

Study on Performance Characteristics of PV Array under Non-uniform Irradiation Conditions

N. Nagaraja¹, Dr. T. Gowri Manohar²

M.Tech Student, S.V. University College of Engineering, Tirupati, Andhra Pradesh, India¹

Professor, EEE Department, S.V. University College of Engineering, Tirupati, Andhra Pradesh, India²

Abstract: Ever increasing energy demand, owing to population growth, technology development, and industrial expansion, has led to exploring alternative sources for energy generation. Renewable energy sources such as Photovoltaic (PV) are help in reducing the levels of greenhouse gases in the atmosphere and mitigate this global warming. Solar energy emerged as the most effective and reliable source of renewable energy as it is pollution free, less maintenance, recyclable and inexhaustible. Photo Voltaic (PV) technology is used for direct conversion of e solar energy into electrical energy. The performance of PV system is mostly affected by irradiation, module temperature and array configuration. The knowledge of relationship between these effects and the output power of the PV array is very important while analyzing the performance of the PV system. This paper presents a MATLAB-programmed model to study the I-V and P-V characteristics of PV array under non-uniform insolation caused by both partially and completely shaded modules. In the first part, with the developed MATLAB/Simulink model the performance characteristics of PV array is illustrated by analyzing the different shading situations, then the impact of shading on PV array is illustrated experimentally by measurements on an array with 3 series connected 60W modules. Both developed model and experimental results shows that, under the non-uniform insolation condition, the output power of a PV array get reduced and output PV curve become more complex with multiple peaks.

Keywords: PV module, PV array, Partial shading, MATLAB Simulink, MATLAB program.

I. NOMENCLATURE

I_{ph} = The current generated by incident light(Amps)
 I = Output current (Amps)
 I_{mp} = Current corresponds to maximum power point (Amps)
 V_{mp} = Voltage corresponds to maximum power point (Volts)
 I_{sc} = Short circuit current of the cell (Amps)
 V_{oc} = Open circuit voltage of the cell (Volts)
 I_d = Diode current (Amps)
 I_{0n} = The reverse saturation of the diode (Amps)
 I_0 = Saturation current of the cell (Amps)
 V_{tr} = Thermal voltage at T_r (Volts)
 V_t = Thermal voltage at T_c (Volts)
 E_g = Band-gap energy,(eV)
 q = Electron charge [$1.60217646 \times 10^{-19}$ C]
 k = Boltzmann's constant [$1.3806503 \times 10^{-23}$ J/K]
 n = Diode ideality constant
 K_i = Temperature co-efficient of 'Isc' [$^{\circ}C$]
 K_v = Temperature co-efficient of 'Voc' [$^{\circ}C$]
 T_c = Operating temperature in $^{\circ}K$
 T_r = Reference temperature in $^{\circ}K$
 G_r = The nominal irradiation, 1000 W/m^2
 G = Actual irradiation, (W/m^2)
 N_p = Number of parallel connected cells

N_s = Number of series connected cells
 P_{max} = Maximum power (Watts)
 STC = Standard Test Condition
 (1000 W/m^2 , $25^{\circ}C$, Air Mass = 1.5)

II. INTRODUCTION

Environmental issues with concerns on greenhouse effects, global warming, depletion of natural reserves like fossil fuels, coal, natural gas, etc. is motivating research to invest in technologies that can harvest energy from renewable energy sources like wind, solar, tidal waves, etc. Of these, the solar energy is the best promising, environment friendly, pollution free and economical source of energy. Energy received by the earth from the sun in one hour is more than the world's population usage in a whole year. The total flux intercepted by the earth on any particular day is 4.2×10^{18} Watt- hours or 1.5×10^{22} Joules or 6.26×10 J/hour [1]. The incident radiant energy arriving on a surface of the ground perpendicular to the sun's rays after atmosphere absorption is typically 1000 watts per square meter.

