ELEC 5564M

POWER GENERATION BY RENEWABLE SOURCES

Report on

MEASUREMENT OF THE CURRENT-VOLTAGE(I-V) CHARACTERISTICS OF A PRACTICAL PV PANEL AND SIMULATION OF PV PANEL USING DIFFERENT WEATHER CONDITION IN MATLAB

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Introduction

This section of the report contains results for experiment done to determine the I-V and P-V characteristics of a photovoltaic (PV) panel. The experiment was done in various weather conditions by varying the value of the temperature and solar irradiance on the solar panel. Below is a plot of current versus Voltage for the PV panel under low-temperature range (23ºC -28ºC) and high-temperature range (31ºC – 36ºC) on figure 1.1, similarly in figure 1.2 is a plot of the output power against the terminal voltage. The maximum power point (MPP) is marked for each weather condition.

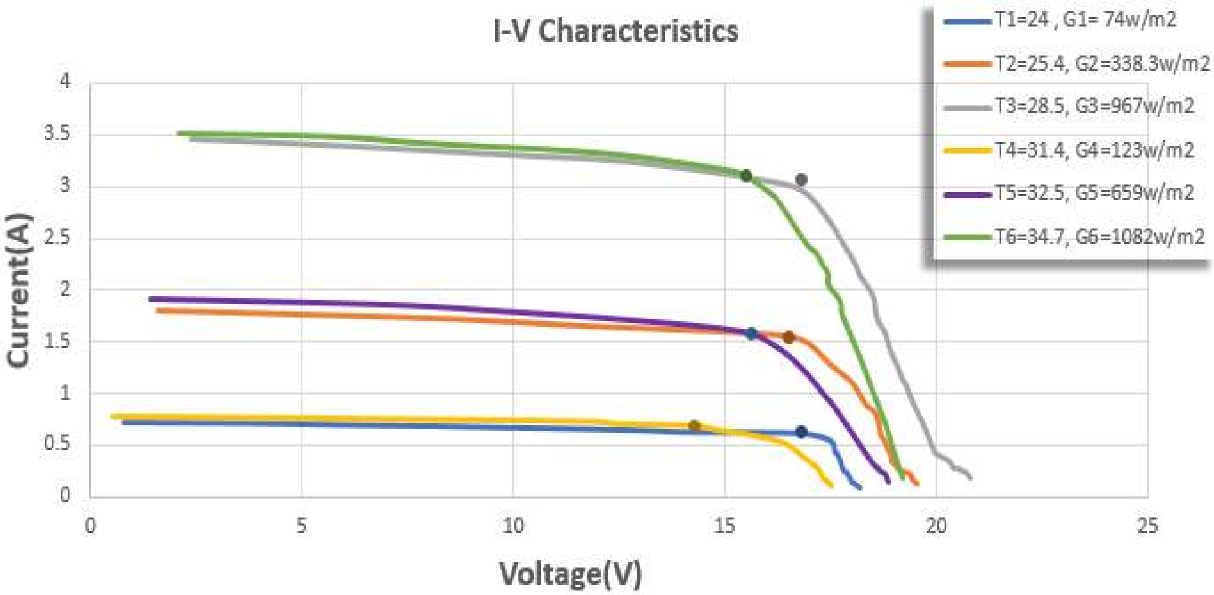


Figure 1.1: I-V characteristics at different weather condition

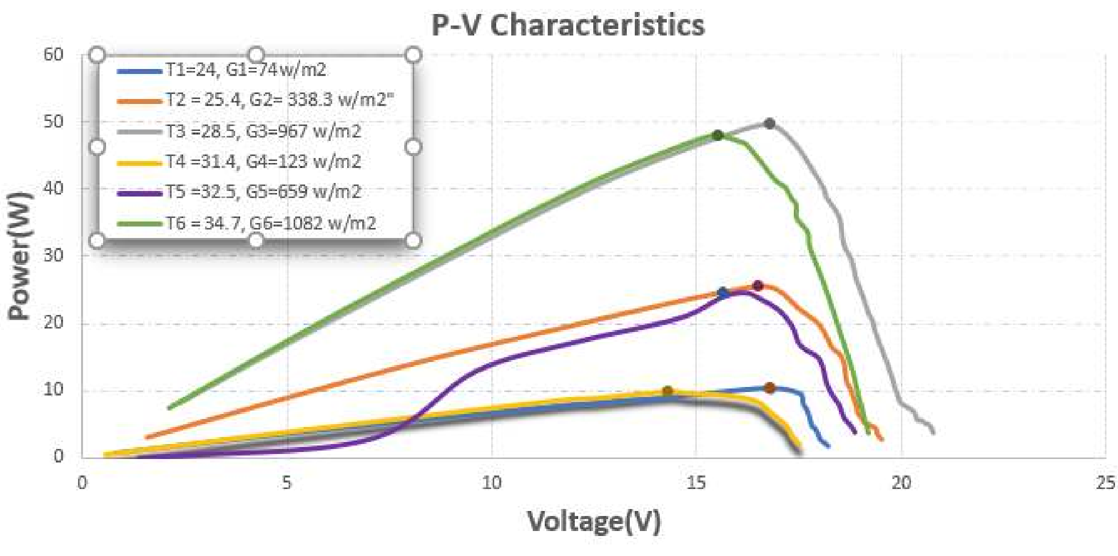


Figure 1.2: P-V characteristics at different weather condition

Maximum Power Point Results

The table below gives the maximum power points and the corresponding voltages and currents for the various weather conditions.

