

Full Length Research Paper

Photovoltaic solar cell simulation of shockley diode parameters in matlab

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In this work, the Shockley diode parameters were simulated using the Matlab software package with the solar cell I - V and P - V characteristics in focus. Our model has been based on previous studies while the effects of varying cell temperature, series resistance, R_s , ambient irradiation and diode quality factor were put into consideration and the output current and power characteristics of the PV model simulated, all for 10 iterations using the Newton - Raphson algorithm. The effect of shunt is neglected throughout the simulation while the results showed expected trends as reported by previous authors. This work therefore will be very useful for users, especially researchers in this field.

Key words: Photovoltaic, solar cell, Matlab, simulation, photocurrent.

INTRODUCTION

The quest for alternative energy sources and requirements in the next decades has attracted a lot of attention because there is a strong worldwide demand for energy, not to mention the fact that there is dwindling fossil-fuel reserves and global warming stemming from climate change that has resulted in various degrees of natural disaster like flooding, extreme heat /drought and rise in ocean levels.

One of the candidates to replace pollutant fossil-fuel energy sources and which is also inexhaustible is the solar energy which can be harvested using the solar cells, modules and arrays.

When exposed to light, photons with energy greater than the bandgap energy of the semiconductor are absorbed and create an electron-hole pair. These carriers are swept apart under the influence of the internal electric fields of the p-n junction and thus creating a photogenerated current proportional to the incident radiation.

In the dark, the I-V output characteristic of a solar cell has an exponential characteristic of a solar cell has an exponential characteristic similar to that of a diode. When

the cell is short circuited, this current flows in the external circuit, and when open circuited, this current is shunted internally by the intrinsic p-n junction diode. The characteristics of this diode therefore set the open circuit voltage characteristics of the cell Geoff (2000).

In all solar power systems, efficient simulations including PV panel are required before any experimental verification is carried out. To this end, several authors (Akihiro, 2005; Ashish and Rakesh, 2011; Abdulkadir et al., 2012; Gonzalez-Longatt, 2010; 2005; Salmi et al 2012; Mohammed 2009; Gow and Manning; 1999) have carried out simulations aimed at harvesting greater amount of solar energy or simply to improve on the efficiency of the solar cell.

Also, Bourdoucen and Gastli (2007) developed an analytical model for PV panels and arrays based on extracted physical parameters of solar cells with an advantage of simplifying mathematical modelling of different cells and panel configurations without losing necessary accuracy of system operation.

This paper therefore focuses on the simulation of an improved model of the solar cell based on the Shockley

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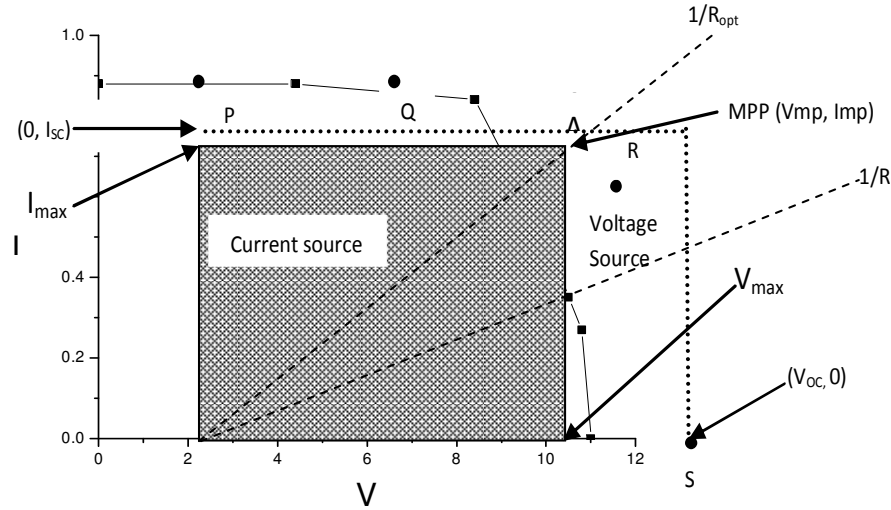


Figure 1. I - V Curve from the constructed and mounted module.

diode parameters using the Newton-Raphson algorithm in conjunction with Matlab software package.

