LabVIEW based PV Cell Characterization and MPPT under Varying Temperature and Irradiance Conditions

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Abstract—**This paper presents an analysis of variations in the output characteristics of the mono-crystalline silicon PV cell under different temperature and irradiance levels using LabVIEW as the simulation tool. The base of study is mathematical modeling of PV cell characteristics using the well-known one-diode equivalent model in LabVIEW. The designed tool computes and displays current–voltage (I–V) curves, power–voltage (P–V) curves, maximum power point values (V_m , I_m and P_m), operating power point plot, fill factor (FF), cell efficiency (η), optimal load resistance (R') for maximum power, open-circuit voltage (V_{oc}), short-circuit current (I_{sc}) and saturation current (I_o) over a range of cell temperature and irradiation levels.**

The user provides essential parameters as inputs on the front panel in LabVIEW from the datasheet which are given for standard test conditions (STC). The developed tool facilitates the prediction of PV cell behavior over a range of temperatures and irradiance levels other than STC. The results obtained from the simulation tool have matched well with the datasheet values, hence validating the tool. The model is flexible in the sense that it can be applied to PV cells of any size from any manufacturer. The values of series and shunt resistances are selected so as to have least effect on the output characteristics.

Index Terms— **LabVIEW, Output characteristics, Single-diode PV cell model, Silicon PV cell, Simulation, Validation.**

I. INTRODUCTION

THE development of non-conventional and renewable energy sources is sufficiently appreciated due to the fact that conventional non-renewable energy sources like oil, gas and other fossil fuels are getting increasingly depleted. Thus renewable energy sources are gaining importance and becoming important contributors to total energy consumed in the world. India's incident solar power, only on its land area, is about 5000 Petawatt-hours per year (PWh/yr) (i.e. 5000 trillion kWh/yr or about 600 TW), which is far more than current total energy consumption [1]. In India the grid-interactive solar power generated as of December 2010 was merely 10 MW. By the end of March 2013 the installed grid connected PV systems had increased to 1686.44 MW [2]. Above statistics show the trend in adoption of solar PV technology and its potential in India.

A photovoltaic (PV) system converts sunlight directly into electrical power. The basic element of a photovoltaic system is a photovoltaic cell. PV Cells can be grouped to form panels or modules. A single silicon PV cell typically generates 0.5V to 0.8V which is very low for practical use hence they are grouped in series or parallel to form panels or modules. Nevertheless, for all practical purposes the output characteristics of a panel are similar to the PV cell which is its basic element [3]. Hence the analysis of the output characteristics of a solar PV cell becomes an essential procedure.

The PV cell represents the fundamental power conversion unit of a PV panel. The output characteristics of a PV cell depend largely on the solar insolation or irradiance (G), cell temperature (T_c), series resistance (R_s) and Shunt resistance (R_{sh}). R_s and R_{sh} remain constant after the cell has been manufactured so their effect is not considered in the model and their values are selected so as to have negligible effect on the output characteristics. The maximum power (P_m) derived from the PV cell or its maximum operating power point depends on the load resistance (R). Due to the non-linear output characteristics of the PV cell, a tool for modeling and simulation is proved to be useful for deriving the maximum power from the PV cell by determining the optimal load resistance (R').

Several researchers have used different ways to simulate the output characteristics of silicon PV cells, using the MATLAB software [4]-[10]. This paper however presents the solar PV cell modeling and simulation using LabVIEW where the graphical programming has replaced the conventional programming techniques and also it comes with an effective user interface. The developed tool facilitates the prediction of PV cell behavior over a range of temperatures and irradiance levels other than STC which proves resourceful during the design of PV panels and serves as a guide for the selection of PV cells for a panel designer.

The efficiency for mono-crystalline cells is generally between 15% to 20% and between 9% to 12% for polycrystalline. In case of thin film cells, the efficiency is 10% for a-Si, 12% for CuInSe2 and 9% for CdTe [6]. Since mono-crystalline silicon based PV cells have the highest efficiency and popularity, this paper focuses on them.