Temperature,T(°C)	Irradiance,G(w/m^2)	Voltage(V)	Current(A)	Maximum Power(W)
24.0	74.0	16.80	0.62	10.416
25.4	338.3	16.50	1.55	25.575
28.5	967.0	16.80	3.06	49.728
31.4	123.0	14.30	0.69	9.867
32.5	659.0	15.62	1.57	24.523
34.7	1082.0	15.50	3.10	48.050

Table 1.1 Maximum power, corresponding voltage and current for each weather condition

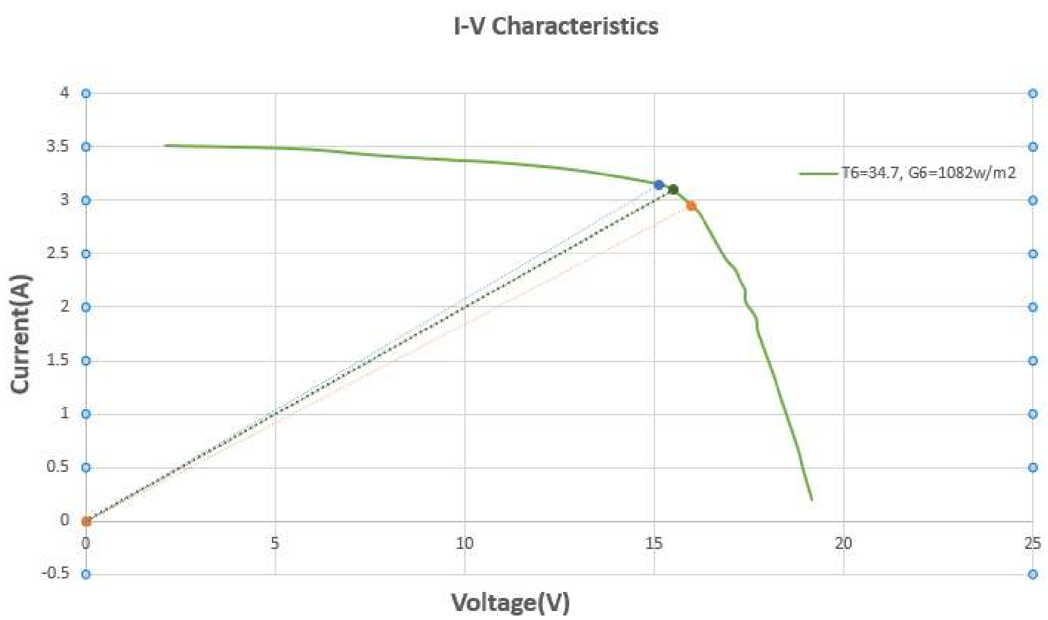
Comment of the power variation in relation to light level and temperature changes

A critical observation of table 1.1 shows that as the light level, G which is supplied to the Photovoltaic cell increases, there is a corresponding increase in the maximum power delivered by the cell. This show that an increase in solar irradiance leads to increased power output.

Similarly, table 1.1 shows that increase in temperature of the cell brings about a proportional decrease in output power of the solar cell.

Investigating points on the I-V characteristics curve

From the sixth weather condition (T6), three values were selected for the evaluation of V/I and dV/dI, Figure 1.3 and table 1.2 summarised the result.



Voltage(V)	Current(I)	V/I (ohms)	Abs(dV/dI)
15.12	3.15	4.80	25.10
15.5	3.1	5.00	3.50
16	2.95	5.424	2.50

Table 1.2 Maximum power and two neighboring points

From the table the R=25.10ohms (at V=16v, I=2.95A) represents the shunt resistance, R_p which signifies losses due to defect in the PV cell, while the resistance R=2.50ohms corresponds to the series resistance. This resistance represents ohmic losses due to metal contacts during the transfer of electric current produced by the solar cell to its terminal, resistor, R=3.50ohms (at V=15.5v, I=3.1A) represents the load resistance, R_L.

Effect of V/I and dV/dI value generated, Characteristics of PV panel, condition when V/I=dV/dI

The effect of R_p and R_s on the PV characteristics can be analyzed using

$$I = I_{SC} - I_S(\exp[\frac{q(V+IR_S)}{AkT_c}]-1) - \frac{V+IR_S}{R_P}$$

From the above equation, the increment in R_s and a corresponding decrease of R_p will affect the I-V characteristics curve significantly, which will, in turn, reduce the short-circuit current and the maximum power.

The above three values of V/I and dV/dI at the corresponding V and I values are equal at maximum power.

Modelling of a PV Module using MATLAB

This section covers the application of Newton Rapson method to solve PV equation in MATLAB, below is the equivalent circuit

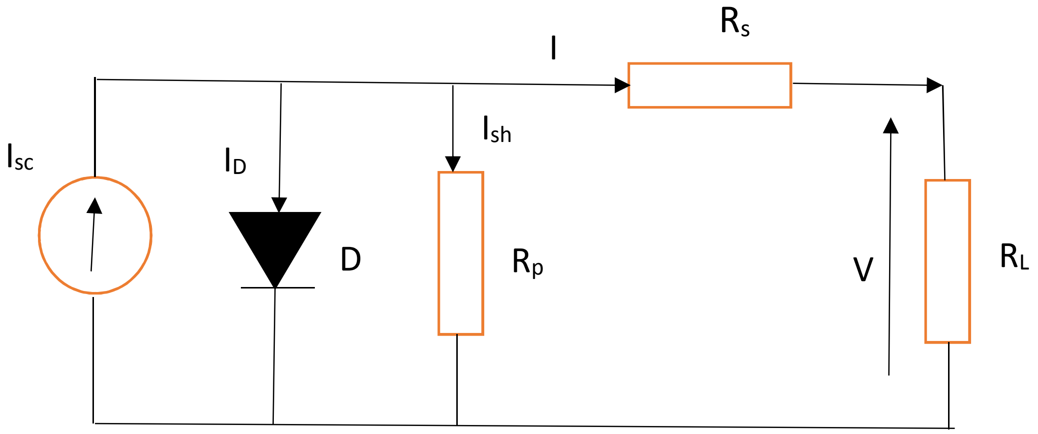


Figure 2.1 Equivalent of a PV panel

Where:

I_{sc} is the photocurrent which is the light generated current in the cell

I_D is the current that flows through the P junction an N junction due to diffusion of charge carriers, it is proportional to the saturation current

R_p is a shunt resistor which is usually of high value, it represents losses due to defect in the PV cell

R_s is a series resistor usually low in value, it represents ohmic losses due to metal contacts during the transfer of electric current produced by the solar cell to its terminal

R_L is the load resistance connected to the output terminal of the PV cell.

