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PV Module Validation, Philadelphia-Solar-P36 150Wp Using MATLAB/SIMULINK

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Abstract: In this paper, analysis has been done for PV model to simulate actual PV module behavior using Matlab-Simulink by using parameters in photovoltaic cells made up of a single diode, a series resistance, and a shunt resistance. A typical P36 150W multi crystalline solar module specifications have been used for model evaluation. The characteristic curves were obtained from the manufacturer`s datasheet which shows the precise correspondence to the model and this prove that the module is reliable.

Keywords: Photovoltaic Module, Performance *I–V* and *P-V*, Parameter Estimation

I. Nomenclature

Iph – photocurrent produced by PV cell, [A];
I_0 – reverse saturation current of diode, [A];
q – Electric charge of electron, [C];
V – Voltage on diode terminal, [V];
k – Boltzmann constant, k = 1.38 × 10−23 J.K −1;
Top – operating temperature of the junction, [K];
n – Ideality factor;
R_s, R_{sh} – series and shunt resistances, [Ω];
Ki – temperature coefficient of Isc, Ki = 0.058 A/°C;
G – Intensity of solar radiation, [W/m2];
T_{nom} – nominal operating temperature of the PV cell, [K];
E_g – band gap of semiconductor. [eV];
VT = KT/q – thermal voltage, [V];
B – Temperature coefficient of Voc , [%/°C];
STC – standard test conditions: G = 1000 W/m2 , Tcell = 25 ºC, AM = 1.5 (IEC Standard);
P_{max} – maximum power output, [W];
IMPP – intensity of the output current at P_{max} , [A];
VMPP – voltage output at P_{max} , [V];

II. Introduction

Renewable energy is reliable and plentiful and will potentially be very cheap once technology and infrastructure improve. Renewable energy is a critical part of reducing global carbon emissions and the pace of investment has greatly increased as the cost of technologies continues to fall and efficiency continues to rise.

The photovoltaic solar cell has become one of the most potential and promising solution in renewable energy resources. Photovoltaics offer the highest versatility among renewable energy technologies due to the oil consumption and its cost, the increased energy demand and the negative effect of pollution on the environment. Jordan is among the highest in the world in dependency on alternative energy sources such photovoltaics solar system.

Several previous researches have been conducted to develop and validate a mathematical modeling of PV module to have a better understanding of its working.

For the modeling of the photovoltaic module, the use of equivalent circuits can be seen from the literature [1]-[4]. To make the PV model easily solvable, the equivalent circuit can be simplified to a circuit with a single-diode [5]-[9].

In addition, Single diode model can be divided into two categories. The first one is the four parameters model, where the shunt resistance is neglected and considered as infinite [8] [9]. The second is called the five parameters model, where the shunt resistance is considered as finite [10]-[12].

A simplified model is presented in the present work and followed by simulation of PV cell according to PV module PS-P36-150Wp Philadelphia-solar/Jordan.

III. PV Cell Equivalent Circuits

A basic PV cell is represented by a diode. It consists of an n-type silicon and p-type silicon doped semiconductor with a resulting space charge layer. Typically, a non-irradiated solar cell has nearly the same behavior as a diode. Therefore, a simple diode can describe the equivalent circuit [13].

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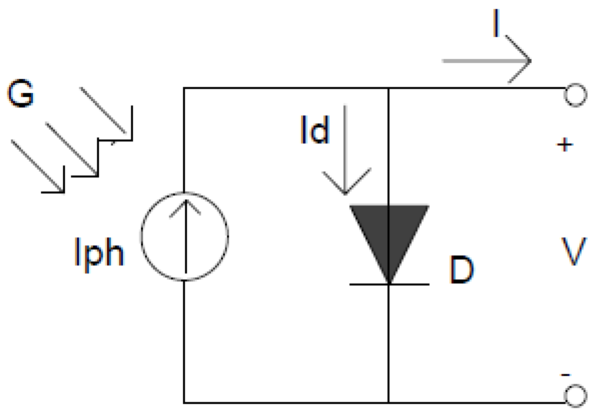

Fig. 1. Ideal single diode model.

