MATLAB Based Modeling and MPPT using Perturb to Observe Algorithm of PV with Shading Patterns

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ABSTRACT

The aim of this Paper is to study the characteristics of a selected PV module and the factors that affect them that is a MATLAB-based model of a PV module to simulate its characteristics for studying the effect of temperature, solar radiation on the available power. I–V and P–V characteristics of large photovoltaic (PV) arrays under partially shaded conditions are characterized by multiple steps and peaks. This makes the tracking of the actual maximum power point (MPP) [Global Peak (GP)] a difficult task. In addition, most of the existing schemes are unable to extract maximum power from the PV array under these conditions. This project proposes standard algorithm to track the global power peak under partially shaded conditions. The proposed algorithm works in conjunction with a dc–dc converter to track the GP. In order to accelerate the tracking speed, a feed forward control scheme for operating the dc–dc converter is also proposed, which uses the reference voltage information from the tracking algorithm to shift the operation toward the MPP. All the observations and conclusions, including simulation and experimental results, will be presented.

With the increasing attention and use of non-conventional energy sources, photovoltaic systems are gaining popularity and large solar farms are getting installed at suitable sites in India. A major challenge in employing the use is that photovoltaic (PV) array has nonlinear output characteristic which vary with the size (number of modules) & configuration (number of modules in series in parallel).The output characteristic is complicated if the array does not receive uniform isolation (partially shaded condition) due to passing clouds, neighboring building & towers, trees, utility and telephone poles as multiple peaks are observed in output characteristic. It is very important to understand and predict the PV characteristics in order to use a PV installation effectively.

Keywords *—GP - Global peak, MPPT - maximum power point tracking, PS -partial shading,*

PV - Photovoltaic. IPV - Solar module output current (A), VPV - Solar module output voltage (V)

INTRODUCTION

SYSTEM MODELLING OF SOLAR PANEL

The entire system has been modeled on MATLAB™ 2009aand Simulink. The block diagram of the solar PV panel is shown in Figure 1 and Figure 2. The inputs to the solar PV panel are temperature, solar irradiation, number of solar cells in series and number of rows of solar cells in parallel.
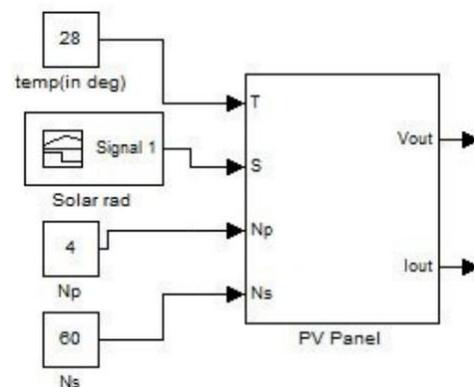

Figure 1 : Masked block diagram of the modeled solar PV panel

The simulation is carried out for a cell surface temperature of 28° C, 60 solar cells in series and 4 rows of solar cells in parallel. The irradiation (shown in Figure 2) is taken to be varying, to reflect real life conditions and effectively show the use of an MPPT algorithm in field runs. It varies from 60 Watt per sq. cm. to 85 Watt per sq. cm, which is close to the day values of solar radiation received on the earth's surface. The simulation is run for a total of 0.12 seconds, with the irradiation taking up a new value every 0.03 seconds and staying constant for the consequent 0.03 seconds.