I the is the current which flows through the load resistor.

V is the voltage across the load.

Newton-Raphson Method

Newton Raph-son method is a classical iterative root finding algorithm, which can be applied in finding a better approximation of the roots (or zeros) of a function.

The Newton Raphson's method assumes that if the initial guess of the root of a function $f(x_i) = 0$ is at x_i, then the tangent drawn to the curve at $f(x_i)$ produces an estimation of the root as an intercept on the x-axis at x_{i+1}, this can be shown as

$$x_{i+1} = x_i - \frac{f(xi)}{f'(xi)}$$

The above process is repeated until a sufficiently accurate value is obtained.

The stopping criterion is a test of accuracy or the degree of closeness of the assumed value to the actual root of the function, it can be achieved by comparing the accuracy point A_{cc} and the error E_{rr}.

$$E_{rr} = x_{i+1} - x_i = -\frac{f(xi)}{f'(xi)}$$

The iteration will continue until abs(E_{rr}) $\leq A_{cc}$

Program Flowchart and Algorithm

The flowchart of the program is given in figure 2.2, the flowchart gives the procedure in evaluating the current and voltage of the PV panel using Newton Raphson Method, the algorithm explains the flowchart, a summarised algorithm is given below

Start
    Input (1) to vary the solar radiation and (2) to vary the temperature
    Input values for Ta or G depending on the weather condition selected
    initialize G_val to update G values
    Evaluate T_c, I_{sc} I_s
    $T_c = T_a + 0.2*G + 273.18$;
    $I_{sc} = (I_{scr} + k_i*(T_c-T_r)) * G$;
    $I_s = I_{or} * (T_c/T_r)^3 * e^{(q*Eg*(1/Tr - 1/Tc) / (k*A))}$
    Initialize accuracy, Acc
    initialize current, voltage and power array
    set initial condition, I = Isc; V = 0;
while I> 0
    evaluate FI, dFI and error
while error > Acc
    update current, voltage and power arrays
    plot graphs
End
End
Stop

Table 2.1 Flowchart of MATLAB program

A listing of a detailed program with comment is shown below

```
% MatLab Simulation program for a PV Panel
%Written Dagogo Orifama, 201177661
%Electronics and Electrical Engineering, University of Leeds

A =  1.72;              %Ideality factor
q = 1.6*10^-19;         %electron charge
k  = 1.380658*10^-23;   %Boltzmann constant
Eg = 1.1*1.6 *10^-19;   %Band gap
Ior = 19.9693*10^-6;    %Reverse saturation current at Tr
Iscr = 3.3;             %short-circuit current generated at the reference
temperature,Tr
ki = 1.7*10^-3;         %Temperature coefficient of the short-circuit
current
ns = 40;                %number of series panel
np = 2;                 %number of parallel panel
Rs = 5*10^-5;           %series resistance
```

```
Rp = 5*10^5;            %shunt resistance
Tr = 301.18;            %Reference temperature

% Promptn for values of Ta and G
disp('input either (1) or (2) to vary the weather condition based on the
value G or Ta respectively');
WC = input('type your selection:'); %user input is stored here, value can
either be 1 or 2
if(WC==1)
 %if value is 1 supply the various G values and ambient temperature
    disp('Input the Values of G and Ta as a singular matrix: G1,G2,G3,Ta,
Example: [0.3 0.5 1.0 25]');
    SM=input('Please input value : ');
%Assigning values received by the user
G_range=[1,3];G_range(1)=SM(1);G_range(2)=SM(2);G_range(3)=SM(3);
Ta=SM(4);
elseif(WC==2)
%if value is 1 supply the various T values and G value
    disp('Input the Values of G and Ta as a singular matrix: T1,T2,T3,G,
Example: [25 40 60 1]');
    SM=input('Please input value : ');
%Assigning values received by the user
T_range=[1,3];T_range(1)=SM(1);T_range(2)=SM(2);T_range(3)=SM(3);
G=SM(4);
end
for G_val = 1:3
 %Generating the value of Ta and Ga
 if(WC==1)
     G = G_range(G_val);
 elseif(WC==2)
     Ta = T_range(G_val);  G = SM(4);
 end
Tc = Ta + 0.2*G + 273.18;     %Evaluating the cell temperature
Isc = (Iscr + ki*(Tc-Tr)) * G; % Evaluating short-circuit current
Is = Ior * (Tc/Tr)*3 * exp( q*Eg*(1/Tr - 1/Tc) / (k*A)); %Evaluating the
diode leakage current
acc = 1e-3;
%initialising arrays for current, voltage and power
I_array = []; V_array = []; P_array = [];

I = Isc; V = 0;  %initial condition
%..................Newton Raphson methods starts here..............%
while I > 0
fI = I - np*Isc + np*Is*(exp(q*(V/ns+I*Rs/np)/(A*k*Tc))-
1)+(V*np/ns+I*Rs)/Rp;
dfI = 1+ Rs/Rp + q*Is*Rs/A*k*Tc*(exp(q*(V/ns+I*Rs/np)/A*k*Tc));
I_val = I - fI/dfI;
error = abs(I_val-I);
while error > acc   %.......stopping criteria...........%
  I = I_val;
fI = I - np*Isc + np*Is*(exp(q*(V/ns+I*Rs/np)/(A*k*Tc))-
1)+(V*np/ns+I*Rs)/Rp;
dfI = 1+ Rs/Rp + q*Is*Rs/A*k*Tc*(exp(q*(V/ns+I*Rs/np)/A*k*Tc));
I_val = I - fI/dfI;
error = abs(I_val-I);
end
%.....................Newton Raphson method stops here............%
I_array = [I_array I_val]; V_array = [V_array V];
P_val = I_val  * V;
P_array = [P_array P_val];
I = I_val; V = V+.1;
```

```
%tracing the maximum value of power and using it to get Vmp and Imp
Pmp = max(P_array);
index = find(P_array==Pmp);
Vmp = V_array(index);
Imp = I_array(index);
end
% Display Values of Current, Voltage and Power
disp(['I Values:', num2str(I_array)]);
disp(['V Values:', num2str(V_array)]);
disp(['P Values:', num2str(P_array)]);
disp(['P Max:', num2str(Pmp)]); disp(['V Max:', num2str(Vmp)]);
disp(['I Max:', num2str(Imp)]);

%Plot the graph for three values of G
figure(1)
plot(V_array,I_array,'linewidth',1);
xlabel('voltage(V)');ylabel('current(A)');title('I-V characteristics
curve');
ylim([0,8]);
if(WC==1)
    title('I-V characteristics curve at Ta = 25 degree celsius');
legend(strcat('G1 = ',num2str(G_range(1)),'kW/cm^2'),strcat('G2 =
',num2str(G_range(2)),'kW/cm^2'), strcat('G3 =
',num2str(G_range(3)),'kW/cm^2'));
elseif(WC==2)
    title('I-V characteristics curve at G = 1.0kW/m2 ');
   legend(strcat('Ta = ',num2str(T_range(1)),'degree celsius'),strcat('Ta
= ',num2str(T_range(2)),'degree celsius'), strcat('Ta =
',num2str(T_range(3)),'degree celsius'));
end
hold on grid on
pplot = plot (Vmp, Imp, 'd-');
pplot.Annotation.LegendInformation.IconDisplayStyle='off';
hold on
figure(2)
plot(V_array,P_array,'linewidth',1);
xlabel('voltage(V)');ylabel('power(W)');
ylim([0,130]);
if(WC==1)
    title('P-V characteristics curve at Ta = 25 degree celsius');
    legend(strcat('G1 = ',num2str(G_range(1)),'kW/cm^2'),strcat('G2 =
',num2str(G_range(2)),'kW/cm^2'), strcat('G3 =
',num2str(G_range(3)),'kW/cm^2'));
elseif(WC==2)
    title('P-V characteristics curve at G = 1.0kW/m2 ');
      legend(strcat('Ta = ',num2str(T_range(1)),'degree
celsius'),strcat('Ta = ',num2str(T_range(2)),'degree celsius'),
strcat('Ta = ',num2str(T_range(3)),'degree celsius'));
end
hold on grid on
pplot2 = plot (Vmp, Pmp, 'd-');
pplot2.Annotation.LegendInformation.IconDisplayStyle='off';
hold on
end
```