METHODOLOGY

Mathematical formulation of the photovoltaic cell

The solar cell which is the basic unit of a photovoltaic module consists of a p-n junction fabricated in a thin wafer or layer of semiconductor. Though the electrical characteristics differ very little from a diode, it is represented by the Shockley Equation (1). In an ideal solar cell, $R_s = R_{sh} = 0$, a very relatively common assumption (Ramos et al., 2010). The Shockley equation is given as:

$$I_D = I_0 \left(e^{\frac{V_C q}{nkT_{CK}}} - 1 \right) \tag{1}$$

Where:

- “ I_0 ” is the dark current (A)
- “ I_0 ” is the saturation current of the diode (A)
- “ V_C ” is a cell voltage (V)
- “ q ” is the electronic charge ($1.6 \cdot 10^{-19}$ (Coul.))
- “ n ” is the diode ideality constant
- “ k ” is the Boltmann constant ($1.38 \cdot 10^{-23}$ J/K)
- “ T_{CK} ” is the cell temperature.

The net current “ I ” which is the difference between the photogenerated current (I_L) and the normal diode current

$$I = I_L - I_D \tag{2}$$

A simplified model [10] is given as:

$$I = I_L - I_0 \left(e^{\frac{(V_C + IR_S) q}{nkT_{CK}}} - 1 \right) \tag{3}$$

Where R_S is the series resistance in Ohms.

Equation (3) does not represent the I - V characteristics of a practical PV module, thus, inclusion of additional parameter R_{SH} (Shunt). Thus, Equation (3) becomes:

$$I = I_L - I_0 \left(e^{\frac{(V_C + IR_S) q}{nkT_{CK}}} - 1 \right) - \left(\frac{V_C + IR_S}{R_{SH}} \right) \tag{4}$$

The Series resistance R_S and the shunt R_{SH} are included in the real operation of the solar module to cater for the losses that exist in the cells and between the cells in the module. Thus, the simplest PV model of a solar cell is as shown in Figure 1.

$$I_L = I_L(T_1) + K_0(T - T_1) \tag{5}$$

$$I_L(T_1) = I_{SC}(T_{1,nom}) \frac{G}{G_{nom}} \tag{6}$$

$$K_0 = \frac{I_{SC}(T_2) - I_{SC}(T_1)}{T_2 - T_1} \tag{7}$$

$$I_0 = I_0(T_1) \times \left[\frac{T}{T_1} \right]^{\frac{3}{n}} \times e^{-\frac{qV_g(T_1)}{nk \left(\frac{1}{T} - \frac{1}{T_1} \right)}} \tag{8}$$

$$I_0(T_1) = \frac{I_{SC}(T_1)}{\left(e^{\frac{qV_{oc}(T_1)}{nkT_1}} - 1 \right)} \tag{9}$$

$$R_S = -\frac{dV}{dI_{Voc}} - \frac{1}{X_V} \tag{10}$$

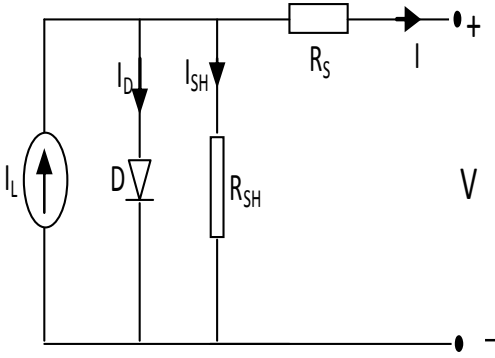


Figure 2. Single diode model of a solar cell.

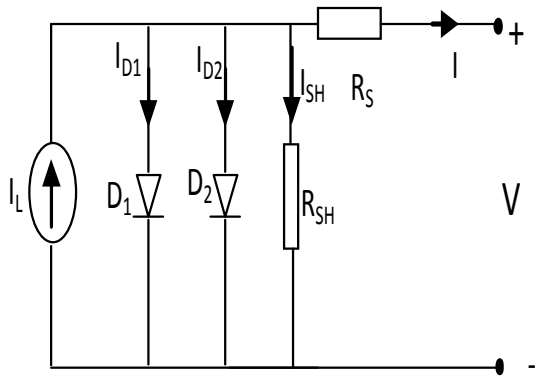


Figure 3. Double diode model of a solar cell.

$$X_V = I_o(T_1) \frac{q}{nkT_1} e^{\frac{qV_{oc}(T_1)}{nkT_1}} - \frac{1}{X_V} \tag{11}$$

In all these equations that is, (5) to (11), the shunt resistance has been neglected while all the constants can be determined by examining the manufacturers' ratings of the PV cell, and then the measured I - V curves of the module.

Important features of a Current – Voltage (I - V) Curve for a solar cell

The plot of current against voltage for a typical solar cell is shown in Figure 1.

- 1). Short-circuit current, I_{sc} . This is the greatest value of the current generated by a cell and is produced when $V = 0$, the short circuit conditions.
- 2). Open circuit voltage, V_{oc} . This is the voltage drop across the diode (p-n junction) when photogenerated current, $I_{ph} = 0$, that is, at night when there is no illumination at all. This is represented mathematically as:

$$V_{oc} = \frac{nkT}{q} \ln \left[\frac{I_L}{I_o} \right] = V_t \ln \left[\frac{I_L}{I_o} \right] \tag{12}$$

$$V_t = \left[\frac{mkT}{e} \right] c$$

Where V_t is known as thermal voltage and T is the absolute cell temperature.

