

MATLAB Based Modelling and Maximum Power Point Tracking using Perturb and Observe Algorithm of Photovoltaic Array, Characteristics Study under Varying Temperature, Solar Irradiance and Shading Patterns

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Abstract— The recent upsurge in the demand of photovoltaic (PV) systems is due to the fact that they produce electric power without hampering the environment by directly converting the solar radiation into electric power. However the solar radiation never remains constant. It keeps on varying throughout the day. This paper presents a MATLAB based simulator cum learning tool, which can be used to enhance the understanding and predict the $I-V$ and $P-V$ characteristics of large PV arrays. It can be used to study the effect of temperature and solar radiation variations, and the role of array configuration on the PV characteristics. A notable advantage of the presented model is that the PV array model can be interfaced with the models of actual systems making it possible to simulate complete PV systems and their interaction with other systems. The reason for using MATLAB is that it is available in most academic, research, and industrial organizations and considered useful for several engineering disciplines. It provides several features that can be used to simulate highly complex systems, electronic and power electronic circuits and systems, and distributed generation power systems. The usefulness of the proposed tool is demonstrated with the help of results. The MPPT system has been tested with the BP Solar 250/1 module will be used to illustrate and verify the module under various operating conditions. The obtained results prove that the Perturb and Observe MPPT algorithm can track even under sudden change in sunlight conditions and loading level. The aim of this paper is also 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, insolation variation, varying shading patterns and the role of array configuration on the PV characteristics.

Index Terms— Photovoltaic (PV), Current- Voltage (I-V), Power-Voltage (P-V), Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O).

I. INTRODUCTION

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 PV array has nonlinear output characteristic which

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vary with the size (number of modules) and 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 and 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.

Solar energy, radiant light and heat from the sun, has been reined by humans since ancient times using a range of ever-evolving technologies. Solar radiant energy accounts for most of the usable renewable energy on earth. Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. In this thesis, the PV array is modelled and its voltage-current characteristics and power-voltage characteristics are simulated and optimized. Each solar cell has a point at which the current (I) and voltage (V) output from the cell result in the maximum power output of the cell. The principle is that if the output from the cell can be regulated to the voltage and current levels needed to achieve a power output at this point, then the power generated by the solar cell will be used most efficiently.

The main encumbrance for the reach of PV systems is their low efficiency and high capital cost. Here we intend to examine a schematic to draw out maximum obtainable solar power from a PV module for use in a DC application. The concept of MPPT using P & O algorithm is to be implemented which results in appreciable increase in the efficiency.

II. PHOTOVOLTAIC MODULES

Simulation can be very useful in many scientific studies that proceed as follows:

1. Observing the physical system.
2. Formulating a hypothesis or mathematical model to explain the observation.
3. Predicting the behavior of the system from solutions or properties of the mathematical model.
4. Testing the validity of the hypothesis or mathematical model.

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

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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_0 .
- 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.

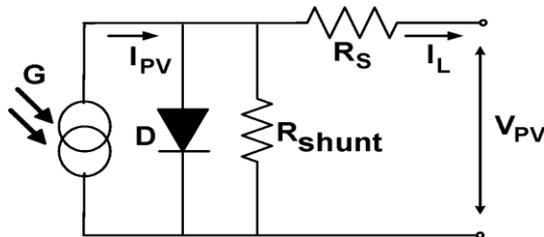


Figure 1: Equivalent circuit of a PV cell. [4]