1. MPPT INTERFACING

The controlled voltage source and the current source inverter have been used to interface the modeled panel with the rest of the system and the boost converter which are built using the Sim Power Systems module of MATLAB. The block diagram for the model shown in Figure is a simulation for the case where we obtain a varying voltage output. This model is used to highlight the difference between the power obtained on using an MPPT algorithm and the power obtained without using an MPPT algorithm. To compare the power output in both the cases stated above, the model is equipped with a manual switch as shown. When the switch is thrown to the left the circuit bypasses the MPPT algorithm and we obtain the desired power, voltage and current outputs through the respective scopes. Contrarily when the switch is thrown to the right, the embedded MPPT function block is included in the circuit and we obtain the desired outputs through the respective scopes.
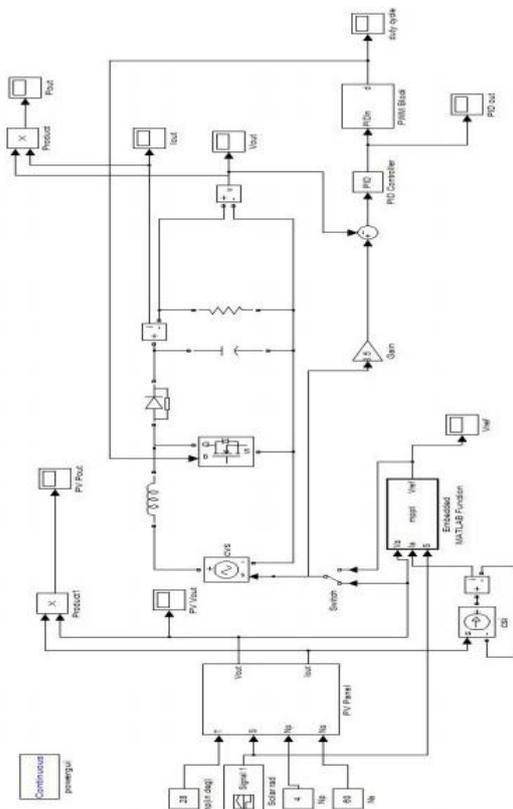

Figure 2: SIMULINK Model of MPPT system using P&O algorithm

2. BOOST CONVERTER

A boost converter has been used in our simulation. It finds applications in various real life scenarios like charging of battery bank, running of DC motors, solar water pumping etc. The simulation has been done for a resistive load of 300Ω. For efficient running of a motor, we should undergo load resistance matching techniques. In the boost converter circuit, the inductor has been chosen to be 0.763 mH and the capacitance is taken to be 0.611 µF for a ripple free current.

3. PI CONTROLLER

The system also employs a PI controller. The task of the MPPT algorithm is just to calculate the reference voltage Vref towards which the PV operating voltage should move next for obtaining maximum power output. This process is repeated periodically with a slower rate of around 1-10 samples per second. The external control loop is the PI controller, which controls the input voltage of the converter. The pulse width modulation is carried in the PWM block at a considerably faster switching frequency of 100 K Hz. In our simulation, K_P is taken to be 0.006 and K_I is taken to be 7. A relatively high K_I value ensures that the system stabilizes at a faster rate. The PI controller works towards minimizing the error between Vref and the measured voltage by varying the duty cycle through the switch. The switch is physically realized by using a MOSFET with the gate voltage controlled by the duty cycle.

PERFORMANCE WITH COMPARISON

A. Perturb and Observe

This method is the most common. In this method very less number of sensors are utilized and the operating voltage is sampled and the algorithm changes the operating voltage in the required direction and samples dP/dV. If dP/dV is positive, then the algorithm increases the voltage value towards the MPP until dP/dV is negative. This iteration is continued until the algorithm finally reaches the MPP. This algorithm is not suitable when variation in the solar irradiation is high. The voltage never the actually reaches an exact value but perturbs around the maximum power point (MPP)

B. Incremental Conductance

The incremental conductance (IncCond), method is based on the fact that the slope of the PV array power curve (Fig.) is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by dP/d = 0, at MPP

dP/dV > 0, left of MPP
dP/dV < 0, right of MPP
ΔI/ΔV = −I/V, at MPP
ΔI/ΔV > − I/V, left of MPP
ΔI/ΔV < − I/V, right of MPP

The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance (ΔI/ΔV). Vref is the reference voltage at which the PV array is forced to operate. At the

MPP, Vref equals to VMPP. Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP. The algorithm decrements or increments Vrefto track the new MPP.