3). Maximum power point, A. This is the point (V_{max} , I_{max}) at which the power dissipated in the resistive load is maximum: $P_{max} = V_{max} I_{max}$.

4). Maximum efficiency, η . The ratio between the maximum power and the incident light power.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max} V_{max}}{AG_a} \tag{13}$$

Where G_a is the ambient irradiation and A, is the cell area.

5). Fill factor, FF. The ratio of the maximum power that can be delivered to the load and the product of I_{sc} and V_{oc} .

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} = \frac{I_{max} V_{max}}{V_{oc} I_{sc}} \tag{14}$$

The fill factor is a measure of the real I - V characteristic with a value higher than 0.7 connoting a good cell. This value diminishes as the cell temperature is increased.

It has also been established, Gonzalez-Longatt (2010) that for a resistive load, the load characteristic is a straight line with slope $1/V = 1/R$. The power delivered to the load depends on the value of the resistance only. If this load R is small, the cell operates in the region P - Q of the curve where the cell behaves as a constant current source, almost equal to the short circuit current. On the other hand, if the load R is large, the cell operates on the region R - S of the curve where the cell behaves more as constant voltage source, almost equal to the open-circuit voltage, Hansen et al. (2000).

Modeling of the solar cell

Various models have been developed and utilized in order to study solar cell behavior. The simplest and the most widely used equivalent circuit of a solar cell is a current source in parallel with a diode as shown in Figure 2. The double diode equivalent circuit Nishioka et al. (2007) shown in Figure 3 has also been reported.

In this work the single diode model is adapted because of its simplicity to program using the Matlab package.

This model is based on the previous works (Geoff, 2000; Gonzalez – Longatt, 2005; Ramos et al., 2010; Akihiro, 2005; Savita et al., 2010).

All the authors used Matlab Software which requires 3 values to calculate the net operating current of the module. These are:

- 1). V_a = Module operating voltage
- 2). $G = [\text{Suns}]$ = Irradiance with 1 suns = 1000 W/m²
- 3). T_aC = Module temperature, in °C

The body of the program is divided in 4 main parts:

- 1). Definition of constants (Boltzmann's constant, k, electronic charge, q, diode –ideality quality factor, A, irradiance, G, etc
- 2). Definition of variables
- 3). Calculation of I_L , I_o and R_s (Equations 5 – 10 are used)
- 4). Calculation of I

Newton – Raphson iterative method is exploited in this work to solve the double –exponential Equation (4) because of its quick convergence. In this work, ten iterations were performed to reduce error. The algorithm of the adopted MPPT logic is shown in figure 4

while The Matlab script file used to generate the simulation results in this work are listed below:

```

function ltt = calcul (Vd,Suns,Temp)
%k = 2 + Temp;
% Given voltage, illumination and temperature
% ltt,Vd = array current, voltage
% G = num of Suns (1 Sun = 1000 W/m^2)
% T = Temp in Deg C
k = 1.38e-23; % Boltzman's const
q = 1.60e-19; % charge on an electron
Voo = Va;
tr = 3.016;
cap = 10;
lph = Voo / tr * exp(- 1/(tr * cap));
A = 1.2; % "diode quality" factor, =2 for crystalline, <2 for amorphous
Vg = 1.12; % band gap voltage, 1.12eV for xtal Si, ~1.75 for amorphous Si.
Ns = 36; % number of series connected cells (diodes)
T1 = 273 + 25;
Voc_T1 = 21.06 /Ns; % open cct voltage per cell at temperature T1
Isc_T1 = 3.80; % short cct current per cell at temp T1
T2 = 273 + 75;
disp(T2);
Voc_T2 = 17.05 /Ns; % open cct voltage per cell at temperature T2
Isc_T2 = 3.92; % short cct current per cell at temp T2
TaK = 273 + Temp; % array working temp
TrK = 273 + 25; % reference temp
% constant "a" can be determined from Isc vs T
lph_T1 = Isc_T1 * Suns;
aa =Isc_T2 - Isc_T1;
ab = Isc_T1 * 1/(T2 - T1);
a = aa/ab;
Vt_T1 = k * T1 / q; % = A * kT/q
lr_T1 = Isc_T1 / (exp(Voc_T1/(A*Vt_T1))-1);
lr_T2 = Isc_T2 / (exp(Voc_T2/(A*Vt_T1))-1);
b = Vg * q/(A*k);
rvl = exp(-b *1/TaK - 1/T1);
lr = lr_T1 * (TaK/T1).^ (3/A) * rvl);
X2v = lr_T1/(A*Vt_T1) * exp(Voc_T1/(A*Vt_T1));
dVdl_Voc = - 1.15/Ns / 2; % dV/dl at Voc per cell --
% from manufacturers graph
Rs = - dVdl_Voc - 1/X2v; % series resistance per cell
% ltt = 0:0.01:lph;
Vt_Ta = A * 1.38e-23 * TaK / 1.60e-19; % = A * kT/q
% solve for ltt: f(ltt) = lph - ltt - lr.*( exp((Vc+ltt.*Rs)/Vt_Ta) -1) = 0;
% Newton's method: ltt2 = ltt1 - f(ltt1)/f'(ltt1)
Vc = Vd/Ns;
ltt = zeros(size(Vc));
% lttv = ltt;
for j=1:10;
ltt = ltt - (lph - ltt - lr.*( exp((Vc+ltt.*Rs)/Vt_Ta) -1))/ (-1 - (lr.*(exp((Vc+ltt.*Rs)/Vt_Ta) -1)).*Rs./Vt_Ta);
end.
    
```