In the following sections, single-diode solar PV cell circuit model and the equation relating the current and voltage of the

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cell is presented. Other essential basic relations for modeling are also listed. The design concept is explained and the LabVIEW block diagram and front panel are shown. The simulation results for varying cell temperatures and irradiance levels on the output characteristics of the PV cell are shown and analyzed. Also the validation of the presented system is demonstrated by comparing simulated results with the datasheet values of existing commercial PV cell. The determination of optimal load resistance (R') using the developed tool for the maximum power point operation for a range of cell temperatures and irradiance levels is demonstrated.

II. PV CELL MATHEMATICAL AND CIRCUIT MODEL

The well-known single-diode electrical equivalent circuit for a PV cell is shown in Fig. 1.

Terminology:

T_c= cell temperature in Kelvin
$I_{sc} \approx I_{ph}$=Short-circuit current at T_c and Irradiance G (W/m^2).
I_d= Diode current in Amperes
I_{sh}= Current through shunt resistance R_{sh} in Amperes
I_o= reverse saturation current at T_c in Amperes
q= electron charge = 1.60×10^{-19} Coulomb
n= diode ideality factor (between 1 and 2)
K= Boltzmann's Constant = 1.38×10^{-23}Joules/Kelvin
V= output voltage of cell in Volts
I= output current of cell in Amperes
T_r= reference temperature, 298.15 Kelvin
V_{ocr}= open circuit voltage in volts at T_r
I_{scr}= short-circuit current in Amperes at T_r

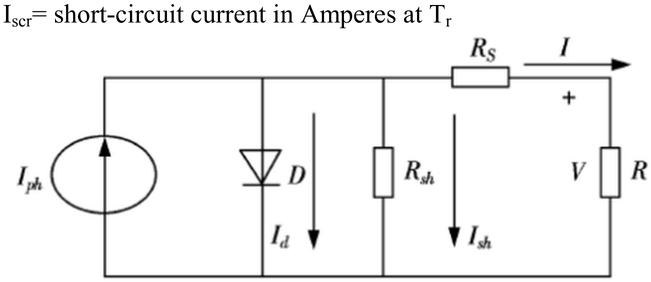

Fig. 1. Single-diode equivalent circuit model for a PV cell [11]

The solar cell can be considered as a current source wherein the photo-current I_{ph}, produced by the solar cell is proportional to the solar irradiation intensity falling on it. A single-diode model is adopted in this paper because of sufficient degree of simplicity and precision. The ohmic losses in the cell occur due to the series and shunt resistances denoted by R_s and R_{sh} respectively. In ideal case R_s is 0 and R_{sh} is ∞. From the fig.1 it is clear that diode forward bias current and the current through the shunt resistance is supplied by I_{ph}. Only the remaining current flows through the load via series resistance R_s [3].

Using the Kirchhoff's current law,

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

The current through the diode is given by,

$$I_d = I_o \, [\exp\,(V_d q / nKT_c) - 1] \qquad (2)$$ [3]

And diode voltage is,

$$V_d = IR_s + V \qquad (3)$$

Leading us finally to the I-V equation of the single-diode equivalent circuit for the PV cell as,

$$I = I_{sc} - I_o \, [\exp\,\{\frac{(V + IR_s)q}{nKT_c}\} - 1] - \frac{V + IR_s}{R_{sh}} \qquad (4)$$

When the terminals of the PV cell are open circuited the voltage produced is maximum and is called open circuit voltage V_{oc} given as,

$$V_{oc} = \ln(\frac{I_{sc}}{I_o} + 1)\,(\frac{nKT_c}{q}) \qquad (5)$$

The reverse saturation current I_{or} at reference temperature is calculated as,

$$I_{or} = \frac{I_{scr}}{[Exp(\frac{qV_{ocr}}{nKT_r}) - 1]} \qquad (6)$$ [9]

The fill factor of the PV cell is the ratio between the maximum power and the product of open circuit voltage and the short circuit current. It is the squareness of the I-V curve of PV cell and mainly related to the resistive losses. This is a very important factor determining the quality of the PV cell and good PV cells usually have a value more than 0.8 or close to this [3].

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} \qquad (7)$$

Where 'V_m' and 'I_m' are the voltage and current values at the maximum power point respectively.