C. Fuzzy Logic Control

Microcontrollers have made using fuzzy logic control popular for MPPT over the last decade. Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling non linearity. Fuzzy logic control generally consists of three stages: fuzzification, rule base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables based on a membership function. In this case, five fuzzy levels are used: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). Seven fuzzy levels are used, probably for more accuracy. The membership function is sometimes made less symmetric to give more importance to specific fuzzy levels. The inputs to a MPPT fuzzy logic controller are usually an error E and a change in error ΔE. The user has the flexibility of choosing how to compute E and ΔE.

D. PI-PPO

The main idea behind this technique is that at the start of any hill climbing technique, large perturb steps are needed to quickly reach the maximum power point and as the maximum power point is approached, the perturb value needs to be decreased to avoid large oscillations around this maximum output power operating point. The P&O techniques are not capable of achieving this target if the perturb value is fixed. Therefore adaptive techniques are better solutions. The adaptive technique utilizes the error between two successive array power signals calculated from the measured array voltage and current signals to create an adaptive perturb.

E. Adaptive Perturb with Sampling Method

The main idea behind the proposed technique is same as that of PI-PPO technique. The proposed adaptive technique utilizes the error between array power signal and next sampled signal calculated from the measured array voltage and current signals to create an adaptive perturb. Therefore, this error can be treated like an error signal in a closed loop system that needs to be minimized at steady state, prevented from overshoot at startup, and free from steady state oscillations.

TABLE NO. 1: COMPARISON RESULTS OF VARIOUS MPPT ALGORITHMS

Method	Voltage Ripples around MPP in V	Maximum Power Output Pm in W	Tracking Time
P & O	0.2	1046.9	More
IncCond	0.2	1046.9	More
PI-PPO	0.02	1046.2	Less
Adaptive Perturb & Sampling	0.004	1048.3	Very Less
FLC	0.3	1049.2	Less
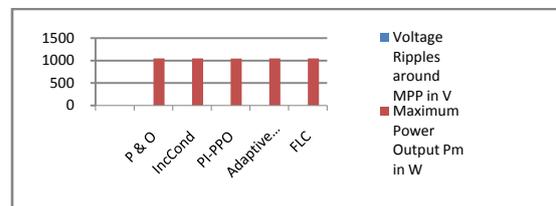
GraphNo.1 : Results showing comparison of various MPPT Algorithms

MATHEMATICAL MODEL OF THE SYSTEM

1. Modeling the Solar Cell:

Thus the simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell. The diode determines the I-V characteristics of the cell. Increasing sophistication, accuracy and complexity can be introduced to the model by adding in turn,

- Temperature dependence of the diode saturation current I_o.
- Temperature dependence of the photo current I_L.
- Series resistance R_S, which gives a more accurate shape between the maximum power point and the open circuit voltage.
- Shunt resistance R_P in parallel with the diode.
- Either allowing the diode quality factor n to become a variable parameter (instead of being fixed at either 1 or 2) or introducing two parallel diodes (one with A = 1, one with A = 2) with independently set saturation currents.
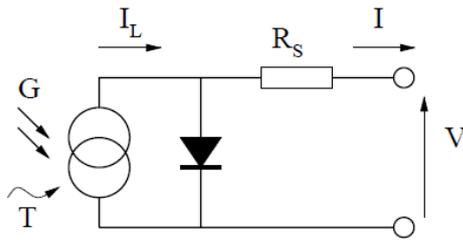
Figure 3: Circuit diagram of the PV model.

For this work, a model of moderate complexity is used. The model included temperature dependence of the photo-current I_L and the saturation current of the diode. A series resistance Rs is included, but not a shunt resistance. A single shunt diode is used with the diode quality factor set to achieve the best curve match. This model is a simplified version of the two diode model. The circuit diagram for the solar cell is shown in Figure.