RESULTS

- 1). Effect of varying cell temperature. The effect of varying cell temperature at solar irradiance G = 1Suns on the open-circuit voltage V_{oc} and the short circuit current I_{sc} is shown in Figures 5 and 6.
- 2). Effect of varying series resistance, R_s. Figures 7 and 8 showed the effect of the variation of R_s,

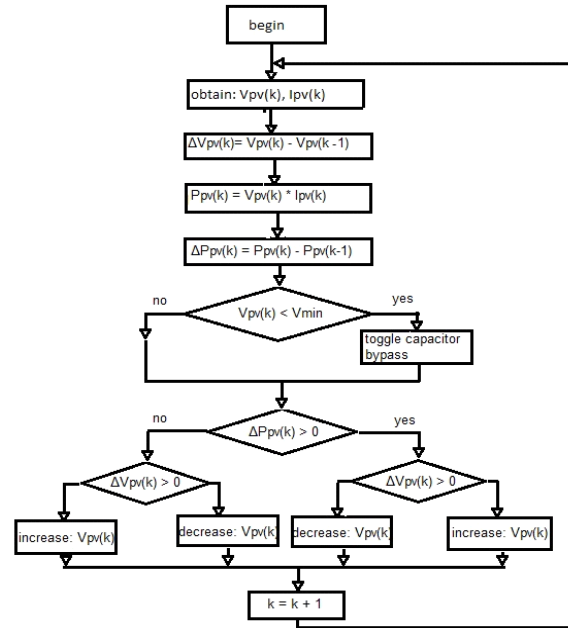


Figure 4. Algorithm of the adopted MPPT logic.

the series resistance on the slope angle of the I - V curves.

3). Effect of ambient irradiation

Figure 9 showed the effect of irradiance variation 0.2 – 1.5 Suns at constant temperature 25°C (Pandiarajan et al., 2011; Atlas and Sharaf, 2007; Kumari et al., 2012; Yushaizad, 2004).

4). Effect of diode quality factor

The response of I_{sc} and V_{oc} with the diode quality factor is shown in Figure 10.

DISCUSSION

With G = 1 Suns, the open circuit voltage V_{oc} dropped slightly with increasing cell temperature while the short circuit current, I_{sc} increased, the cell being thus less efficient. For instance, when the cell temperature is 24 °C at an irradiance of G = 1 suns, the open circuit voltage is about 15.05 V. However, if the temperature is reduced to 0°C at the same irradiance, the open circuit voltage increased to 20.1 V. This behaviour is presented in Figures 5 and 6.

Also, the variation of R_s, the series resistance of the PV affected the slope angle of the I - V curves with the attendant deviation from the maximum power point as shown in Figures 7 and 8. This series resistance which is always very low, and some cases be neglected (Tsai et al., 2008; Savita et al., 2010), was included in this work so as to enable the model to be used for any given PV cell.