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 R_s 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, [1]

$$I = I_L - I_0 (e^{q(V+IR_s)/nkT} - 1) \quad \dots\dots(1)$$

$$I_L = I_{L(T_1)} (1 + K_0 (T - T_1)) \quad \dots\dots(2)$$

$$I_{L(T_1)} = G * I_{SC(T_1, nom)} / G_{(nom)} \quad \dots\dots(3)$$

$$K_0 = (I_{SC(T_2)} - I_{SC(T_1)}) / (T_2 - T_1) \quad \dots\dots(4)$$

$$I_0 = I_{0(T_1)} * (T/T_1)^{3/n} * e^{-qV_g/nk*(1/T)-(1/T_1)} \quad \dots\dots(5)$$

$$I_{0(T_1)} = I_{SC(T_1)} / (e^{qV_{OC(T_1)}/nkT_1} - 1) \quad \dots\dots(6)$$

$$R_s = -dV/dI_{V_{OC}} - (1/X_V) \quad \dots\dots(7)$$

$$X_V = I_{0(T_1)} * q/nkT_1 * e^{qV_{OC(T_1)}/nkT_1} \quad \dots\dots(8)$$

Where, R_s : Series resistance on ohms.

q : magnitude of charge on an electron.

k : Boltzman's constant.

I_L : Photo current.

I_0 : 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 $^{\circ}K$.

T_1 : Initial standard temperature in $^{\circ}K$.

T_2 : Final considered temperature in $^{\circ}K$.

I_{sc} : Short circuit current.

V_{oc} : Open circuit voltage.

K_0 : Temperature coefficient of I_{sc} .

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 in 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 = $1000W/m^2$).

A. Mathematical model

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 $25^{\circ}C$

Table 1: Technical specifications for BP Solar 250/1 module. [10]

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 (V_{oc})	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, irradiance 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. A simple iterative technique initially tried only converged for positive currents.

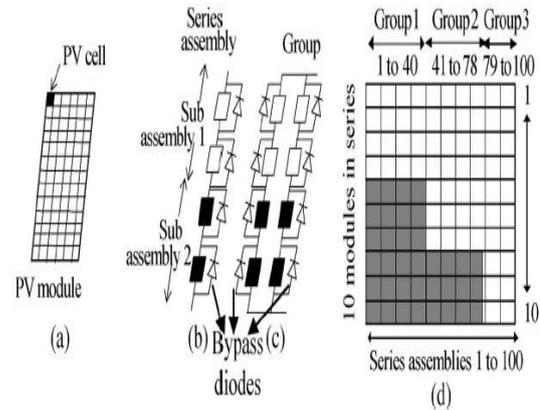


Figure 2: Terminology used for the various components of a partially shaded PV array. (a) PV module. (b) Series-assembly with two series-connected subassemblies (c) Group. (d) PV array with three groups. [3]

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 i^{th} group represented by " G_i "), 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 °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 = $1.60217733 \times 10^{-19}$ 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 °K = $273 + 25^\circ\text{C} = 298^\circ\text{K}$.
- T_2 : Final initial temperature in °K = $273 + 75^\circ\text{C} = 348^\circ\text{K}$.
- V_{oc} : Open circuit voltage (21.2 V at temperature T_1 and 17.15 V at temperature T_2).
- I_{sc} : Short circuit current (3.22 A at temperature T_1 and 3.31 A at temperature T_2).
- 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.
- T_{rk} : Standard reference temperature in °K = $273 + 25^\circ\text{C} = 298^\circ\text{K}$.

Calculations for mathematical modelling,

T_{ak} = Array working temperature °K = $273 + \text{Temp}$.

$I_{ph-T_1} = I_{sc-T_1} \times \text{Sun}$.

Now, constant a is to be calculated from I_{sc} versus temperature variation. We know I_{sc} at T_1 and T_2 .

$$a = \frac{I_{sc-T_2} - I_{sc-T_1}}{I_{sc-T_1} \times (T_2 - T_1)}$$

and constant b can be calculated as

$$b = \frac{V_g \times q}{A \times k}$$

$$I_{ph} = I_{ph-T_1} \times (1 + a \times (T_{ak} - T_1))$$

$$V_{t-T_1} = \frac{q}{k \times T_1}$$

$$I_{r-T_1} = \text{Array current at temperature } T_1 = \frac{I_{sc-T_1}}{\left(\frac{V_{oc-T_1}}{e^{(A \times V_{t-T_1})} - 1} \right)}$$

$$I_{r-T_2} = \text{Array current at temperature } T_2 = \frac{I_{sc-T_2}}{\left(\frac{V_{oc-T_2}}{e^{(A \times V_{t-T_2})} - 1} \right)}$$

$$I_r = I_{r-T_1} \times \left(\frac{T_{ak}}{T_1} \right)^{3/A} \times e^{-b \times \left(\frac{1}{T_{ak}} - \frac{1}{T_1} \right)}$$

$$X2V = \frac{I_{r-T_1}}{A \times V_{t-T_1}} \times e^{\frac{(V_{oc-T_1})}{A \times V_{t-T_1}}}$$