Solar energy utilized in two forms, one as heat energy and another one as electrical energy. Thermal system, capture the heat energy (infra red radiation) from the sun in some form of solar collectors and use it to heat the water or space heating and this heat can also used to heat the working fluid of the steam generator to generate electricity. PV systems capture the radiation at higher frequencies (visible and ultra violet) and convert the

radiant energy directly into DC electricity. Although there are several benefits in solar energy, there are some challenges that obstruct its rapid growth. The challenges are: high initial cost, low conversion efficiency (between 10% to 20% only) [2] and output power changes with change in weather conditions.

The performance of PV array is strongly depends on operating conditions, such as the solar insolation level, the ambient temperature and PV array configuration. As the voltage generated by a single solar cell is very low, around 0.5V. So, a number of solar cells are connected in both series and parallel to form a module and modules also connected in similar fashion to obtain higher powers at desired level of voltage and current [3].

Shading is the common phenomenon that facing the PV array by the passing clouds, shadows of tress, neighbor constructions, dirt, debris, bird droppings, different orientations and tilts, and so on. The partial or complete shading on PV array causes reduction in output power and also results non-linearity in output I-V characteristics with multiple local maxima on P-V curve [2-5]. In a PV module the shading results, not only power reduction but also leads to hot-spot and causes damage to these cells. To avoid that heat stress on shaded cells, a bypass diode is connected in anti-parallel with a PV module [6]. Shade impact depends on module type, bypass diode placement, string configuration and severity of shade. Power loss occurs from shade, also current mismatch within a PV string and voltage mismatch between parallel strings [7].

This paper presents a MATLAB-based model to study the performance characteristics of the PV array with change in the various factors, such as insolation change, temperature change and under different shading conditions. The experimental results were obtained using DC Rheostat as load.

III. OPERATING PRINCIPLE

The building block of PV array is the solar or PV cell, which converts solar light energy directly renewed into electrical energy based on photovoltaic effect. The PV cell is basically a semiconductor p-n junction device, when solar light incident on the surface of PV cell the photons with energy greater than the band-gap energy are absorbed, causing the formation of electron-hole pairs. These carriers are separated under the influence of electric fields within the junction, creating a current that proportional to the incidence of the solar energy [2]. Generally, the output voltage of solar cell is very low (about 0.5V). To obtain voltages and currents at desired level, the solar cells are connected in series and parallel respectively and form a PV module. The combination of series and parallel connected modules form an array to obtain higher power outputs at desired level of voltages and currents [3].

IV. MATHEMATICAL MODEL

Single diode and two diode models are the most widely used equivalent circuit models for defining the electrical characteristics of a PV cell. In this paper single diode model is considered, as it is simple and accurate enough in many cases [5-6], [8-9]. A PV cell can be represented by a current source and a diode connected across it, since it generates current when it is illuminated and generates no power if it is not illuminated. The current source accounts for solar irradiance and diode accounts for diffusion current.

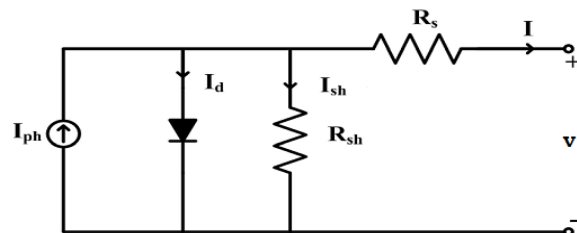


Fig.1: Equivalent circuit of a single diode model PV cell [8]

The equivalent circuit model also includes parasitic resistances, that indicated by R_s and R_{sh} as shown in figure 1. R_s , consists resistance of junctions, contacts and cables, so it is connected in series, whereas the R_{sh} accounting for recombination of charge carriers, so it is connected as parallel element in the circuit.