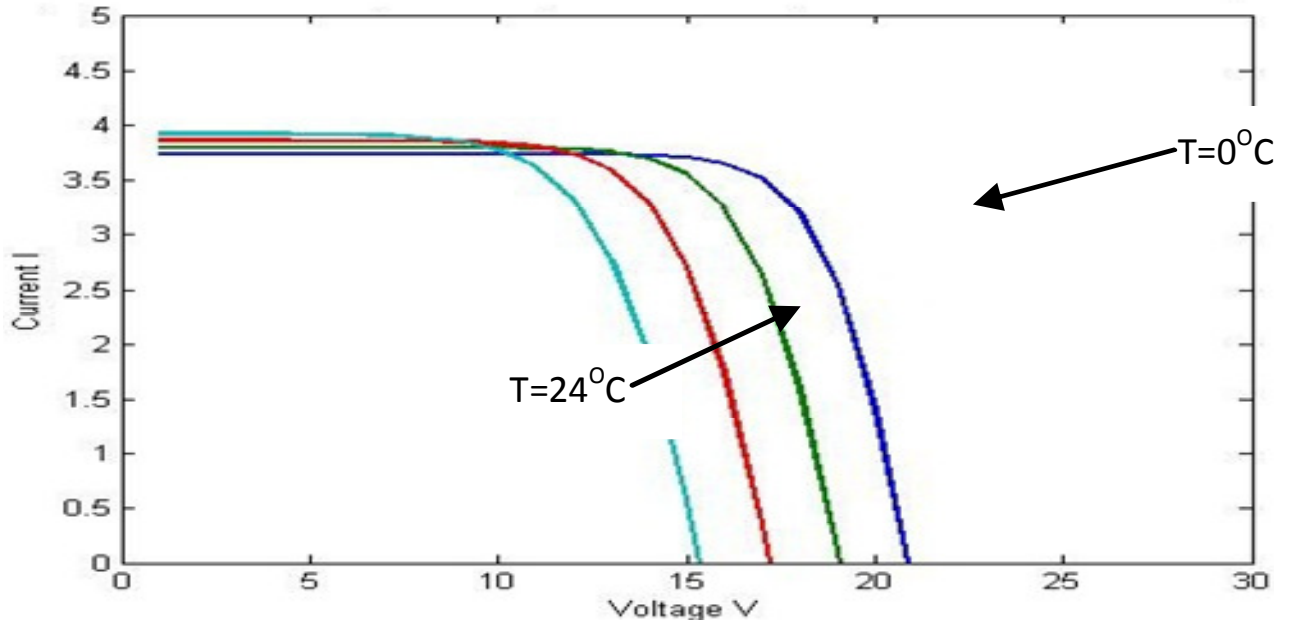


Figure 5. Module current against voltage at G = 1 Sun and at various temperature levels for zero bias.