$dV/dI_{V_{oc}} = -\frac{1.15 \times 2}{N_s} \frac{dV}{dI}$ This is calculated at V_{oc} per cell from manufacturer's graph.

$R_s = \frac{dV/dI_{V_{oc}} - \frac{1}{X2V}}{A \times k \times \frac{1}{T_1}}$ This gives series resistance per cell.

$$V_{t-T} = \frac{q}{k}$$

Then increment I by 0.001A in each step starting from 0 to I_{ph} to calculate V for each step.

$$V = V_{t-T} - I \times R_s$$

PV array voltage in volts, Volt = $36 \times V \times n$.

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

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

Current – Voltage (I-V) curve for selected PV array is given by, Plot (Volt, Curr)

Power – Voltage (P-V) curve for selected PV array is given by, Plot (Volt, Power)

III. SYSTEM MODEL

PV Array Model with 10 Strings of 50 Modules of BP Solar 250/1 giving 25 kW Peak, a plotting function for graphs and a function for P&O MPPT algorithm; forming a complete model in MATLAB is shown in figure 3.

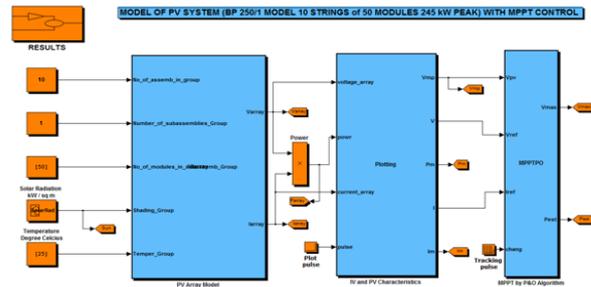


Figure 3: PV array model block diagram (functions) with BP Solar 250/1 (50 W max) of 10 strings of 50 modules each (Total :10*50*10 W = 25 kW).

Inputs (Variable parameters) allowed in the PV model:

- Simulation time: 1 sec.
- Number of assemblies in a group : 10
- Number of sub-assemblies in a group: 1
- Number of modules in a sub-assembly of a group: 50
- Temperature : 25°C and Solar radiation in kW/ m²

IV. SIMULATION RESULTS

The PV array model is simulated for above mentioned inputs where solar radiation varies in steps every 0.2 s in the way described in above figure, producing changes in the maximum power drawn from the PV array. PV array exhibits a highly nonlinear radiation and temperature dependent P-V and I-V characteristic curve. Such characteristics can be obtained for different configurations under solar radiation and temperature changes.

A. Effect of temperature on PV array characteristics:

The effect of temperature can be clearly displayed by a PV panel I-V (current vs. voltage) curve. I-V curves show the different combinations of voltage and current that can be produced by a given PV panel under the existing conditions. The results show that there is an indirect proportionality between the power output produced by the system and the ambient temperature of the locality. Thus the application of photovoltaic technology in the conversion of solar energy to electricity is not favorable during the period of very high ambient temperature than the period of low ambient temperature. The results indicated that PV solar panels must be installed at a place where they receive more air current so that the temperature remains low while the power output remains high. [5]

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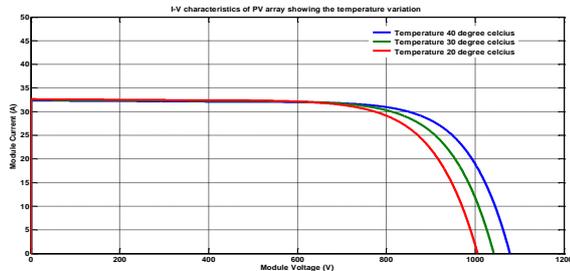


Figure 4: Simulated I-V characteristics of the PV array under varying temperature.