Table 2.2 detailed MATLAB program with comment

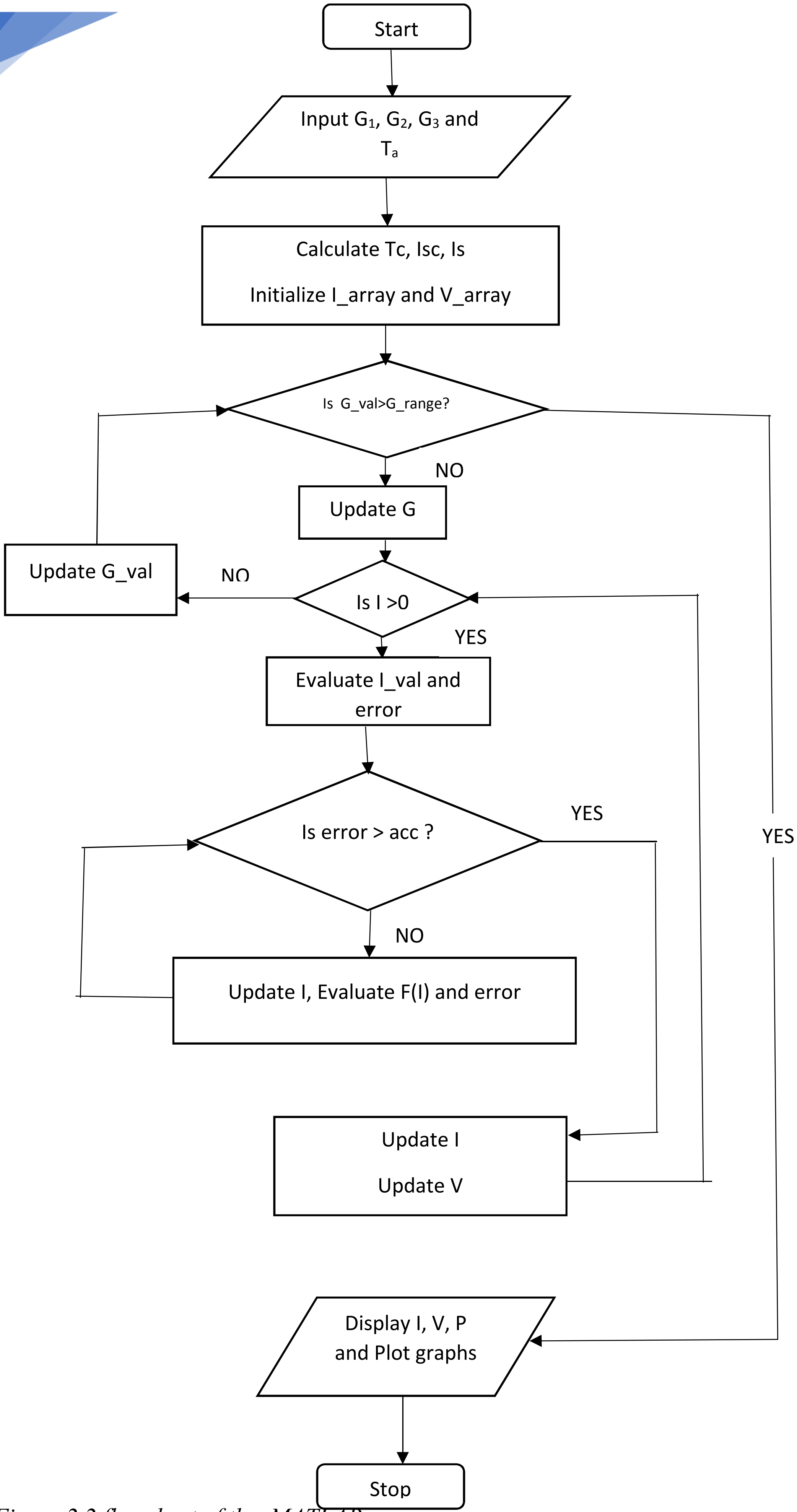


Figure 2.2 flowchart of the MATLAB program

The figure 2.3 and figure 2.4 shows the I-V and P-V characteristics curve for the PV panel when the ambient temperature is kept constant, T_a= 25°C and the solar irradiance varying from G = 0.3, 0.5 and 1.0w/cm^2 .

