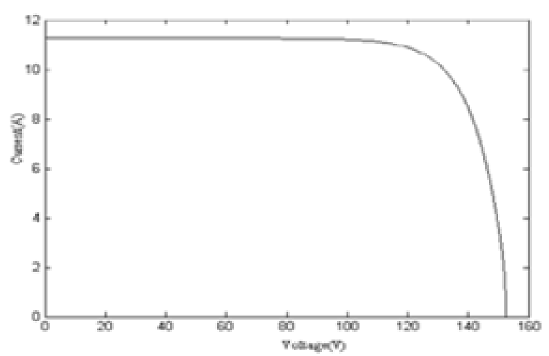

Fig.11 V-I Characteristics curve

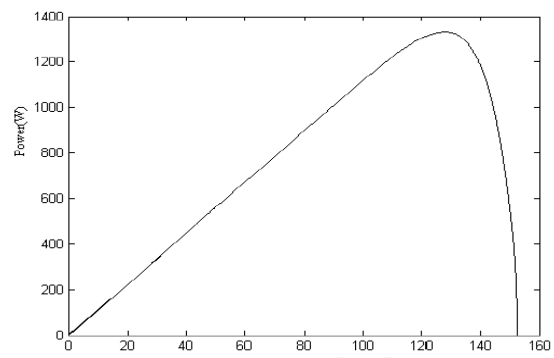

Fig.12 P-V Characteristic curve

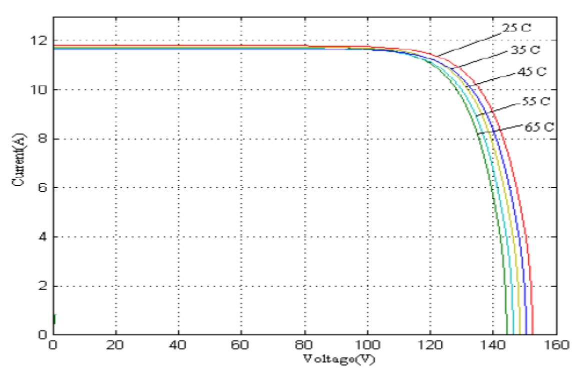

Fig.13 V-I curve with different temperatures

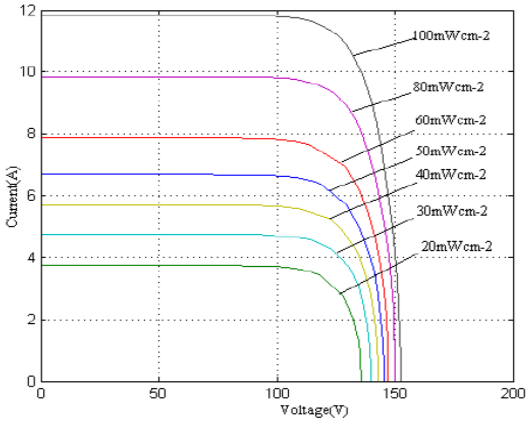

Fig.14 V-I curve with different irradiations

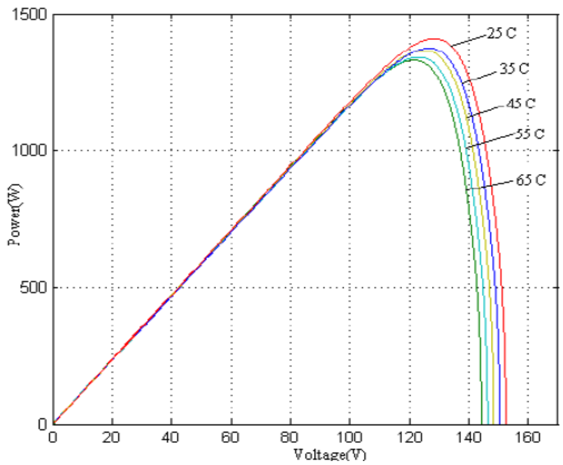

Fig.15 P-V curve with temperature variations

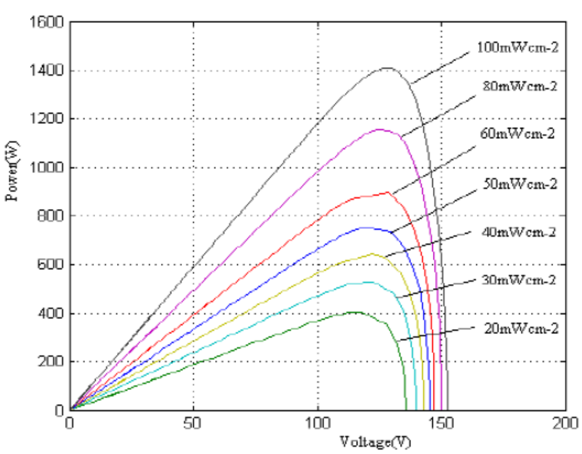

Fig.16 P-V curve with different irradiations

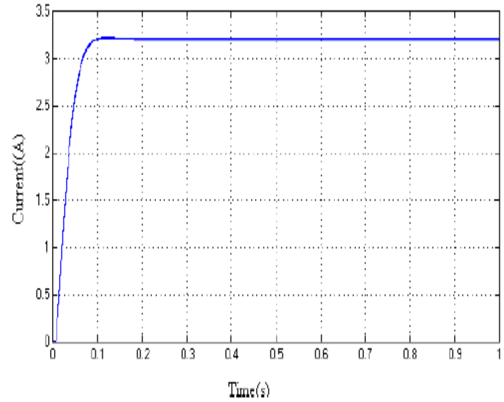

Fig.17 Current Response of Boost Converter

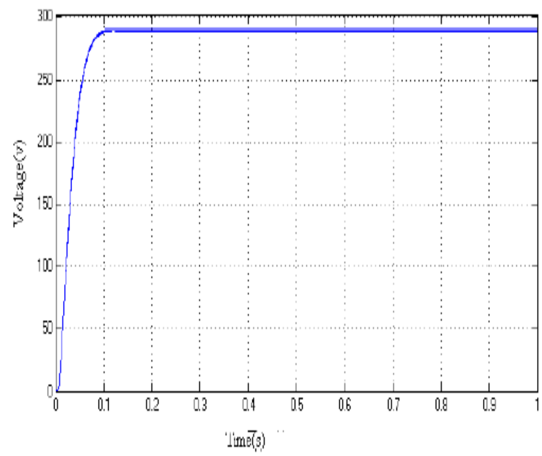