Fig. 1. represent the ideal PV cell and one of the simplified and basic module consist of a single diode connecting in parallel with a light generating current source I_{ph} where is the output current and voltage relations is [14]:

$$I = I_{ph} - I_d \quad (1)$$

$$I_d = I_o\left(e^{\frac{V}{n_s V_T}} - 1\right) \quad (2)$$

$$V_T = \frac{nkT}{q} \quad (3)$$

IV. PRACTICAL EQUIVALENT CIRCUITS – ONE DIODE MODEL

Expanding (2) gives the simplified circuit model as shown in Fig. 2 and the following associated equation.

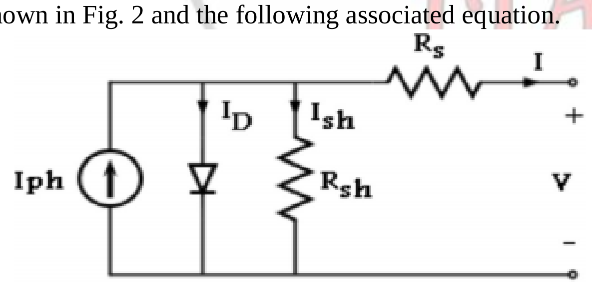

Fig. 2. PV cell equivalent circuit [15].

Fig. 2. Represent the equivalent circuit of a PV cell. The Current source Iph represents the cell photocurrent. Rsh and Rs are the intrinsic shunt and series resistances of the cell, respectively. Several researches take into account different properties of solar cell as: Series resistance (Rs): it considers the voltage drop and internal losses due to flow of current. Shunt resistance (Rsh): it considers the current leakage to the ground when diode is in reverse biased. Usually the value of Rsh is very large and that of Rs is very small, hence they may be neglected to simplify the analysis [15] [16].

In view of that, the current to the load can be given as: [17] [18].

$$I = I_{ph} - I_s\left(\exp\frac{q(V + R_s I)}{NKT} - 1\right) - \frac{(V + R_s I)}{R_{sh}} \quad (4)$$

Where in this equation, I_{ph} is the photocurrent, I_s is the reverse saturation current of the diode, q is the electron charge 1.6x10^(-19) Coulombs, V is the voltage across the diode, K is the Boltzmann's constant, T is the junction temperature, N is the ideality factor of the diode (typically between 1 and 2), and R_s and R_{sh} are the series and shunt resistors of the cell, respectively.

According to *I-V* characteristics of PV cell, at extreme points, from (4), it changes to:

At open circuit $V=V_{oc}$ at I=0:

$$0 = I_{ph} - I_o\left(e^{\frac{V_{oc}+IR_s}{n_s V_T}} - 1\right) - \frac{V_{oc} + IR_s}{R_{sh}} \quad (5)$$

At Short circuit $I=I_{sc}$ at V=0:

$$I_{sc} = I_{ph} - I_o\left(e^{\frac{I_{sc}R_s}{n_s V_T}} - 1\right) - \frac{I_{sc}R_s}{R_{sh}} \quad (6)$$

At Maximum power point $V=V_{mp}$, $I=I_{mp}$

$$I_{mp} = I_{ph} - I_o\left(e^{\frac{V_{mp}+I_{mp}R_s}{n_s V_T}} - 1\right) - \frac{V_{mp}+I_{mp}R_s}{R_{sh}} \quad (7)$$

V. MODELING OF PV DEVICES

The *I–V* characteristic of the PV module depends on the relationship between the current and voltage produced on a typical solar cell. *I-V* characteristics curve and the most parameters affected the characteristics of the PV cell are R_s, R_{sh} and on the intensity of the irradiation level and temperature. The generated current I_{ph} of the PV cells, without the effect of the series and parallel resistances, is hard to determine. Datasheets only inform the standard short-circuit current I_{scs}, which is the maximum current available at the terminals of the PV module.

The assumption $I_{phs} \approx I_{scs}$ is generally used in the modeling of PV module because in practical devices the series resistance is low and the parallel resistance is high, in an ideal cell, where R_{sh} is infinite and R_s is zero, the load current is equal to the current generated by the photoelectric effect minus the diode current, according to (1) [19] - [22].