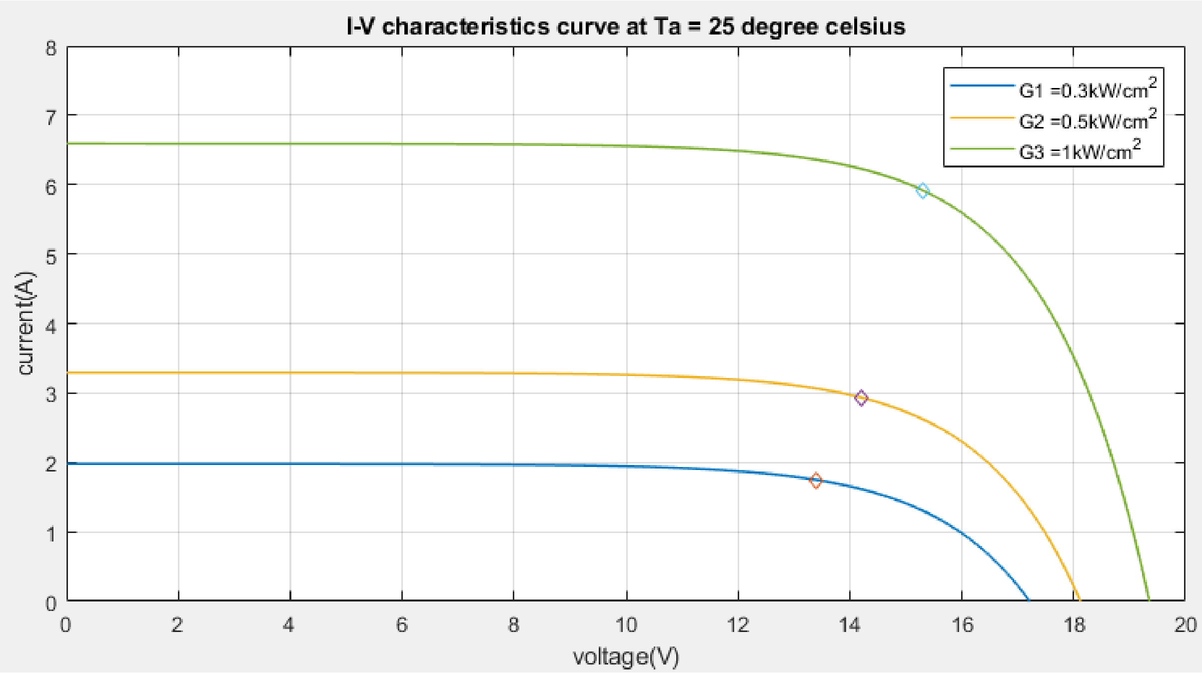


Figure 2.3 I-V characteristcs at T_a= 25°C and G = 0.3, 0.5 and 1.0W/cm^2

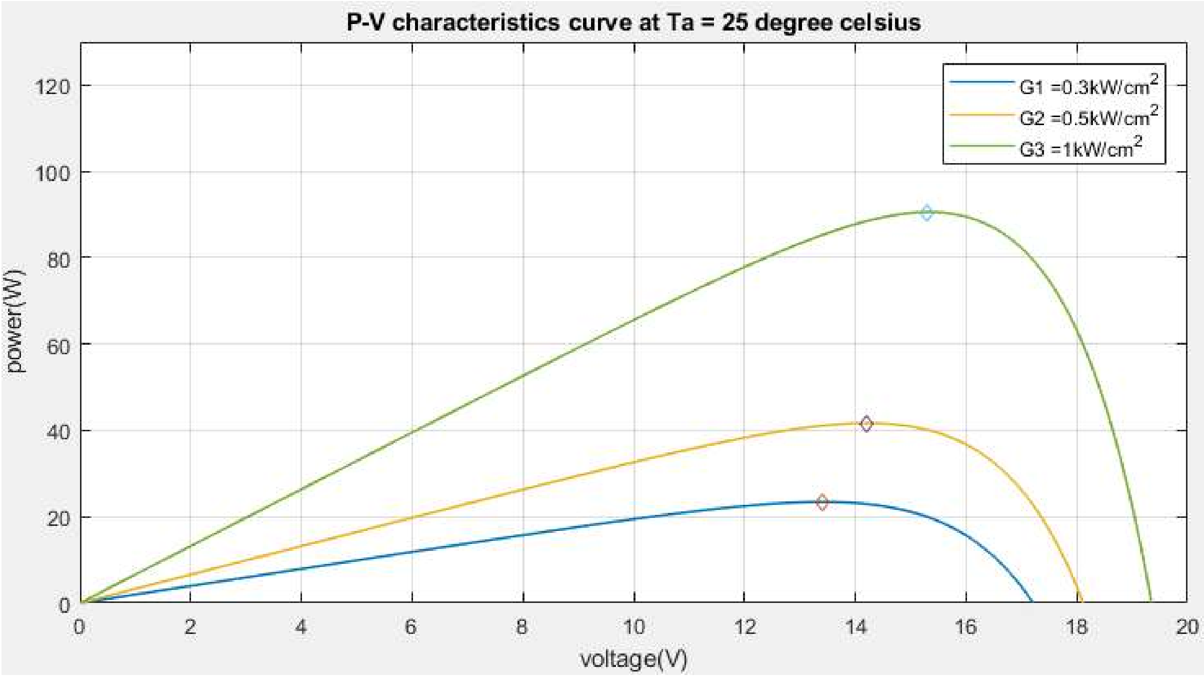


Figure 2.4 P-V characteristcs at T_a= 25°C and G = 0.3, 0.5 and 1.0W/cm^2

The figure 2.5 and 2.6 shows the I-V and P-V characteristics for the PV panel when the solar irradiance is kept constant, G = 1.0W/cm^2 and the solar irradiance varying from T_a = 25, 40 and 60°C.