Fig.18 Voltage response of Boost Converter

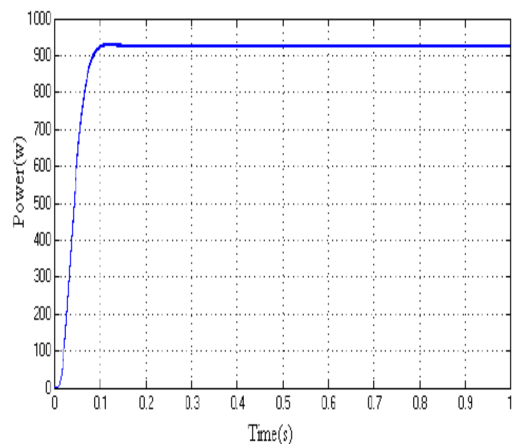

Fig.19 Power response of Boost Converter

IV. CONCLUSION

The paper studies the P&O MPPT algorithm with a DC-DC boost converter. The mathematical modeling of PV array is discussed and the implementation of the MPPT algorithm is done. The P-V and V-I curves obtained from the simulation of the PV array designed in MATLAB environment explains its dependence on the temperature and irradiation levels. Thus, the Photovoltaic system works most of time with maximum efficiency.

VI. ACKNOWLEDGEMENT

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