By using Kirchoff's Current Law, the governing equations of I-V characteristics of PV cell are:

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

Where, photon current

$$I_{ph} = [I_{sc} + K_i(T_c - T_r)](G/G_r) \tag{2}$$

Diode current

$$I_d = I_0 \left[\exp\left(\frac{qV_d}{nkT_c}\right) - 1 \right] \tag{3}$$

Current through shunt resistance

$$I_{sh} = \frac{V_{sh}}{R_{sh}} = \frac{V_d}{R_{sh}} = \frac{V + IR_s}{R_{sh}} \tag{4}$$

Now the cell out put current, I is

$$I = I_{ph} - I_0 \left[\exp\left(\frac{qV_d}{nkT_c}\right) - 1 \right] - \frac{V_d}{R_{sh}} \tag{5}$$

I_0 , the cell saturation current, which changes with change in operating temperature, is defined as

$$I_0 = I_{on} \left(\frac{T_c}{T_r} \right)^3 \exp \left[\frac{qE_g}{nk} \left(\frac{1}{T_c} - \frac{1}{T_r} \right) \right] \tag{6}$$

I_{on} , reverse saturation current of the diode, is given as

$$I_{on} = \frac{I_{sc}}{\left(\exp\left(\frac{V_{sc}}{nV_{tr}}\right) - 1 \right)} \tag{7}$$

V_{tr} , the thermal voltage at reference temperature is

$$V_{tr} = N_s * \left(\frac{kT_r}{q} \right) \tag{8}$$

And thermal voltage at operating temperature, V_t is

$$V_t = N_s * \left(\frac{kT_c}{q} \right) \quad (9)$$

The equivalent circuit model of an array with N_s , series connected cells and N_p , parallel connected cells, is shown in figure 2.

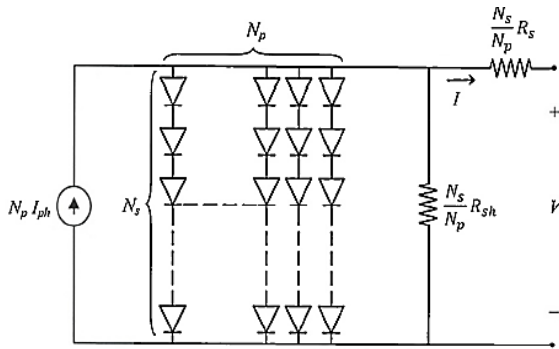


Figure 2: Equivalent circuit of a PV array

Now, I-V characteristic equation of an array is

$$I = N_p I_{ph} - N_p I_0 \left[\exp \left(\frac{\left(\frac{V}{N_s} \right) + \left(\frac{I R_s}{N_p} \right)}{n V_t} \right) - 1 \right] - \frac{1}{R_{sh}} \left[\left(\frac{N_p}{N_s} \right) V + I R_s \right] \quad (10)$$

V. MODELING OF PV MODULE AND PV ARRAY

The above given equations (1 – 10) are used to develop the model for a PV module and PV array. The proposed work is done on a PV array with 3 series connected 60W, MSX60 PV modules. The module consists of 36 polycrystalline silicon solar cells connected in series. The values of R_s and R_{sh} are taken as 0.1Ω and 161.344Ω . The electrical specifications of MSX60 PV module are given in below table1 [9].

Table No.1: Electrical specifications of MSX60 PV module

Maximum Power (Pm)	60W
Voltage @ Pmax (Vm)	17.1A
Current at @ Pmax (Im)	3.5A
Guaranteed Minimum Pm	58W
Short Circuit current (Isc)	3.8A
Open Circuit voltage (Voc)	21.1V
Temperature co-eff of Voc	$-(80 \pm 10) \text{ mV}/^\circ\text{C}$
Temperature co-eff of Isc	$(0.065 \pm 0.15) \% / ^\circ\text{C}$
NOCT	$47 \pm 2^\circ\text{C}$

Ideality constant (n) value depends on the PV technology. The below table 2 shows the ideality constant for different PV technologies [12].

Table 2: Ideality constant (n) for different PV technologies

Technology	Ideality Factor
Si-mono	1.2
Si-poly	1.3
a-Si:H	1.8
a-Si:H tandem	3.3
a-Si:H triple	5
CdTe	1.5
CIS	1.5
AsGa	1.3

Algorithm for modeling a PV array using MATLAB-Software:

Step 1:

According to the solar panel being simulated, choose the required input data at STC, number of cells in series and parallel to create desired module. And choose the number of panels in series/parallel as per the actual array.