The equations which describe the I-V characteristics of the cell are,

$$I = I_L - I_0 (e^{q(V + I Rs)/nkT} - 1)$$
………………………………….(1)
$$I_L = I_{L(T1)} (1 + K_0 (T - T1))$$
………………………………… (2)
$$I_{L(T1)} = G * I_{SC (T1, nom)} / G_{(nom)}$$
….……..……………………… (3)
$$K_0 = (I_{SC(T2)} - I_{SC(T1)}) / (T2 - T1)$$
....…………………………….(4)
$$I_0 = I_{0(T1)} * (T/T1)^{3/n} * e^{-qVg/nk*((1/T)-(1/T1))}$$
……………………………(5)
$$I_{0(T1)} = I_{SC(T1)} / (e^{qVOC(T1)/nkT1} - 1)$$
…………....................................(6)
$$R_S = -dV/dI_{VOC} - (1/X_V)$$
……………………………………….…..(7)
$$X_V = I_{0(T1)} * q/nkT1 * e^{qVOC(T1)/nkT1}$$
…………………………………..(8)

Where, Rs: Series resistance on ohms.
q: magnitude of charge on an electron.
k: Boltzman's constant.
I_L: Photo current.
Io: Saturation current of diode.
I: Output current of solar cell.
V: Output voltage of solar cell.
G: Solar irradiance in Sun (1 Sun = 1000 W per m^2)
T: Working temperature in ^{o}K.
T1: Initial standard temperature in ^{o}K.
T2: Final considered temperature in ^{o}K.
I_{sc}: Short circuit current.
V_{oc}: Open circuit voltage.
Ko: Temperature coefficient of Isc.

All of the constants in the above equations can be determined by examining the manufacturer's rating of the PV array, and then the published or measured I-V curves of the array. As a typical

example, the BP Solar 250/1 module will be used to illustrate and verify the model.

The photo-current I_L (A) is directly proportional to irradiance G (W/m^2). When the cell is short circuited, negligible current flows through the diode. Hence the proportionality constant in equation (3) is set so the rated short circuit current I_{SC} at is delivered under rated irradiation (usually 1 Sun = 1000W/m^2).

For the BP Solar 250/1, I_{SC} = 3.22 A at 1 Sun at T1 = 25 ^{o}C (298^{0}K), so $I_{L(T1)}$ = 3.228 A/Sun. The relationship between the photo-current and temperature is linear (eqn. 2) and is deduced by noting the change of photo-current with the change of temperature (eqn. 4). For the BP 250/1, Temperature coefficient of Isc is 0.68 mA/module/°C. When the cell is not illuminated, the relationship between the cell's terminal voltage and current is given by the Shockley equation. When the cell is open circuited and illuminated, the photo-current flows entirely in the diode. The I-V curve is offset from the origin by the photo generated current I_L (eq 1). The value of the saturation current I_0 at 25 ^{0}C is calculated using the open circuit voltage and short circuit current at this temperature (eq 6). An estimate must be made of the unknown "ideality factor". It takes a value between 1 and 2, being near one at high currents, rising towards two at low currents. A value of 1.771 is used in the model.

The relationship of I_O to temperature is complex, but fortunately contains no variables requiring evaluation (eqn 5). The series resistance of the panel has a large impact on the slope of the I-V curve at V = V_{OC}. Equations 7 and 8 are found by differentiating equation 1, evaluating at V = V_{OC}, and rearranging in terms of R_S. For the BP Solar 250/1, a value of total panel series resistance is R_S can be calculated from equation 7.

I)Mathematical Calculation and Results

The BP Solar 250/1, a typical 50W PV module, was chosen for modelling. The module has 36 series connected polycrystalline cells. The key specifications are shown in table. The model was evaluated using MATLAB m file programming. The model parameters at a temperature of 25 ^{0}C are,

TABLE NO. 2: TECHNICAL SPECIFICATIONS FOR BP SOLAR 250/1 MODULE.

Parameter	Value
Typical Peak Power (P_{max})	50 W
Voltage @ maximum power (V_{mp})	17.00 V
Current @ maximum power (I_{mp})	2.94 A
Short-circuit current (I_{sc})	3.22 A
Open-circuit Voltage (Voc)	21.2 V

Parameters are evaluated during execution using the equations listed above using the above

data points contained in the script. The current I is then evaluated using these parameters, and the variables Voltage, Irradiation, and Temperature. If one of the input variables is a vector, the output variable (current) is also a vector. The inclusion of a series resistance in the model makes the solution for current a recurrent equation (refer to eq 1). A simple iterative technique initially tried only converged for positive currents.