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The semiconductor are sensitive to temperature and the illumination generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature When a PV cell is exposed to higher temperatures, I_{sc} increases slightly, while V_{oc} decreases more significantly according to the following equations [5] [20].

$$I_{ph} = (I_{ph} + K_i(T - T_{ref}))\frac{G}{G_{ref}} \quad (8)$$

The diode reverse saturation current I_o and its dependence on the temperature may be expressed as [5] [20].

$$I_o = I_{os}\left(\frac{T_{ref}}{T}\right)^3 e^{\frac{qE_g}{nK}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \quad (9)$$

Where E_g is the band gap energy for the considered PV module type. The value of E_g is a function of temperature and is linked to its value at STC (i.e., E_{gs}) by [16] [22].

$$\frac{E_g}{E_{gs}} = 1 - 0.0002677(T - T_{ref}) \quad (10)$$

Note that for the considered type of PV module, which is a multicrystalline silicon, $E_{gs} = 1.121\ ev$.

From (2) substitute $I_d = I_{scs}$ where $I_o = I_{os}$. The value of the standard reverse saturation current is given by [5].

$$I_{os} = \frac{I_{scs}}{\left[\exp\left[\frac{qV_{ocs}}{nKT_{ref}}\right] - 1\right]} \quad (11)$$

The saturation current I_o of the PV cells that set the module depends on the saturation current density of the semiconductor, where generally given in A/cm^2, and on the active area of the cells. The current density I_0 depends on the intrinsic characteristics of the PV cell, which depend on several physical parameters such as the coefficient of diffusion of electrons in the semiconductor, the lifetime of minority carriers, the intrinsic carrier density, etc [13] [20]. This kind of information is not usually available for commercial PV modules. In this paper work, I_{os} of the considered PV module is estimated, using (11) and the available module's data in Table I:

$$I_{os} = \frac{8.63}{\left[\exp\left[\frac{1.6*10-19*22.06}{36*1.3*1.38*10-23*298}\right] - 1\right]} = 7.38 \times 10\text{-}8\ A.$$

TABLE I
Electrical characteristics of Philadelphia Multi-crystalline solar modules PS-P36 150 Wp at STC [24].

Maximum power (Pmaxs)	150.04 W
Voltage at Pmax (Vmps)	18.41 V
Current at Pmax (Imps)	8.15 A
Short-circuit current (Iscs)	8.63 A
Open-circuit voltage (Vocs)	22.06 V
Temperature coefficient of Isc (KI)	0.058 A/°C
Temperature coefficient of Voc (KV)	-0.33 V/°C
Number of cells in series (Ns)	36

A. *Ideality Factor*

The value of the diode ideality factor (n) may be arbitrarily chosen. Several researchers have studied ways to estimate the correct value of this constant. Usually, $1 \le n \le 2$ and the chosen value depends on PV technology and other parameters of the *I–V* curve. And it's given in Table II [5] [23], any initial value of n can be chosen. In this paper work, ideality factor considers $n_{initial} = 1.3$.

TABLE II
Ideality Factor [23].

PV 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
CTs	1.5
AsGa	1.3

B. *Series and Shunt Resistance*

The determination of the parameters R_S and R_{sh} of the actual single diode PV cell model is complex. With higher numbers of independent parameters, the best fit has to be determined iteratively such Newton Raphson method. However, the estimation of initial values for R_{sh} and R_s is relatively simple. In the standard approaches R_s has been calculated using (12). But (12) is applicable only if the output characteristic curves are provided by the manufacturer.

It is possible to estimate the series and shunt resistances, R_s and R_{sh}, from the slopes of the *I-V* curve at

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V_{os} and I_{sc}, respectively. The resistance at Voc, is at best proportional to the series resistance. R_{sh} is represented by the slope at Isc. Only then the value of dV_{PV} / dI_{PV} at open circuit can be extracted. However, there are some datasheets that do not give any output curves. Thus, in (6) cannot be applied for these modules.

$$R_s = -\frac{nKN_sT_{ref}}{qI_o} e^{\frac{-qV_{ocs}}{nN_sKT_{ref}}} - \frac{dV_{pv}}{dI_{pv}} \mid V_{oc} \qquad (12)$$

Alternatively, the value of R_s can be estimated, for this module, from (13) [7].
Note that, (13) can be derived from (7)

$$I_{mp} = I_{ph} - I_o\left(e^{\frac{V_{mp}+I_{mp}R_s}{n_sV_T}} - 1\right) - \frac{V_{mp}+I_{mp}R_s}{R_{sh}},$$

substitute $I_{ph} = I_{scs}$, the estimation of the initial value of $R_{sh} = \infty$ and rearrange the equation.