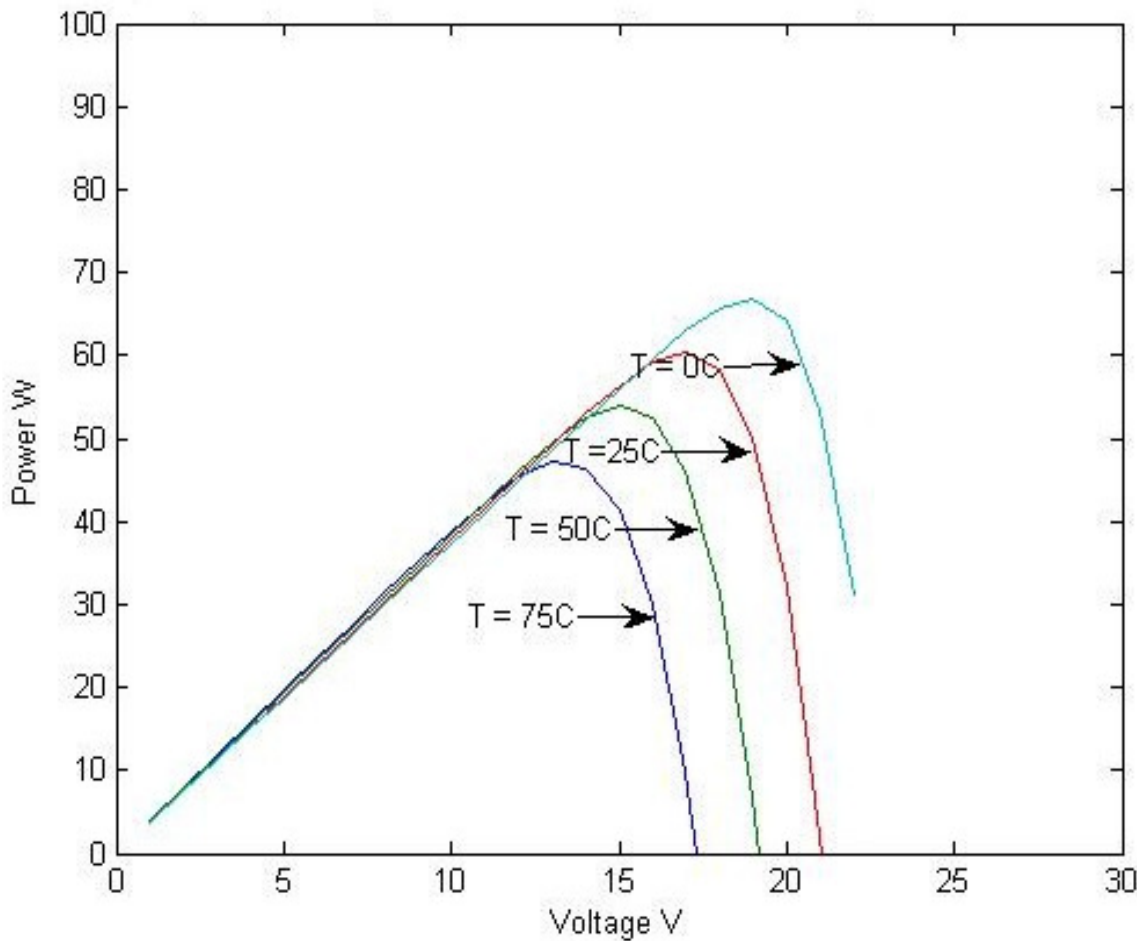


Figure 6. Power against module voltage at G = 1 Sun and at various temperature levels.

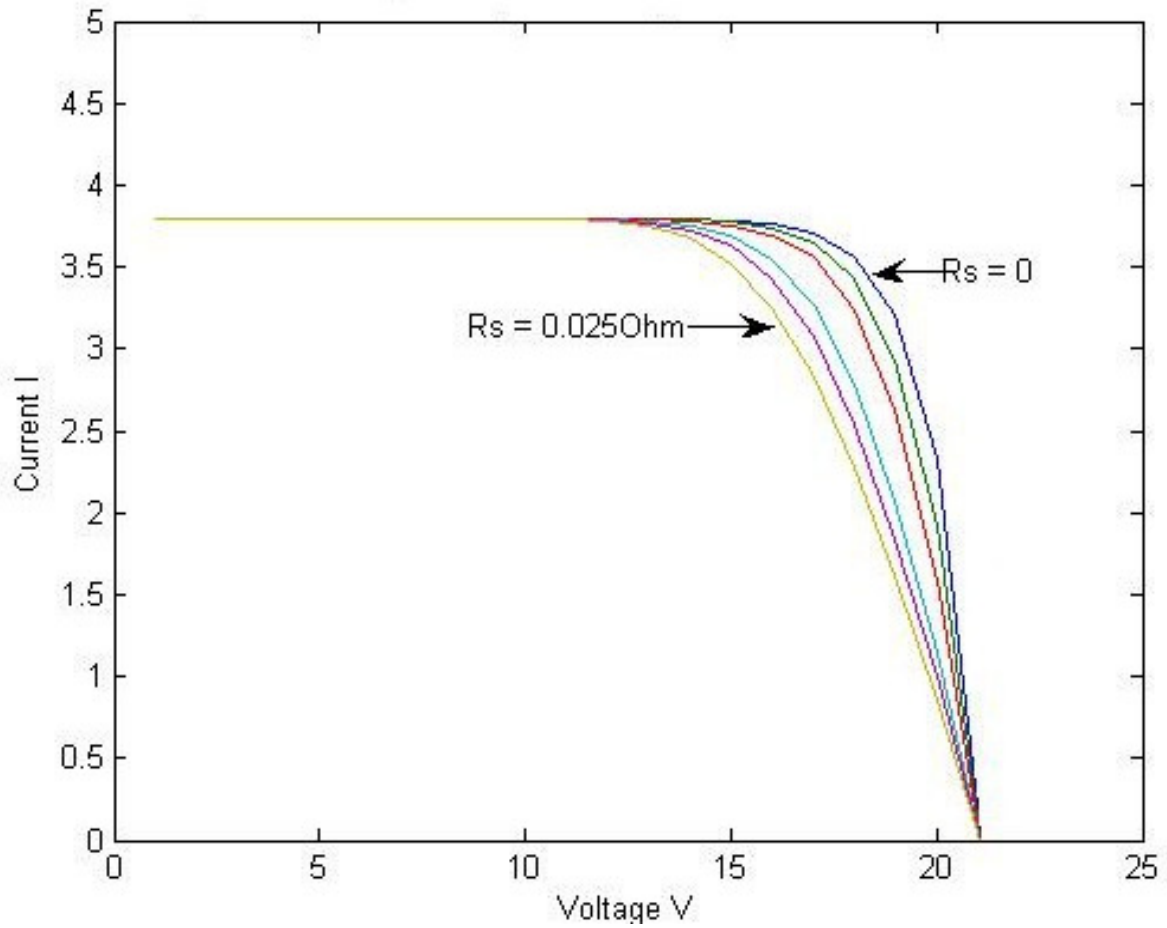


Figure 7. Graph of current against module voltage at $G = 1$ Sun and at various series resistance (R_s).