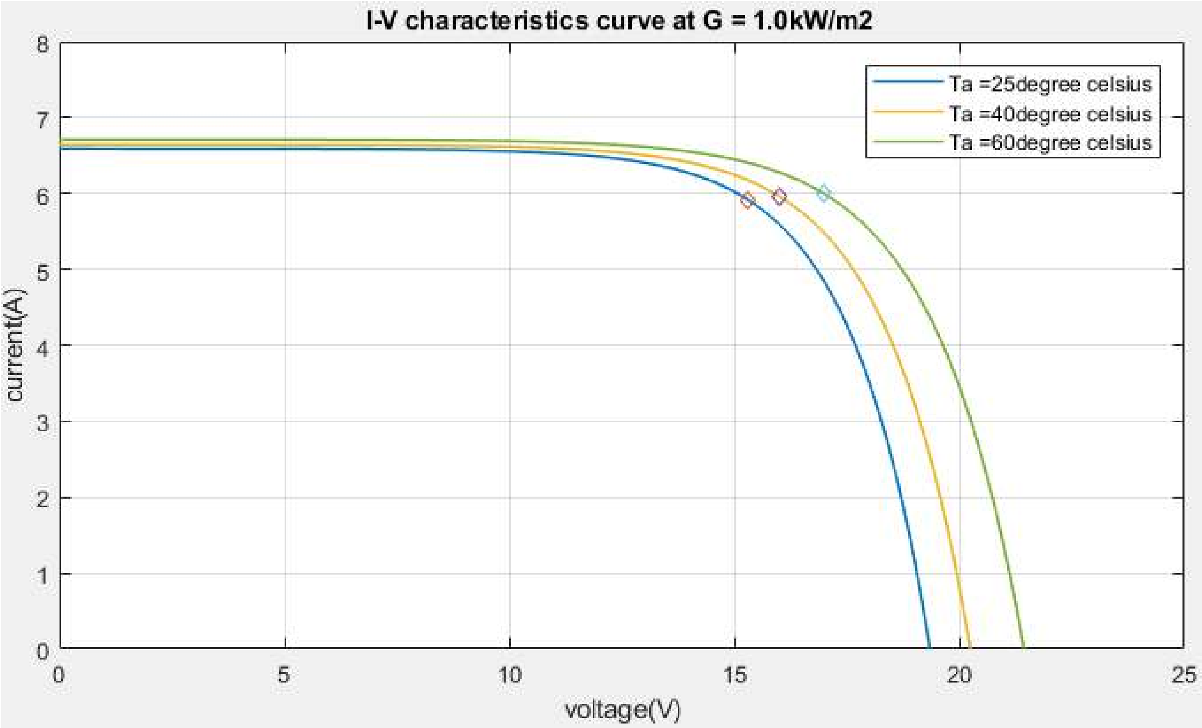


Figure 2.5 I-V characteristcs at G = 1.0W/cm^2 and T_a = 25, 40 and 60^{o}C

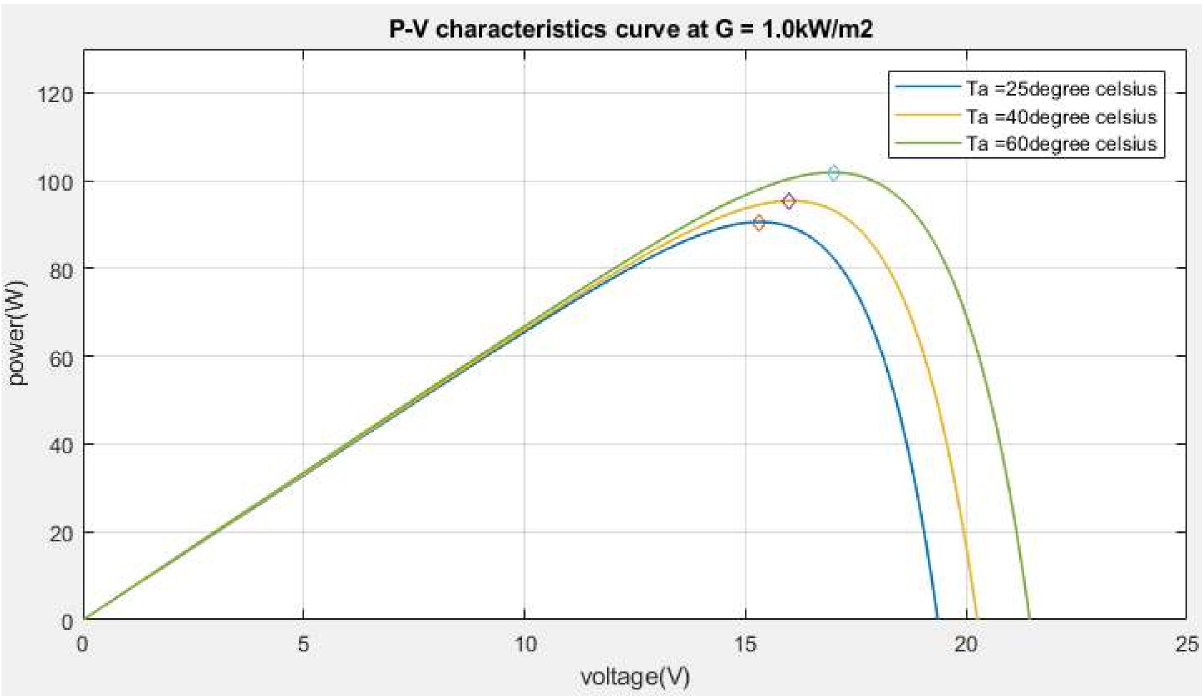


Figure 2.6 P-V characteristcs at G = 1.0W/cm^2 and T_a = 25, 40 and 60^{o}C

Dependence of maximum power on temperature

The performance of a solar cell is inversely proportional to the temperature of the cell, this means an increase in the temperature will bring about decrease in the maximum power of the cell. An increased cell temperature brings about increase in the internal carrier recombination rate caused by the increased carrier concentration. The increased carrier concentration also reduces the band gap of the solar cell by affecting the solar output parameters

Dependence of maximum power on Irradiance

From figure 2.3, as you can see, the I-V characteristics of the solar cell vary under different level of solar radiation. An increase in the solar irradiance increases the short-circuit current and open circuit voltage.This implies more photon energy is available to excite electrons leading to a proportional increase in the maximum power of the solar cell. Hence maximum power increase with increasing solar irradiance.

Evaluation of Fill Factor, FF at various weather conditions and comments

The fill factor is given by

$P_{mp} = I_{mp}V_{mp} = FFV_{ov}I_{sc}$

$$FF = \frac{Pmp}{VovIsc}$$

Table 2.3 shows the calculated values of the fill factor for the various values the irradiance at a constant temperature of 25°C. From the table, it observed that there is an increase in fill factor as the solar irradiance increases. In table 2.4, however, shows a reverse case, where the fill factor is observed to decrease with an increase in ambient temperature (the solar irradiance is kept constant).

Ambient Temperature, T_a =25°C						
G(kw/cm^2)	I_{mp}(A)	V_{mp}(V)	P_{mp}(W)	I_{sc}(A)	V_{oc}(V)	FF
0.3	1.74	13.4	23.41	1.98	17.20	0.690