The shading pattern for a large array is very complex to model. A special categorization and terminology is used to describe the various components of a PV array. These are explained with the help of figure2.
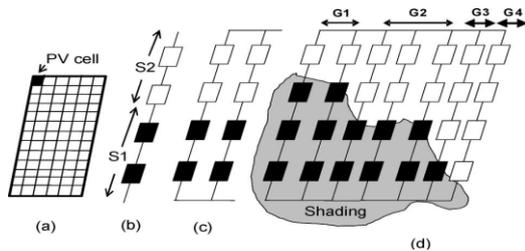

Figure4: PV array terminologies. (a) PV module. (b) Series-assembly with two series-connected subassemblies S1 and S2. (c) Group. (d) PV array with groups G1 to G4.

A "subassembly" is formed with several series-connected PV modules receiving the same level of insolation. Several such series-connected subassemblies, each with a different level of insolation, form a series assembly. Series assemblies, having similar shading patterns, form a "group". Various groups (with ith group represented by "Gi"), having different shading patterns and connected in parallel, form a PV$_{array}$, as shown in figure 2.

Inputs used in the mathematical modelling,
N : Number of assemblies in a group = 10.
Sub_assemblies : Number of sub-assemblies in a group = 1.
n : Number of modules in a sub-assembly = 50.
Temp : temperature for sub-assembly in ^{o}C = 25.
Sun : Shading of each assembly.

Data and constants used in mathematical modelling,
k :Boltzman's constant = 1.380658*10^{-23}.
q : magnitude of charge on an electron = 1.60217733*10^{-19} C.
A : Diode Quality Factor = 1.771. (= 2 for crystalline structure, < 2 for amorphous)
V$_g$: Band gap voltage = 1.12. (1.12 for Silicon, 1.75 for Germanium)
N$_s$: Number of series connected cells (diodes) = 36.
T$_1$: Standard initial temperature in ^{0}K = 273 + 25^{0}C = 298 ^{0}K.

T$_2$: Final initial temperature in ^{0}K = 273 + 75^{0}C = 348 ^{0}K.
V$_{oc}$:Open circuit voltage (21.2 V at temperature T1 and 17.15 V at temperature T2).
I$_{sc}$: Short circuit current (3.22 A at temperature T1 and 3.31 A at temperature T2).
V$_{oc}$_T$_1$:Open circuit voltage at temperature T$_1$ per cell = V$_{oc}$ / N$_s$ = 21.2/36 = 0.5889 V.
V$_{oc}$_T$_2$: Open circuit voltage at temperature T$_2$ per cell = V$_{oc}$ / N$_s$ = 17.15/36 = 0.4764 V.
I$_{sc}$_T$_1$: Short circuit current at temperature T$_1$ per cell = 3.22 A.
I$_{sc}$_T$_2$: Short circuit current at temperature T$_2$ per cell = 3.31 A.
T$_{rk}$: Standard reference temperature in ^{0}K = 273 + 25^{0}C = 298 ^{0}K.

Comparison between analytical and graphical method:
I) Analytical method.
Calculations for mathematical modelling,
T$_{ak}$ = Array working temperature ^{0}K = 273 + Temp = 298 ^{0}K
I$_{ph}$_T$_1$ = I$_{sc}$_T$_1$ * Sun = 3.22 *0.6 = 1.9320.
Now, constant ais to be calculated from I$_{sc}$ versus temperature variation. We know I$_{sc}$ at T$_1$ and T$_2$.