Step 2:

Define the essential constants and input data obtained in step 1.

Step 3:

Choose the nominal temperature in degree Kelvin ($^\circ\text{K}$). Obtain the actual temperature, which is in degree Celsius and convert into ($^\circ\text{K}$).

Step 4:

Choose the nominal irradiance, G_r in W/m^2 .

Step 5:

According to the array design, choose the R_s and R_{sh} values in Ohms (Ω).

Step 6:

Set a matrix having different irradiances as values.

Step 7:

For $j=1$:no.of elements in the matrix.

Calculate thermal voltages and saturation current using equations 6,8, and 9 respectively.

Step 8:

Set a voltage vector from 0 to maximum value of voltage with specified steps.

Step 9:

For $i=1$:length (V) Find the output current of the module, I using equations (1-10) for all values of V . This process is repeated for every level of irradiation.

Step 10:

Plot the I-V characteristics corresponds to the all I and V values.

Step 11:

Calculate output power of the module, to perform element by element multiplication for the current and the voltage.

Step 12:

Plot the P-V characteristics, for all P and V values.

Step 13:

To analyze the partial shading effect, the above steps are repeated with shaded conditions [8].

Flowchart for performance calculation of PV system:
The following flowchart shown in figure 3, illustrates the step by step sequence for calculating the PV system performance.

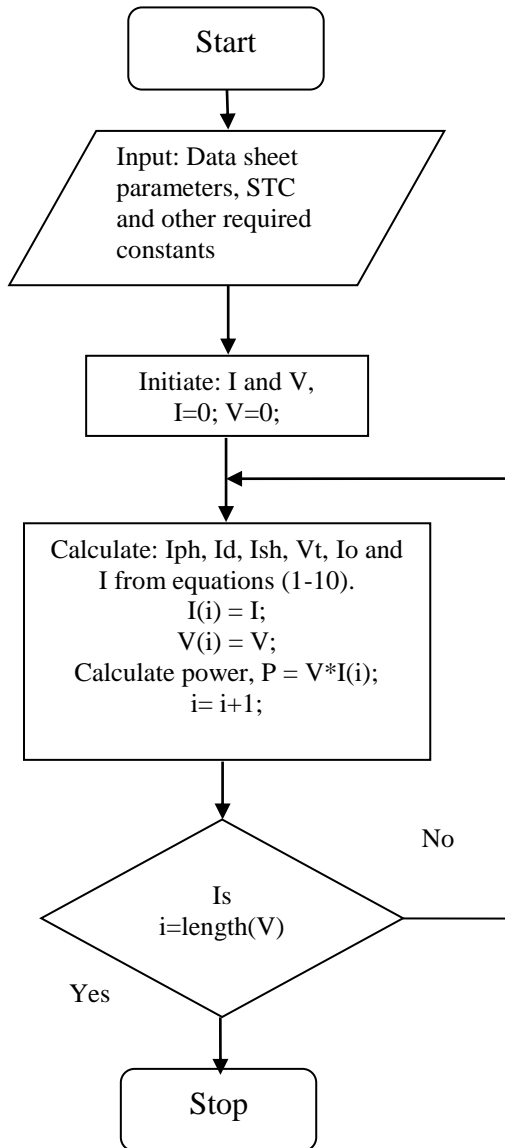


Fig. 3: Flowchart for Calculating PV System Performance.

MATLAB/Simulink model of PV Array:

The figure 4 shows the developed MATLAB/Simulink model of PV array with 3 modules connected in series under non-uniform irradiation condition.