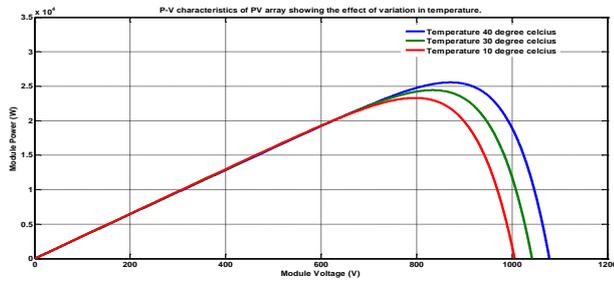


Figure 5: Simulated P-V characteristics of the PV array under varying temperature.

B. Effect of solar irradiation on PV array characteristics:

For several solar radiations varies between 0.1 to 1 kW/m² and for a constant temperature equal to 25 °C, presented the I-V and P-V characteristic of PV array. Current and power output decreases with the decrease in solar irradiance.

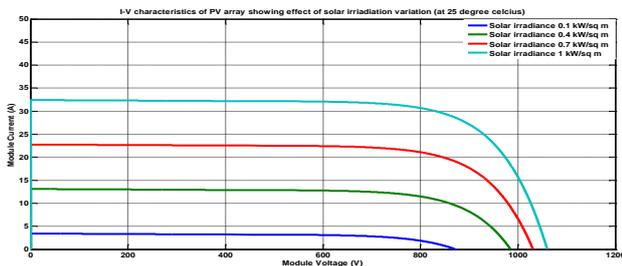


Figure 6: Simulated I-V characteristics of the PV array under varying solar irradiance.

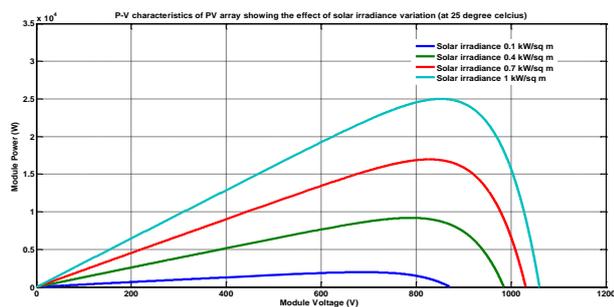


Figure 7: Simulated P-V characteristics of the PV array under varying solar irradiance.

C. Partial Shading effect on on PV array characteristics:

A PV module is considered to be shaded if three or more of its cells are receiving lower than normal insolation. In any outdoor environment, the whole or some parts of the PV system might be shaded by trees, passing clouds, high building, etc., which result in non-uniform insolation conditions. During partial shading, a fraction of the PV cells which receive uniform irradiance still operate at the optimum

efficiency. Since current flow through every cell in a series configuration is naturally constant, the shaded cells need to operate with a reverse bias voltage to provide the same current as the illuminated cells. However the resulting reverse power polarity leads to power consumption and a reduction in the maximum output power of the partially-shaded PV module. Exposing the shaded cells to an excessive reverse bias voltage could also cause “hotspots” to appear in them, and creating an open circuit in the entire PV module. This is often resolved with the inclusion of a bypass diode to a specific number of cells in the series circuit.

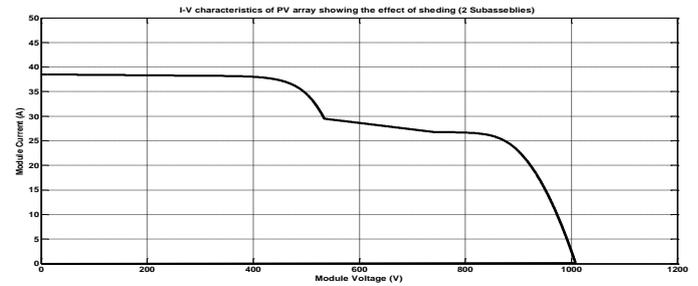


Figure 8: Simulated I-V characteristics of the groups (parallel connected series assemblies (sub-assemblies) under varying shading pattern.