0.5	2.93	14.1	41.66	3.29	18.10	0.700
1.0	5.92	15.3	90.56	6.59	19.30	0.712

Table 2.3 fill factor values at constant T_a and varying G

Solar Irradiance G = 1kw/cm^2						
T_a(°C)	I_{mp}(A)	V_{mp}(V)	P_{mp}(W)	I_{sc}(A)	V_{oc}(V)	FF
25	5.92	15.3	90.56	6.59	19.3	0.712
40	5.96	16.0	95.40	6.64	20.2	0.711
60	5.99	17.0	101.91	6.71	21.4	0.709

Table 2.4 fill factor values at constant G and varying T_a

Evaluation of Load Resistance, R_L at various weather conditions and comments

The load resistance R_L can be determined as follows

$R_L = Rmp = \frac{Vmp}{Imp}$

Table 2.5 and 2.6 below show the evaluated values of the load resistance required for maximum power point operation for both weather condition. Table 2.5 shows a decrease in load resistance against a proportional increase in solar irradiance. However, in the second weather condition tabulated in table 2.6 the load resistance was observed to have increased with increasing temperature.

Ambient Temperature, T_a =25°C				
G(kw/cm^2)	I_{mp}(A)	V_{mp}(V)	P_{mp}(W)	R_L(ohms,Ω)
0.3	1.74	13.4	23.41	7.70
0.5	2.93	14.1	41.66	4.81
1.0	5.92	15.3	90.56	2.58

Table 2.5 Load resistance values at constant G and varying T_a

Solar Irradiance G = 1kw/cm^2				
T_a(°C)	I_{mp}(A)	V_{mp}(V)	P_{mp}(W)	R_L(ohms,Ω)
25	5.92	15.3	90.56	2.58
40	5.96	16.0	95.40	2.68
60	5.99	17.0	101.91	2.83

Table 2.6 Load resistance values at constant G and varying T_a

Appendix

T1 = 24°C		G1 = 74w/m^2	
Voltage(V)	**Current(A)**	**Power(W)**	**V/I (ohm)**
0.8	0.73	0.584	1.09589
3.8	0.72	2.736	5.277778
5.2	0.71	3.692	7.323944
6.53	0.7	4.571	9.328571
8.41	0.69	5.8029	12.18841
9.5	0.68	6.46	13.97059
10.9	0.67	7.303	16.26866
13	0.65	8.45	20
14.2	0.63	8.946	22.53968
16.8	0.62	10.416	27.09677
17.5	0.55	9.625	31.81818
17.6	0.45	7.92	39.11111
17.7	0.39	6.903	45.38462
17.8	0.27	4.806	65.92593
17.9	0.23	4.117	77.82609
18	0.15	2.7	120
18.1	0.12	2.172	150.8333
18.2	0.09	1.638	202.2222