$$R_s = \frac{nKN_sT_{ref}}{qI_{mps}} \ln\left(\frac{I_{scs} - I_{mps} + I_o}{I_o}\right) - \frac{V_{mps}}{I_{mps}} \qquad (13)$$

By applying the MPP condition and rearranging the resulted terms (14) determines the minimum value of R_{sh} [5], which is represented by the slope at I_{sc} and the MPP. Although the actual value of R_{sh} is still unknown, it is surely greater than $R_{sh,\ min}$ and this is a good initial guess. Therefore, by using (14).

$$R_{sh,min} = \frac{V_{mp}}{I_{scs}-I_{mp}} - \frac{V_{ocs}-V_{mp}}{I_{mp}} \qquad (14)$$

VI. Result And Discussion

With the developed model and step by step procedure, the PV module characteristics are shown in the figures below:

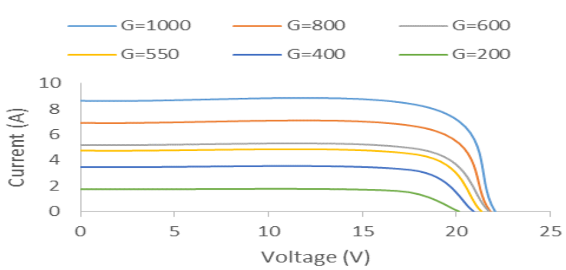

Fig. 3. *I-V* characteristics under varying irradiation at constant temperature 25c°.

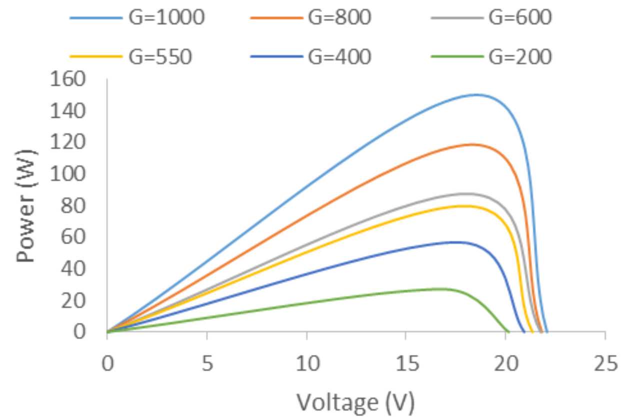

Fig. 4. *P-V* characteristics under varying irradiation at constant temperature 25c°.

Fig. 3 and Fig. 4, represent current – voltage and voltage -power characteristics (*I-V* & *P-V* curve) respectively, under different irradiation with temperature keeps constant based on the modeling equations present in the paper work.

In the present work, the solar irradiation changes with values of 1000, 800,600,400,200 and 550 W/m^2 and this is the average irradiance in Jordan [25], while temperature at standard condition at 25 °C. The Figures shows, the PV cell current is dependent on the radiation with constant temperature. However, when the irradiation increased the current and voltage of PV cell increase. This results in rise in power output in this operating condition.

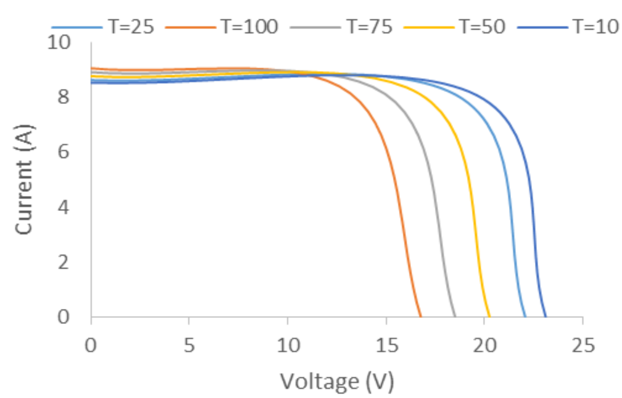

Fig. 5. *I-V* characteristics under varying temperature at constant irradiation 1000w/m^2.

Fig. 5 represent current – voltage characteristics (*I-V* curve) under different temperature value with irradiation keeps constant based on (9). When varying cell temperatures and keep irradiation constant at STC 1000W/m2, the temperature varies from (25, 50, 75,100 and 10 c^o) respectively.