$$a = \frac{I_{sc-T2} - I_{sc-T1}}{I_{sc-T1} \times (T_2 - T_1)} = \frac{3.31 - 3.22}{3.22 \times 50} = 5.5901 \times 10^{-4}$$

and constant b can be calculated as

$$b = \frac{V_g \times q}{A \times k} = \frac{1.12 \times 1.6021 \times 10^{-19}}{1.771 \times 1.380658 \times 10^{-23}} = 7.3388 \times 10^3$$

$$I_{ph} = I_{ph-T1} \times (1 + a \times (T_{ak} - T_1)) = 1.9320 \times (1 + 5.5901 \times 10^{-4} \times (298 - 298)) = 1.9320$$

$$V_{t-T1} = \frac{k \times T_1}{q} = \frac{1.380658 \times 10^{-23} \times 298}{1.6021 \times 10^{-19}} = 0.0257$$

$$I_{r-T1} = \text{Array current at temperature } T_1 = \frac{I_{sc-T1}}{(e^{\frac{(V_{oc-T1})}{(A \times V_{t-T1})}} - 1)} = \frac{3.22}{e^{(\frac{0.5889}{(1.771 \times 0.0257)})} - 1} = 7.6621 \times 10^{-6}$$

$$I_{r-T2} = \text{Array current at temperature } T_2 = \frac{I_{sc-T2}}{(e^{\frac{(V_{oc-T2})}{(A \times V_{t-T1})}} - 1)} = \frac{3.31}{e^{(\frac{0.4764}{(1.771 \times 0.0257)})} - 1} = 9.3462 \times 10^{-5}$$

$$I_r = I_{r-T1} \times (\frac{T_{ak}}{T_1})^{3/A} \times e^{-b \times (\frac{1}{T_{ak}} - \frac{1}{T_1})} = 7.6621 \times 10^{-6} \times (\frac{298}{298})^{3/1.771} \times e^{-7.3388 \times 10^3 \times (\frac{1}{298} - \frac{1}{298})} = 7.6621 \times 10^{-6}$$

$$X2V = \frac{I_{r-T1}}{A \times V_{t-T1}} e^{\frac{(V_{oc-T1})}{(A \times V_{t-T1})}} = \frac{7.6621 \times 10^{-6}}{1.771 \times 0.0257} e^{\frac{(0.5889)}{(1.771 \times 0.0257)}} = 70.8022$$

$$dVdI_{V_{oc}} = -(\frac{1.15}{N_s}) \div 2 = -\frac{1.15}{36} \div 2 = -0.0160$$

This is calculated at Voc per cell from manufacturer's graph.

$R_s = -dVdI_{V_{oc}} - \frac{1}{X2V}$ = $0.0160 - \frac{1}{70.8022} = 0.0019$ This gives series resistance per cell.

$V_{t-T} = \frac{A \times k \times T_1}{q} = \frac{1.771 \times 1.380658 \times 10^{-23} \times 298}{1.6021 \times 10^{-19}} = 0.0455$

Then increment I by 0.001A in each step starting from 0 to Iph to calculate V for each step.

Step 1: I = 0.

$V = (V_{t-T} \times complex\,(\log((Iph - I)/Ir + 1))) - I \times R_s)$ =(0.0455 × $complex\,(\log\frac{1.9320 - 0}{7.6621 \times 10^{-6}} + 1))) - 0 \times 0.0019) = 0.5659$

PV array voltage in volts, Volt = $36 \times V \times n$. = $36 \times 0.5659 \times 50 = \mathbf{1018.7}$

PV array current in ampere, Curr = $I \times N = 0 \times 10 = 0$

PV array power in watts, Power = $Volt \times Curr = 0$

Step 2: I = 0.001.

Calculation of Pm, Vm and Im analytically by the use of Perturb and Observe (P & O) algorithm.

1) Define some change in voltage as C = 1 V and $\Delta P_{critical} = 0$.

2) Take a voltage sample V(k) at k[th] instant and its respective current I(k) from I-V curve. Also calculate P(k) = V(k) * I (k).

3) Find $\Delta P = P(k) - P(k-1)$.

4) If $\Delta P = \Delta Pcritical$, then STOP, else follow the steps,

　　　i) If P(k) > P(k-1) and V(k) > V(k-1), Vref(k) = Vref(k-1) + C.

　　　ii) If P(k) > P(k-1) and V(k) < V(k-1), Vref(k) = Vref(k-1) - C.

　　　iii) If P(k) < P(k-1) and V(k) > V(k-1), Vref(k) = Vref(k-1) - C.

　　　iii) If P(k) < P(k-1) and V(k) < V(k-1), Vref(k) = Vref(k-1) + C.