The optimal load resistance (R') is that resistance at which the operating power point of the PV cell is at its maximum. Hence it can be expressed as follows,

$$R' = \frac{V_m}{I_m} \qquad (8)$$

The PV cell efficiency is given by the relation,

$$\eta = \frac{I_{sc} \times V_{oc} \times FF}{P_{in}} \qquad (9)$$

Where P_{in} is the incident irradiance in W/m^2. P_{in} is multiplied by the cell area in m^2 to obtain the total P_{in} for the PV cell for which the simulation is carried out.

All the above equations are implemented in the LabVIEW software for the PV cell characterization.

Typical I-V and P-V characteristics of a PV cell are shown in Fig. 2.

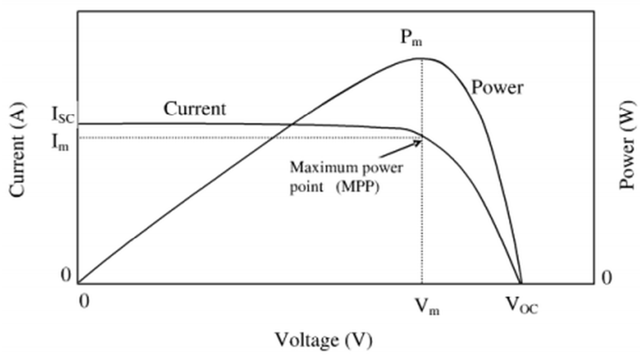

Fig. 2. Typical characteristics of PV cell [7]

III. MODEL DESIGN IN LABVIEW

The designed tool computes and displays on the front panel, current–voltage (I–V) curves, power–voltage (P–V) curves, maximum power point values (V_m , I_m and P_m) and its curve, fill factor (FF), cell efficiency (η), optimal load resistance (R') for maximum power, open-circuit voltage (V_{oc}), short-circuit current (I_{sc}) and saturation current (I_o) over a range of cell temperatures and irradiation levels. The significance of using LabVIEW is its user friendly interface and the graphical programming technique feature. The front panel in LabVIEW allows the user to provide the input parameters to the tool from the datasheet and on running the tool the user is presented with the previously mentioned results in a single click event.

The tool accepts the various input parameters from user pertaining to the PV cell from the datasheet. These parameters are given at STC (25^{o}C and 1000W/m^2).They are open-circuit voltage (V_{ocr}), short-circuit current (I_{scr}), temperature co-efficient of short-circuit current (K_i) in Amps/Kelvin, cell area in cm^2 and diode ideality factor (n) usually 1.3 for silicon based solar cells. Apart from these the three other inputs are the incident solar irradiance in W/m^2, Cell temperature (T_c) and the load resistance (R) which are typically the parameters for which the simulation is required. Series and shunt resistance are chosen sufficiently low and high respectively so as to have negligible effect.

Open circuit voltage is calculated using Eq. (5). Then this value is split into 100 parts and output current under different voltages are obtained from Eq. (4) [11]. The results are bundled and are displayed on the graph producing the I-V curve. Similarly the P-V curve is obtained. The optimal load resistance can be calculated by Eq. (8). The operating power point plot is obtained by the bundled results of I-V curve and the load characteristic curve. The block diagram in LabVIEW is shown in Fig. 3.