T2=25.4 °C		G=338.25 w/m^2	
Voltage(V)	**Current(A)**	**Power(W)**	**V/I (ohm)**
1.6	1.8	2.88	0.888889
5.2	1.76	9.152	2.954545
8.5	1.72	14.62	4.94186
11.74	1.65	19.371	7.115152
13.5	1.62	21.87	8.333333
15.2	1.59	24.168	9.559748
16.5	1.55	25.575	10.64516
17	1.47	24.99	11.56463
17.5	1.27	22.225	13.77953
18	1.1	19.8	16.36364
18.3	0.9	16.47	20.33333
18.5	0.83	15.355	22.28916
18.6	0.75	13.95	24.8
18.67	0.6	11.202	31.11667
18.75	0.55	10.3125	34.09091
18.8	0.5	9.4	37.6
18.85	0.45	8.4825	41.88889
18.91	0.4	7.564	47.275

18.93	0.35	6.6255	54.08571
19.02	0.31	5.8962	61.35484
19.1	0.27	5.157	70.74074
19.37	0.22	4.2614	88.04545
19.4	0.18	3.492	107.7778
19.52	0.13	2.5376	150.1538

T3=28.5°C		**G=967w/m²**	
Voltage(V)	**Current(A)**	**Power(W)**	**V/I (ohm)**
2.4	3.45	8.28	0.695652
5.19	3.4	17.646	1.526471
9.81	3.3	32.373	2.972727
12.2	3.25	39.65	3.753846
14	3.17	44.38	4.416404
15.8	3.06	48.348	5.163399
16.8	2.96	49.728	5.675676
17.4	2.7	46.98	6.444444
17.8	2.44	43.432	7.295082
18.1	2.23	40.363	8.116592
18.2	2.13	38.766	8.544601
18.5	1.94	35.89	9.536082
18.6	1.72	31.992	10.81395
18.8	1.57	29.516	11.97452
18.9	1.426	26.9514	13.25386
19	1.33	25.27	14.28571
19.1	1.237	23.6267	15.44058
19.2	1.132	21.7344	16.96113
19.3	1.064	20.5352	18.1391
19.4	0.948	18.3912	20.46414
19.7	0.689	13.5733	28.59216
19.9	0.489	9.7311	40.6953
20	0.412	8.24	48.54369
20.3	0.345	7.0035	58.84058
20.4	0.28	5.712	72.85714
20.5	0.275	5.6375	74.54545
20.6	0.25	5.15	82.4
20.7	0.237	4.9059	87.34177
20.8	0.18	3.744	115.5556

T4=31.4 °C		**G=123w/m²**	
Voltage(V)	**Current(A)**	**Power(W)**	**V/I (ohm)**

0.55	0.78	0.429	0.705128
3.65	0.77	2.8105	4.74026
4.85	0.765	3.71025	6.339869
6.06	0.76	4.6056	7.973684
8.38	0.75	6.285	11.17333
10.6	0.74	7.844	14.32432
11.98	0.73	8.7454	16.41096
12.5	0.71	8.875	17.60563
14.3	0.69	9.867	20.72464
14.8	0.65	9.62	22.76923
15.6	0.6	9.36	26
16.4	0.52	8.528	31.53846
16.8	0.4	6.72	42
17.1	0.304	5.1984	56.25
17.2	0.264	4.5408	65.15152
17.3	0.19	3.287	91.05263
17.4	0.15	2.61	116
17.5	0.11	1.925	159.0909

T5=32.5		**G6=659w/m^2**	
Voltage(V)	**Current(A)**	**Power(W)**	**V/I (ohm)**
1.4	1.905	2.667	0.734908
6.96	1.85	12.876	3.762162
9.61	1.79	17.2019	5.368715
12.05	1.724	20.7742	6.989559
14.59	1.636	23.86924	8.918093
15.62	1.57	24.5234	9.949045
16.2	1.448	23.4576	11.18785
16.6	1.324	21.9784	12.53776
17	1.157	19.669	14.69317
17.32	0.994	17.21608	17.42455
17.48	0.921	16.09908	18.97937
17.65	0.828	14.6142	21.31643
18	0.618	11.124	29.12621
18.17	0.514	9.33938	35.35019
18.31	0.428	7.83668	42.78037
18.48	0.333	6.15384	55.4955
18.58	0.291	5.40678	63.8488
18.67	0.254	4.74218	73.50394
18.77	0.231	4.33587	81.25541
18.81	0.203	3.81843	92.6601
18.86	0.15	2.829	125.7333

T6=34.7°C		G6 = 1082w/m^2	
Voltage(V)	**Current(A)**	**Power(W)**	**V/I (ohm)**
2.1	3.51	7.371	0.598291
5.6	3.48	19.488	1.609195
7.68	3.42	26.2656	2.245614
9.5	3.38	32.11	2.810651
11	3.35	36.85	3.283582
13	3.28	42.64	3.963415
15.12	3.15	47.628	4.8
15.5	3.1	48.05	5
16	2.95	47.2	5.423729
16.2	2.88	46.656	5.625
16.5	2.7	44.55	6.111111
16.9	2.45	41.405	6.897959
17.15	2.35	40.3025	7.297872
17.28	2.25	38.88	7.68
17.42	2.16	37.6272	8.064815
17.43	2.05	35.7315	8.502439
17.67	1.92	33.9264	9.203125
17.73	1.856	32.90688	9.552802
17.75	1.77	31.4175	10.02825
18.12	1.404	25.44048	12.90598
18.3	1.214	22.2162	15.07414
18.54	0.957	17.74278	19.37304
18.8	0.683	12.8404	27.52562
18.94	0.483	9.14802	39.21325
19	0.411	7.809	46.22871
19.06	0.333	6.34698	57.23724
19.1	0.284	5.4244	67.25352
19.14	0.24	4.5936	79.75
19.18	0.191	3.66338	100.4188