5) Take V(k) = Vref(k) and go to step 2.

6) At $\Delta P = \Delta P_{critical}$, Vm=Vref(k), corresponding value of current will be Im and Pm = Vm*Im.
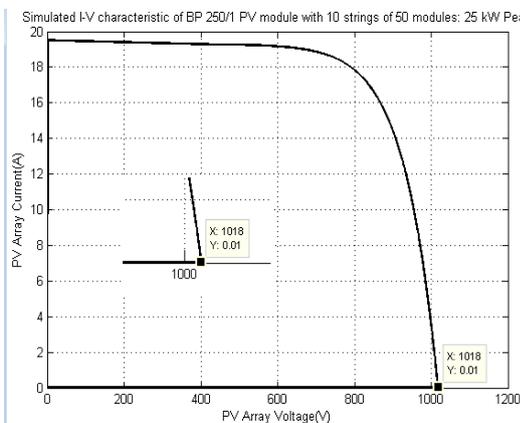
II) GRAPHICAL METHOD.
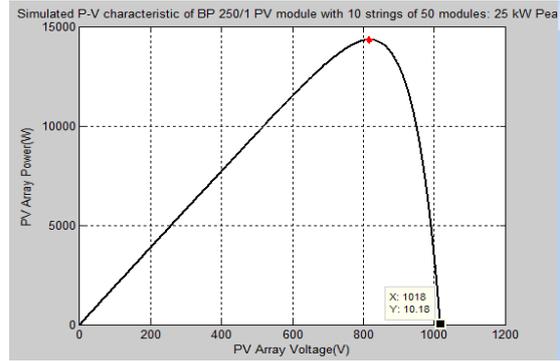

Figure 5: Simulated I-V characteristic

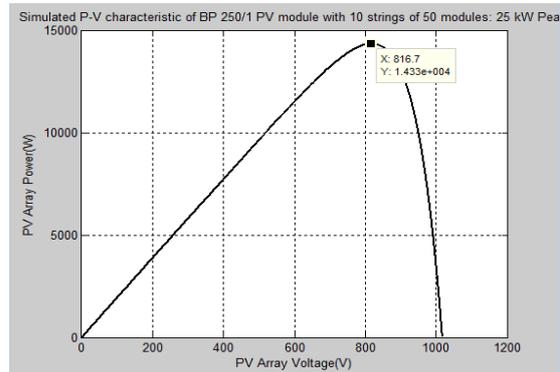Figure 6: Simulated P-V characteristic

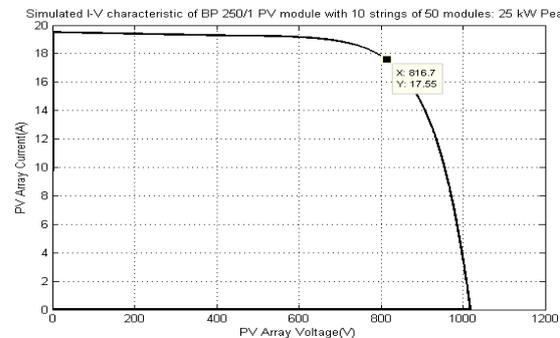Figure 7: Simulated P-V characteristic showing maximum power 14330 W at 816.7 V.

Figure 8: Simulated I-V characteristic showing current of 17.55 A at 816.7 V corresponding to maximum power point.

CONCLUSIONS

TABLE 3: COMPARISON BETWEEN RESULTS OBTAINED BY ANALYTICAL AND GRAPHICAL METHOD.

Parameter	Analytical Result	Graphical Result
Voltage at first iteration	1018.7 V	1018 V
Current at first iteration	0 A	0.01A
Power at first iteration	0 W	10.18W
Maximum power by P&O method	14337W	14330 W
Voltage at maximum power point by P&O method	816 V	816.7
Current at maximum power point by P&O method	17.57A	17.55

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