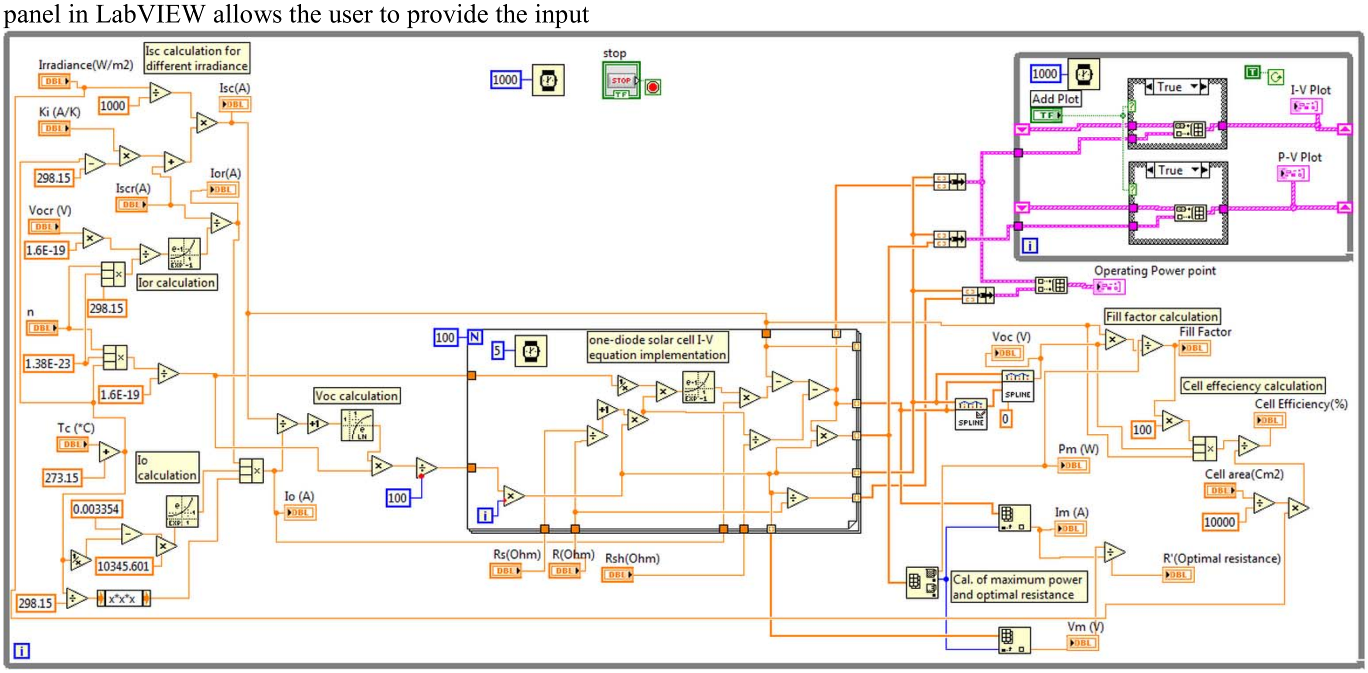

Fig. 3. Block diagram of the simulation system in LabVIEW

The tool compares the various voltage and current values to find the maximum voltage and maximum current and the corresponding maximum power. The tool also has a feature to hold the previous graph for the I-V and the P-V curve to allow the user to easily compare the various plots. The front panel of tool in LabVIEW is shown in Fig. 4.

IV. SIMULATION RESULTS

This section covers the validation of the presented tool by comparing the simulation results with the values given the datasheet of KL156MB2 monocrystalline solar cell of KL Solar Pvt. Ltd. Company [12]. Then the usefulness of the developed tool is realized from the simulation results for other than standard test conditions.

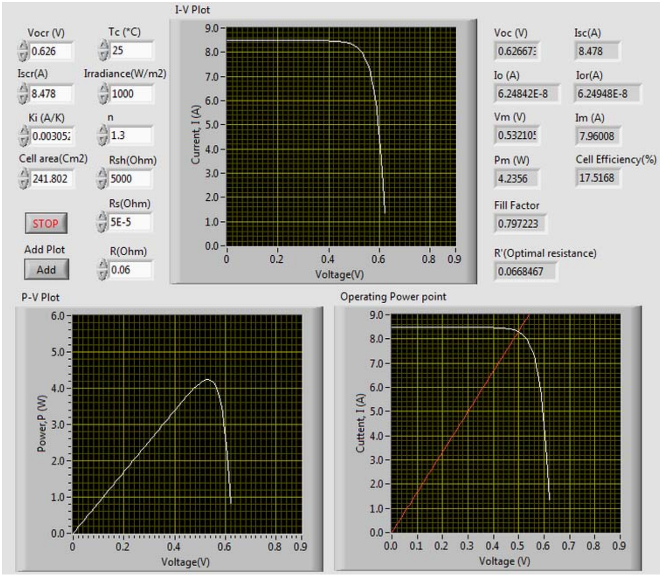

Fig. 4. Front panel of the simulation system

The simulation is also done for standard test conditions to verify the results of tool. The results obtained matched well with the datasheet information. The following table lists the specifications of the KL156MB2 mono-crystalline solar cell used in simulation.