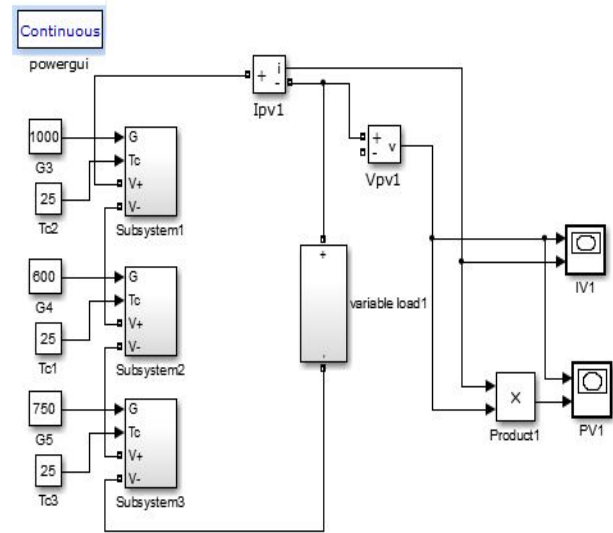


Figure 4: PV array model

VI. I-V AND P-V CURVES OF PV SYSTEM WITH DEVELOPED MATLAB-SOFTWARE MODEL

The I-V and P-V characteristics of PV system under different irradiation, temperature, change in parasitic resistances and shading conditions are explained below.

I-V and P-V curves of PV module and PV array:

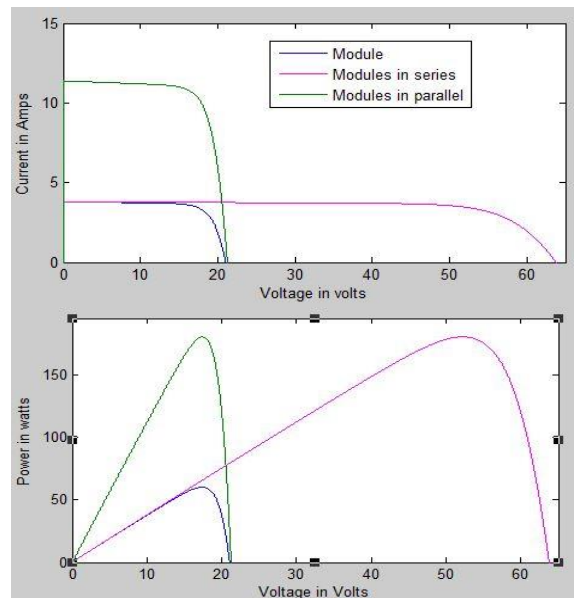


Figure 5: I-V and P-V characteristics of module, array (with series and parallel connected modules)

The figure.5 depicts the typical I-V and P-V characteristics of a PV module, array with 3 modules connected in series and array with 3 modules connected in parallel. From the curves it is observed that, the output power of the array increases with added modules. When modules are added in series the output voltage of the array is equal to the sum of the all module voltages, but the current through the modules and array is same as the module current.

Similarly, when modules are added in parallel, the resultant array current increase and it is equal to the sum of individual modules output currents, but the voltage across modules and array is maintained at same level.

I-V and P-V curves of PV module with Irradiation changes:

Figure 6 Shows the I-V and P-V curves with different irradiation levels. Here, the solar irradiation changes with values of 1000,900,800 and 700W/m² while temperature kept constant at 25°C. I-V curve shows that, the change in irradiation affects the short circuit current more, but its impact is less on open circuit voltage and P-V curve shows that the output power of the module increases with the increase in irradiation level.

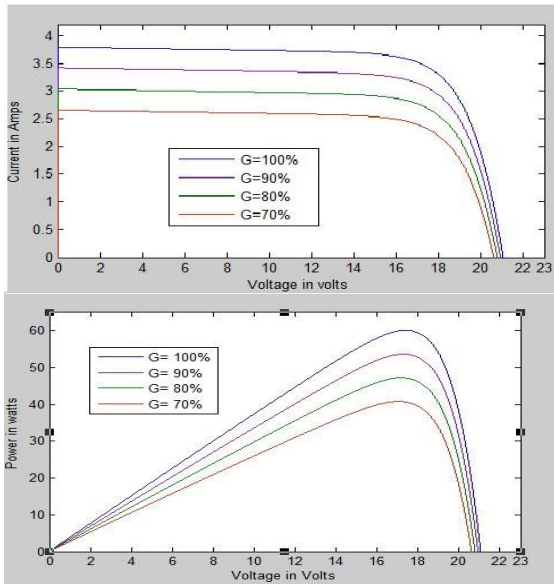


Figure 6: I-V and P-V curves with change in irradiation

I-V and P-V curves of PV module with temperature changes:

The figures 7a and 7b shows the I-V and P-V curves of a PV module with change in temperature. Here, the temperature with values 25°C, 35°C, 40°C and 45°C, but irradiation kept constant at 1000W/m². I-V curve shows that the impact of temperature is

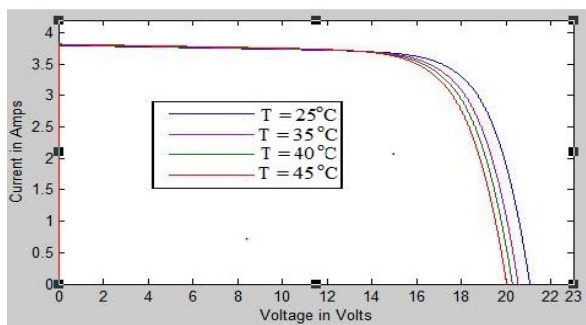


Figure 7a: I-V curves with change in temperature

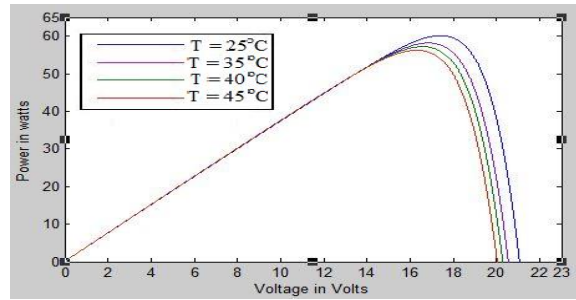


Figure 7b: P-V curves with change in temperature

significant on open circuit voltage and I_{sc} has less effect with temperature changes. V_{oc} decreases with increase in temperature. P-V curve shows that, the output power decreases with increase in temperature.

With change in parasitic resistances, R_s and R_{sh}:

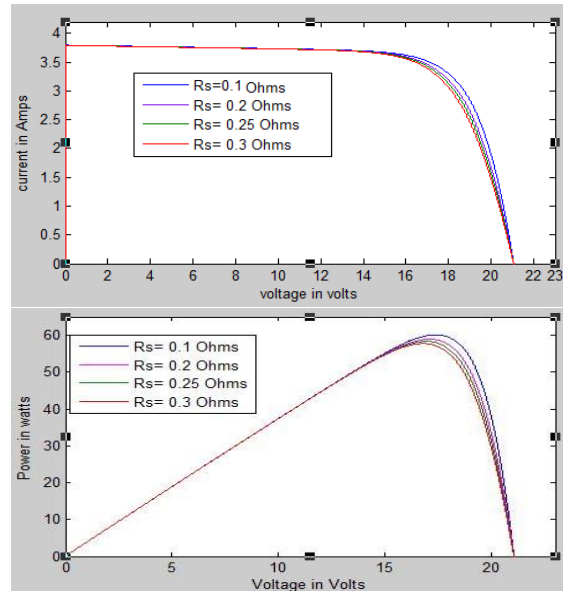


Figure 8a: I-V and P-V curves with change in R_s

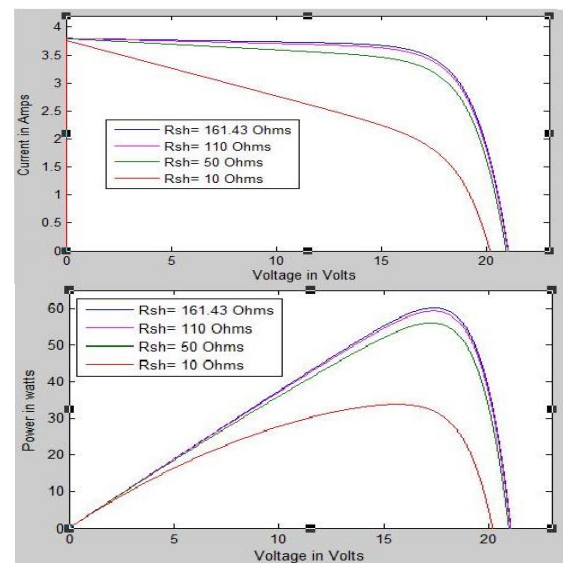


Figure 8b: I-V and P-V curves with change in R_{sh}

The figures 8.a and 8.b shows the I-V and P-V curves with change in R_s and R_{sh} respectively by keeping the temperature and irradiation at constant. I-V curves shows that, with increase in R_s from 0.1Ω to 0.3Ω the point at which maximum power occurs will be decreases and with decreases in R_{sh} from 161.43Ω to 10Ω the current and voltage outputs decreases. P-V curves shows that the increase in R_s and decrease in R_{sh} causes reduction in output power.

I-V and P-V characteristics PV array under different shading conditions:

In this study, the shading effect can be analyzed by considering the proposed PV array with 3 modules connected in series under 4 different shaded conditions. The 4 different cases are as follows:

- 1) **Case 1:** All 3 modules with 100% irradiation.
- 2) **Case 2:** One of the modules with 75% irradiation and remaining two modules with 100% irradiation.
- 3) **Case 3:** Three modules with different irradiance levels 100%, 60% and 75% respectively.
- 4) **Case 4:** Two modules with irradiance level $1000W/m^2$ and remaining one is completely shaded.

The resultant I-V and P-V curves for all the above cases with developed MATLAB/Simulink model [8],[10] are shown in figures 9a and 9b.

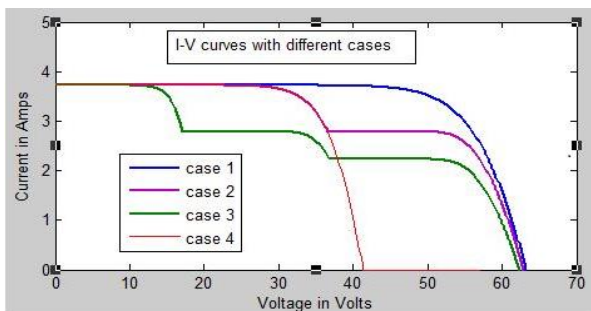


Figure 9a: I-V of PV array under different shaded conditions

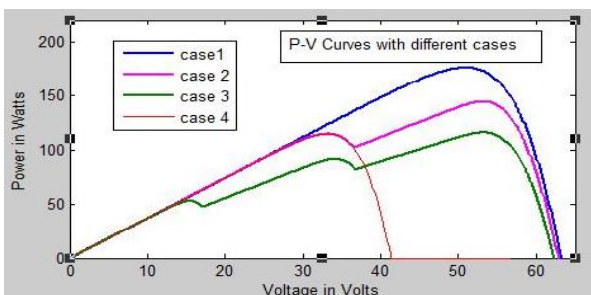


Figure 9b: P-V curves of PV array under different shaded conditions

VII. EXPERIMENTAL SET-UP AND RESULTS

The setup contains a PV array with 3 modules connected in series. Set up consists, two types of diodes. One is blocking diodes, which are connected in series with modules and other type is by-pass diodes, which are connected in parallel with modules. DC Rheostat as a load.

Digital multi-meter is used to measure the voltage and current. The insulation level is measured with reference to short circuit current, that is for $G=100\%$ the short circuit current is 3.8A. The shading effect is artificially generated by tilting the modules at different angles. The PV module is tilted in such a way that, the required level of insulation is obtained by measuring the value of I_{sc} [10-11].