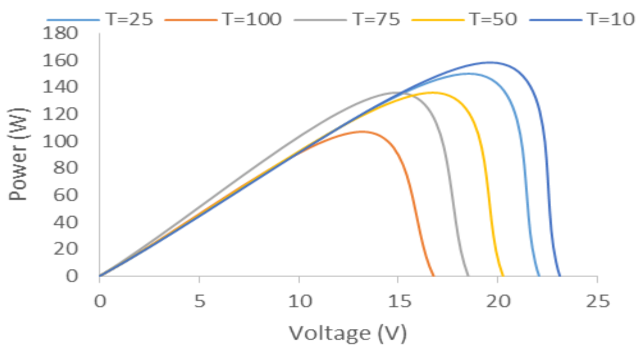

Fig. 6. *P-V* characteristics under varying temperature at constant irradiation 1000w/m^2.

In this case for *I-V* and *P-V* characteristics, when the operating temperature Increase, the current output is increased marginally while the voltage output decrease drastically and that will affect the net power output reduction with rise in temperature.

According to the analysis and results finding, *I-V* characteristics under varying shunt resistance with keep temperature and irradiation constant at STC 1000 w/m^2 and 25c^o respectively. In this case, the effect of shunt resistance resulting in a deviation of the maximum power point for large value. The effect is very low and in some case, it can be neglected as shown in Appendix B. Usually the value of Rsh is very large, hence it may be neglected.

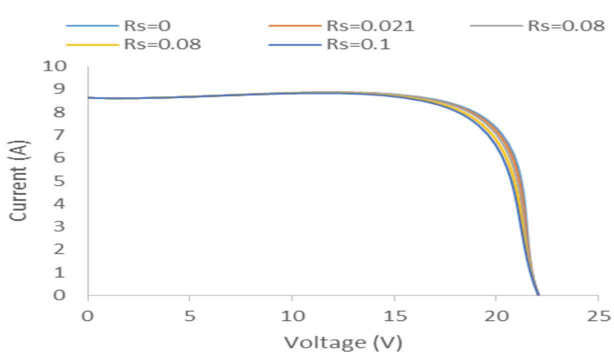

Fig. 7. *I-V* characteristic at STC considers the effect of series resistance variation.

Fig. 7 Series resistance varying value (0, 0.021, 0.04, 0.08 and 0.1) respectively, the Figure shows, the effect of series resistance resulting in a deviation of the maximum power point. The effect is low and in some case, it can be neglected.

The Matlab/SIMULINK model was evaluated for the PS-P36-150Wp solar panel module. The results are shown in Fig. 8. The *I-V* and *P-V* simulation results show a good correspondence in terms of short circuit current, open circuit voltage and maximum power.

In this work, in order to predict the behavior of PV cell under different physical and environmental conditions, the Matlab/SIMULINK model can be considered as a smart tool to extract the internal parameters of any solar PV cell including the ideal factor, series and shunt resistance. Some of these parameters are not always provided by the manufactures.

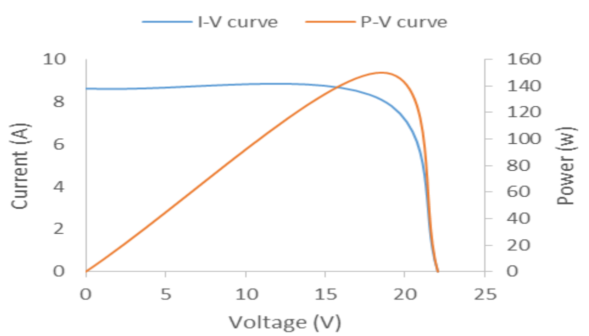

Fig. 8. MATLAB simulation results.

Generally Fig.8 show that, the output power of the PV cell is increases with the radiation intensity by the corresponding linear increase in the current with also the radiation intensity.

VII. Conclusion

The mathematical model of PV cell is presented in this paper works. The proposed procedure provides an accurate and validates model of PV cell. The results from the Matlab model show excellent correspondence to manufacturer`s data from datasheet.

This model was so developed to be used and to show the effect on *I-V* characteristics of temperature, irradiation, shunt and series resistances. The maximum power produced by PV module is about 150.04 W, at parameters near the values presented by the producer: I = 8.15 A and V = 18.41 V (Table I).

By comparing the P36 150W data sheet I-V characteristics at different values of solar irradiance and temperature with one obtained by the Matlab model shown in the Figures 3,4,5,6 and 7 it's clear that the Figures obtained by the model are almost identical to the one found in the module datasheet, this proves that the module is reliable.