TABLE I
KL156MB2 DATA SHEET

Parameter	Value
Size	155.5mm X 155.5mm
K_i	0.003052 A/K
V_{ocr}	0.626 V
I_{scr}	8.478 A
V_m	0.520 V
I_m	7.915 A
P_m	4.11 W
Fill Factor	0.78
Efficiency	17.3% to 17.5%

A. Comparison between datasheet values and simulated results

The values in the datasheet in Table I are given for standard test conditions i.e. 25^0C and 1000W/m^2. The snapshot of the front panel in fig.4 was taken when temperature and irradiance were 25^oC and 1000 W/m^2 respectively. It is clearly seen that the results of the simulation model for V_{oc} , I_{sc} , V_m , I_m , P_m , fill factor and efficiency match well with those values in the datasheet from Table I validating the model. These results are summarized in Table II.

TABLE II
COMPARISON OF DATASHEET AND SIMULATED RESULTS

Parameter	Datasheet value	Simulated value
V_{oc}	0.626 V	0.626 V
I_{sc}	8.478 A	8.478 A
V_m	0.520 V	0.532 V
I_m	7.915 A	7.960 A
P_m	4.112 W	4.235 W
η	17.40 %	17.50 %
FF	0.774	0.797

B. Simulation under varying cell temperatures and constant irradiance 1000W/m^2

Increase in temperature results in the decrease in the band gap of the semiconductor material. The parameter most affected is the open-circuit voltage (V_{oc}) because of its dependence on saturation current (I_o). This can be seen through Eq. (10).

$$I_o = I_{or}[\frac{T_c}{T_r}]^3 \exp[\frac{qE_g}{nK}\{\frac{1}{T_r}-\frac{1}{T_c}\}] \quad ....(10)\ [9]$$

Where I_{or} is saturation current at T_r and is calculated by equation (6), T_r is the reference temperature which is 298.15K, E_g is the band gap energy which is 1.3ev for silicon based PV cells.

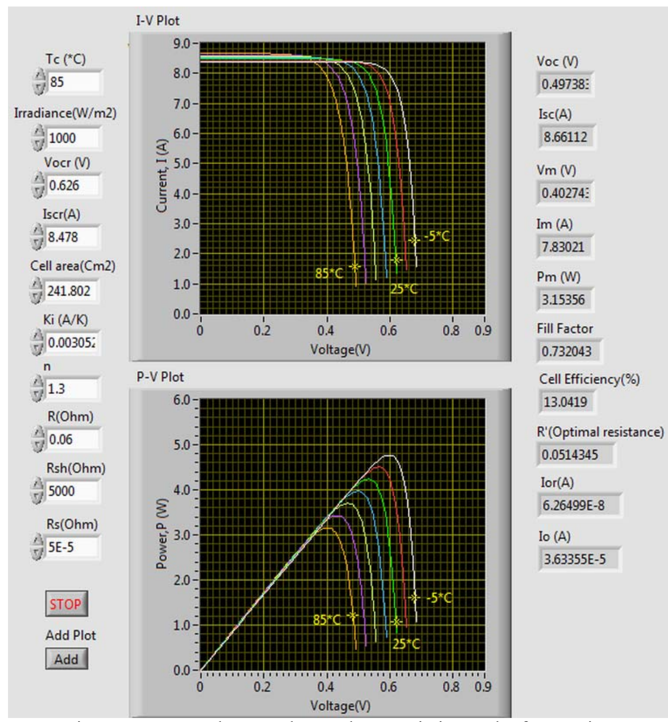

Fig. 5. Front panel I-V and P-V characteristic results for varying temperatures.

The front panel in LabVIEW with the I-V and the P-V characteristics for the various temperatures are shown in Fig. 5. The temperature is varied from -5^{o}C to 85^{o}C in steps of 15^{o}C at a constant irradiance of 1000W/m^2. As the cell temperature increases V_{oc} decreases linearly due to the increase in I_o, with only a slight increase in the I_{sc} but the net power output decreases linearly, the cell thus becoming less efficient [8].