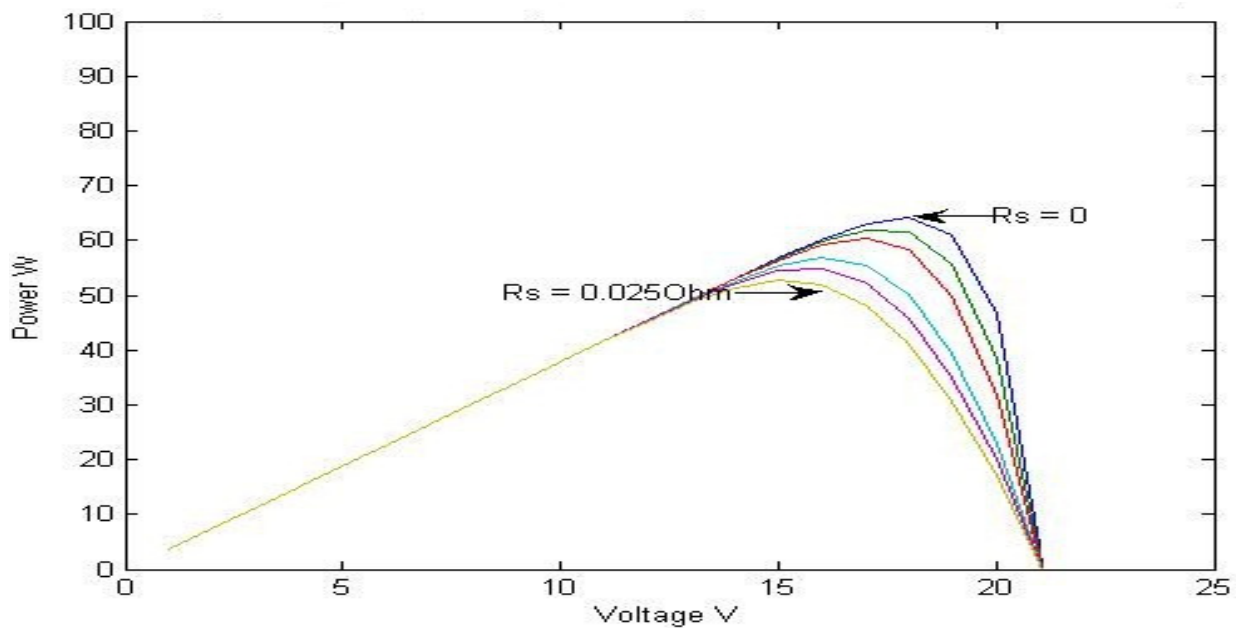


Figure 8. Power against module voltage at $G = 1$ Sun and at various series resistance, (R_s).