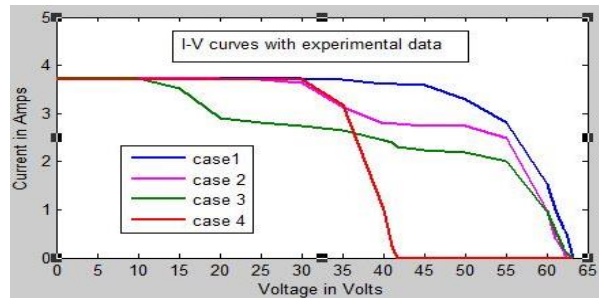


Figure 10a: I-V curves of PV array with practical results

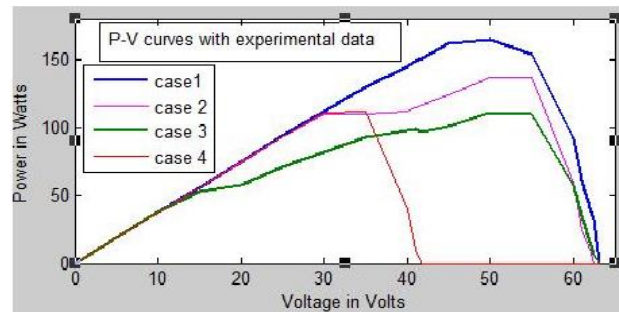


Figure 10b: P-V curves of PV array with practical results

Table No. 3 Practical Results

Shading Type	MATLAB/Simulink	Practical
Case 1: Maximum G	$P_{max} = 176.2 \text{ W}$ $I_{sc} = 3.724 \text{ A}$ $V_{oc} = 63.16 \text{ V}$	$P_{max} = 165 \text{ W}$ $I_{sc} = 3.724 \text{ A}$ $V_{oc} = 63.18 \text{ V}$
Case 2: $G_1=G_2=100\%$, $G_3=75\%$	$P_{max} = 144.1 \text{ W}$ $I_{sc} = 3.724 \text{ A}$ $V_{oc} = 62.73 \text{ V}$	$P_{max} = 136.8 \text{ W}$ $I_{sc} = 3.72 \text{ A}$ $V_{oc} = 62.4 \text{ V}$
Case 3: $G_1=100\%$, $G_2= 60\%$, $G_3= 75\%$	$P_{max} = 115.9 \text{ W}$ $I_{sc} = 3.72 \text{ A}$ $V_{oc} = 62.14 \text{ V}$	$P_{max} = 111 \text{ W}$ $I_{sc} = 3.72 \text{ A}$ $V_{oc} = 63.18 \text{ V}$
Case 4: $G_1=G_3=100\%$	$P_{max} = 114.7 \text{ W}$ $I_{sc} = 3.724 \text{ A}$ $V_{oc} = 41.28 \text{ V}$	$P_{max} = 109.2 \text{ W}$ $I_{sc} = 3.7 \text{ A}$ $V_{oc} = 41.8 \text{ V}$

During the measurements, the temperature is at 38°C . The obtained results under above said 4 different shaded cases are shown in table 3.

I-V and P-V curves with the measured results are shown in figures 10a and 10b.

VIII. RESULTS AND DISCUSSION

The observations from both theoretical and practical results are as follows,

1. Due to partial shading, the output power of the PV array decreases. Higher number of shaded modules, lowering the output power.
2. Shaded modules causes for multiple peaks in the output P-V curve. The number of these peaks increases with increase in number of shaded modules.
3. I-V curve experiences multiple steps. These steps, also depends on the number of shaded modules.
4. Modules with partially shaded, produces lesser current but V_{oc} unchanged.
5. When module is completely shaded, it generates no power, the power output of un-shaded modules bypassed through the by-pass diode which is connected across the module. Therefore, the array operates at lowered voltage but current at rated I_{sc} .

IX. CONCLUSION

In this paper, an educational approach for studying the PV system characteristics is presented. The mathematical equations for modeling a PV cell are derived and simulations of PV array carried out using MATLAB code based on a single diode model circuit representation. The effect of irradiation, temperature, parasitic resistances and shading effect on PV array characteristics are studied and effect on PV system performance under different shaded conditions was examined. The proposed MATLAB/simulation and coding work and the obtained practical results will help the beginners to carry out the simulations and coding themselves and see the effect of the various parameters on the I-V and P-V curves of the cells, modules and arrays. Also, the proposed work will allow the beginners to better understanding the shading effect and its negative consequences on the PV system output.

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