Referring to Fig. 5 it is seen that as T_c increases from -5^{o}C to 85^{o}C , V_{oc} reduces from 0.69V to 0.49V and I_{sc} increases slightly from 8.38A to 8.65A from the I-V plot. Also there is an increase in I_o form 9.38 x 10^{-10}A to 3.63 x 10^{-5}A which is the primary factor causing V_{oc} to decrease. It can be seen from the P-V plot that P_m reduces from 4.76W to 3.15W. The FF goes down from 0.82 to 0.73 and efficiency from 19.7% to 13.0% which is significant. Hence it is very important to find ways to regulate the cell temperature and keep it as low as possible. The above results are summarized in Table III.

TABLE III
SIMULATION RESULTS FOR VARYING CELL TEMPERATURES

T_c(°C)	I_o(A)	Voc(V)	I_{sc}(A)	V_m(V)	I_m(A)	P_m(W)	FF	η(%)
-5	9.38×10^{-10}	0.69	8.38	0.59	7.94	4.76	0.82	19.70
10	8.53×10^{-9}	0.65	8.42	0.56	7.95	4.50	0.81	18.61
25	6.26×10^{-8}	0.62	8.47	0.53	7.95	4.23	0.79	17.50
40	3.82×10^{-7}	0.59	8.52	0.49	7.94	3.96	0.78	16.39
55	1.99×10^{-6}	0.56	8.56	0.46	7.92	3.69	0.76	15.28
70	9.03×10^{-6}	0.52	8.61	0.43	7.88	3.42	0.75	14.16
85	3.63×10^{-5}	0.49	8.65	0.40	7.82	3.15	0.73	13.03

C. Simulation under different irradiation levels and constant cell temperature 25°C

There is a direct relationship between the output power of solar cell and solar irradiation. This is because the light generated current I_{ph} is directly dependent on the solar irradiation and hence I_{sc} increases with the increase in the incident irradiation [11].

$$I_{sc} = \frac{G}{1000}[I_{scr} + K_i(T_c - T_r)] \quad ....(11) \;\; [10]$$

Where G is the incident solar irradiation in W/m^2, I_{scr} is the short circuit current at reference temperature T_r, K_i is the temperature coefficient of short-circuit current in A/K given in data sheet and T_c is the cell temperature. Therefore short-circuit current increases linearly with the increase in the solar irradiance but the open circuit voltage increases logarithmically as seen in Eq. (5).

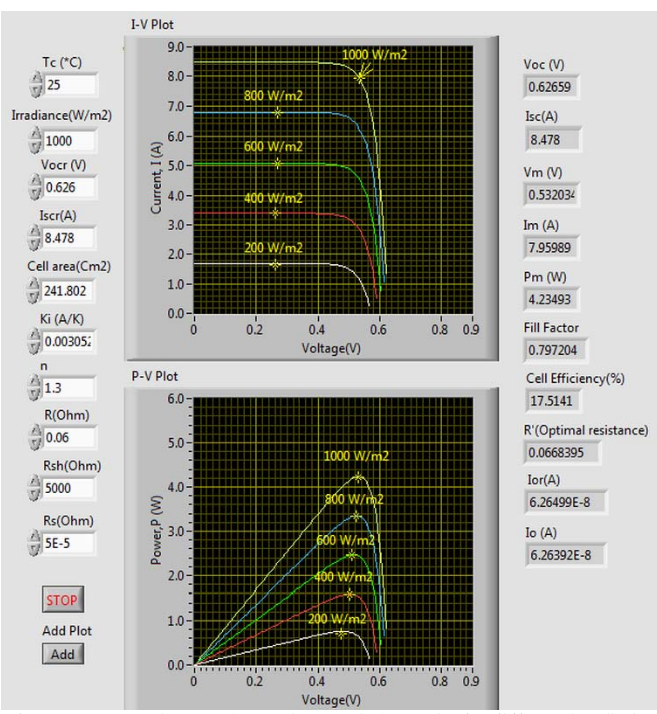

Fig. 6. Front panel I-V and P-V characteristic results for different irradiation levels.

The front panel in LabVIEW with the I-V and the P-V characteristics for the different irradiation levels are shown in Fig. 6. The levels chosen are from 200W/m^2 to 1000W/m^2 in steps of 200W/m^2 at a constant cell temperature of 25°C. The rest of the parameters are taken from the datasheet given in Table I.