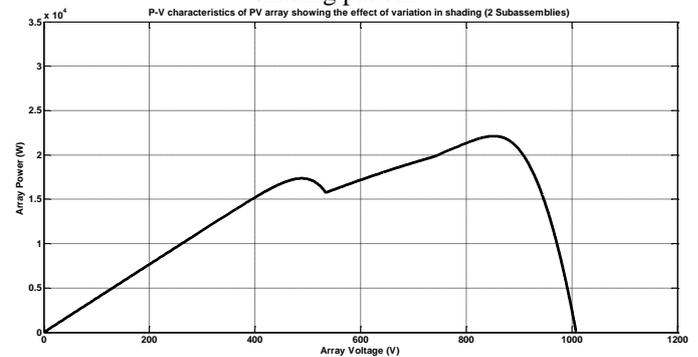


Figure 9: Simulated P-V characteristics of the groups (parallel connected series assemblies (sub-assemblies) under varying shading pattern.

D. Results for MPPT tracking by P&O algorithm under varying solar irradiance:

Figure 10 and 11 shows simulated result of actual and P&O estimated PV array voltage (V) and power in (kW) versus time (s) respectively. P&O method proves to be accurate following the Maximum Power Point (MPP) and corresponding array voltage.

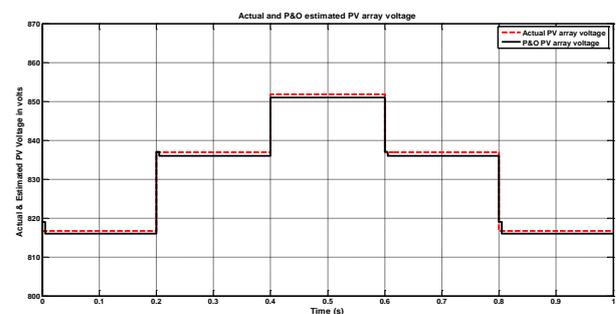


Figure 10: Simulated result for actual and P&O estimated PV array voltage (V) versus time (s).

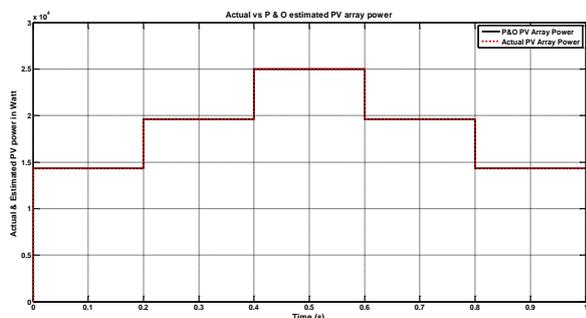


Figure 11: Simulated result for actual and P&O estimated PV array power (kW) versus time (s).

V. CONCLUSION

An accurate PV module electrical model is presented and demonstrated in MATLAB for a typical 50W BP 250/1 solar module. The PV array consists of 10 strings of 50 modules, making up the peak installed power of 25 kW. Given solar insolation and temperature, the model returns a current vector for a given voltage vector. A method to obtain the I-V and P-V characteristics of a PV array, having a large number of series- and/or parallel-connected modules, under varying temperature and solar radiation is described.

The existing MPPT schemes, which assume a unique maximum power point, therefore, remain inadequate. The magnitude of the global peak is dependent on the PV array configuration and shading pattern besides the commonly known factors, i.e. insolation level and temperature. It is demonstrated that, if the likely shading pattern on the PV array is known, the simulation model is handy to design the most optimum configuration of the PV array to extract the maximum power. The results obtained with this model can be effectively used with off-line capabilities of MATLAB/SIMULINK to investigate the effectiveness of MPPT methods working under non-uniform insolation conditions.

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