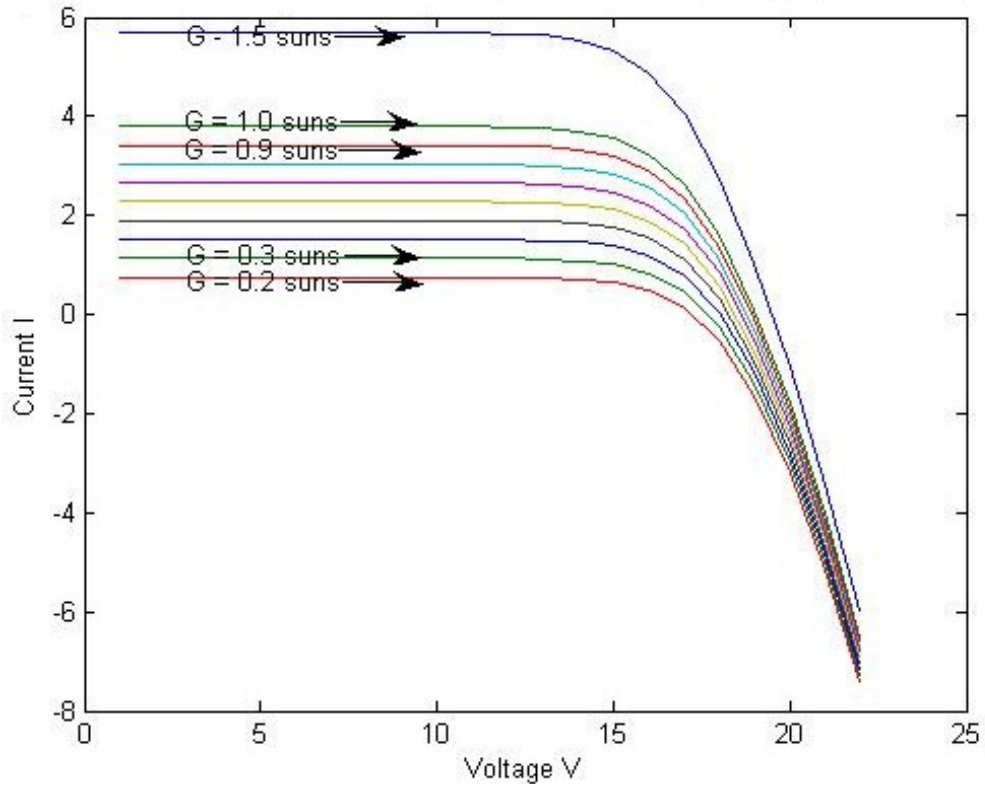


Figure 9. Module current against voltage at $T = 25^{\circ}\text{C}$ and at various irradiation levels.

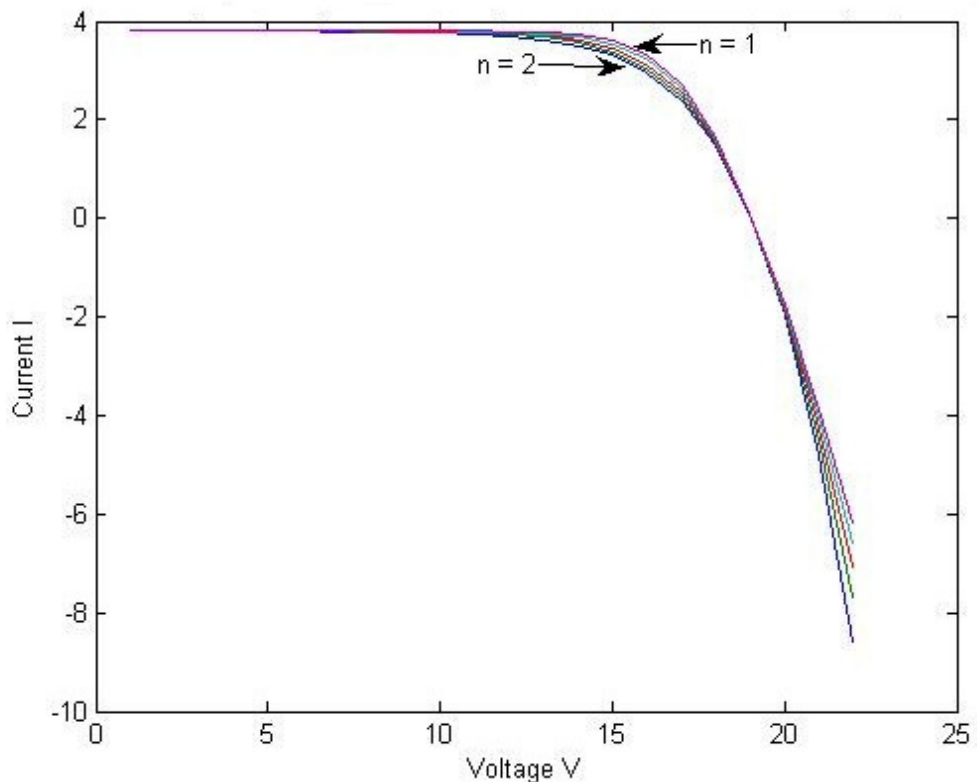


Figure 10. Module current against voltage at $G = 1$ Sun, 25°C with various diode quality factor values.

Figure 9 showed the effect of irradiance variation 0.2 – 1.5 Suns at constant temperature 25°C (Pandiarajan et al., 2011; Atlas and Sharaf, 2007; Yushaizad, 2004). The open circuit voltage, V_{oc} did not vary much as it is logarithmically dependent on the solar irradiance while the short circuit current is a linear function of the ambient irradiation since photocurrent depends on the irradiation. The higher the irradiation, the greater the current. It was also noted that reducing the irradiation will result in decreasing the output voltage of the panel.

As the diode quality factor is increased, the open circuit voltage of the cell increased. The ideal value of quality factor for solar cell is unity but its practical value for Silicon PV cell ranges between 1 and 2. Green (1992) states that diode quality factor takes a value between 1 and 2; being near 1 at high currents, rising towards 2 at low currents. This is demonstrated in Figure 10.

Conclusion

A Matlab simulation of PV solar cell using the Shockley diode circuit equations of a solar cell using the single diode equivalent circuit and taking into account the effects of physical and environmental parameters like cell temperature, series resistance, R_s , ambient irradiation and diode quality factor was carried out. The effect of shunt is however not considered. The results obtained followed the expected trends as reported by previous authors. This is the first step in the use of our results to model the I - V and P - V characteristics of a solar module deployed to take data in our location.

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