In the future work, the behavior of the PV module will be created using the model with experimentally obtained values of the *I-V* and *P-V* characteristics and comparing by the values of the *I-V* and *P-V* characteristics that created by Simulink to find an agreement with better understanding of the PV module.

VIII. Appendix A

Matlab code

```
k = 1.381e-23; % Boltzmann constant, J/K
q=1.602e-19;   % Electronic charge, C
N= 1.3; % Diode quality facror
Eg=1.12;%Band gap voltage,V
Ns=36; % Number of cells in series
% Tref=0+273;% Temperature for which values are known
Ta=25;% Ta Temperature for which values have to be found
Voc=22.06; %Open circuit voltage, V
Isc=8.63;%Short circuit current,
G=1000;% Irradiance,W/m^2
Tref=273+25;
Vt_ref=k*Tref/q;
%Calculation of Iph
Voc_Tref=22.06/Ns;
TK=Ta+273;
K0=0.0058; %Temperature coefficient of Isc
```

R_{sh} input	R_s input	V_{oc} (V)	I_{oc} (A)	V_{mp} (V)	I_{mp} (A)	P_{mp} (W)
37.9	0.021	22.06	8.63	18.53	8.1	150.13
50		22.06	8.63	18.53	8.1	150.13
100		22.06	8.63	18.53	8.1	150.13
400		22.06	8.63	18.53	8.1	150.13

T input	V_{oc} (V)	I_{oc} (A)	V_{mp} (V)	I_{mp} (A)	P_{mp} (W)
100	16.76	9.065	13.18	8.15	107.0713
75	18.5	8.92	14.94	8.1303	121.6776
50	20.25	8.775	16.72	8.118	136.0576
25	22.06	8.63	18.53	8.1	150.13
10	23.1	8.54	19.6	8.08	158.4124

```
Gref=1000;
Vmp=18.41;
Imp=8.15;
Iph_Tref=Isc*(G/Gref);
Iph=Iph_Tref+K0*(TK-Tref);
%Calculation of Saturation current Is
Is_Tref=Isc/(exp(Voc/N/Vt_ref/Ns)-1);
Is=Is_Tref*(TK/Tref).^(3/N).*exp(-q*Eg/(N*k).*((1./TK)-(1/Tref)));
Rs=(((N*k*Ns*Tref)/(q*Imp))*log((Isc-Imp+Is)/Is))-(Vmp/Imp);
Rsh=(Vmp/(Isc-Imp))-((Voc-Vmp)/Imp);
Vt_Ta=N*k*TK / q;
V=Voc:-0.009:0;
 Vc=V/Ns;
   I = zeros(size(Vc));
 for j=1:5;
I = I - (Iph - I - Is.*( exp((V+I.*Rs)./(Vt_Ta*Ns)) -1))./(-1 -(Is.*( exp((V+I.*Rs)./(Vt_Ta*Ns)) -1)).*Rs./(Vt_Ta*Ns)-Rs/Rsh);
    end
     P=I.*V;
    % P=(Iph-Is*(exp((V+I.*Rs)/Vt/Ns/N)-1)-(V+I.*Rs)/Rsh).*V;
% figure(1)
% grid on
% hold on
% plot(V,P)
  figure(2)
  grid on
  hold on
  plot(V,I,'k')
  xlabel('Voltage (V)');
  ylabel('Current (A)')
%ylabel('Power (W)')
```

IX. Appendix B

Relevant input and output data

G input	V_{oc} (V)	I_{oc} (A)	V_{mp} (V)	I_{mp} (A)	P_{mp} (W)
1000	22.06	8.63	18.53	8.1	150.13
800	21.8	6.904	18.31	6.5	118.5924
600	21.47	5.178	18.019	4.85	87.4303
550	21.33	4.746	17.92	4.43	79.7169
400	20.92	3.462	17.587	3.23	56.82
200	20.14	1.726	16.84	1.6	27.12

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R_s input	R_{sh} input	V_{oc} (V)	I_{oc} (A)	V_{mp} (V)	I_{mp} (A)	P_{mp} (W)
0	37.9	22.06	8.63	18.66	8.12	151.51
0.021		22.06	8.63	18.53	8.11	150.13
0.04		22.06	8.63	18.36	8.10	148.89
0.08		2.06	8.63	18.16	8.10	146.27
0.1		22.06	8.63	17.96	8.07	144.97

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