Referring to Fig. 6 it is seen that as the solar irradiation is increased from 200W/m^2 to 1000W/m^2, I_{sc} increases linearly from 1.69A to 8.47A with a slight increase in V_{oc} from 0.57V to 0.62V from the I-V plot. The P-V plot shows the increase in P_m from 0.76W to 4.23W. The efficiency is increased from 15.74% to 17.5 % and fill factor from 0.78 to 0.79. By these results it is deduced that solar irradiance does not affect the efficiency and fill factor as much as cell temperature. But the cell power output is directly related to the irradiance. These results are summarized in Table IV.

TABLE IV
SIMULATION RESULTS FOR DIFFERENT IRRADIATION LEVELS

G(W/m^2)	Voc(V)	I_{sc}(A)	V_m(V)	I_m(A)	P_m(W)	FF	η(%)
200	0.57	1.69	0.48	1.58	0.76	0.78	15.74
400	0.59	3.39	0.50	3.19	1.59	0.78	16.50
600	0.61	5.08	0.52	4.75	2.46	0.79	16.94
800	0.62	6.78	0.52	6.35	3.34	0.79	17.26
1000	0.63	8.47	0.53	7.95	4.23	0.79	17.50

D. Operating power point plot and maximum power point tracking (MPPT).

As of now the cost per unit power for solar cells is expensive than the conventional methods based on fossil fuels [3]. Given this fact, if at any time maximum power is not derived from the solar cell then the consumer is at loss. The operating power point of the solar cell depends on the load resistance connected to it. The operating point is at maximum power when the load resistance connected is of the value given by Eq. (8). Maximum power point can be tracked by replacing the load resistance (R) with optimal load resistance (R') which the tool calculates for the cell temperature and irradiance inputs from the user.

The operating power point is the intersection of the PV cell I-V characteristics curve and the load characteristic curve as shown in the Fig. 7 as point 'P'.

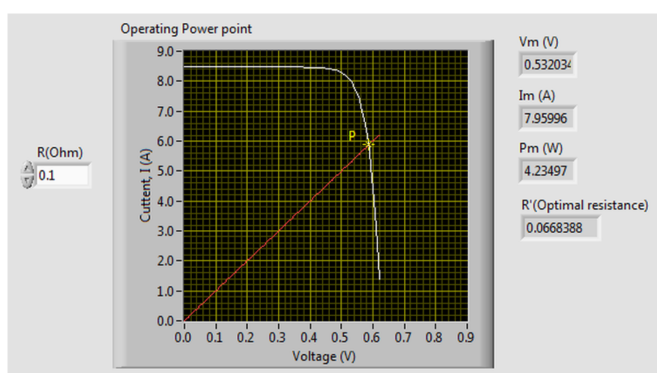

Fig. 7. Operating point plot for R=0.1 Ohm.

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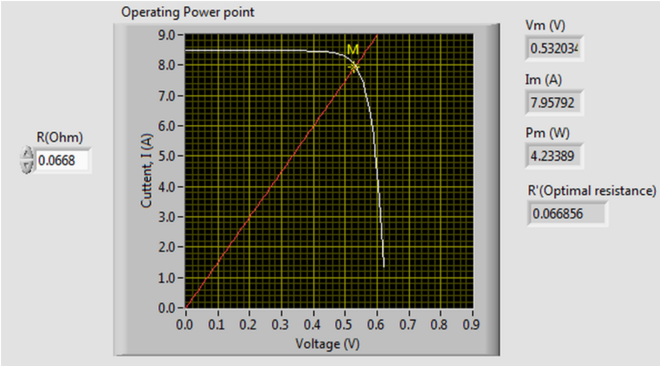

Fig. 8. Maximum power point M at R=R’= 0.0668 Ohm

Comparing the Fig. 7 and Fig. 8 the point 'P' in the Fig. 7 is not operating at the maximum power meaning $P \neq P_m$. This is because the load resistance R=0.1Ohm is not the optimum value. The tool calculates the optimal value of the load resistance as R'=0.0668Ohm indicated on the front panel in Fig. 7. It is important to notice that after replacing the load resistance R with the optimal load resistance R' the operating power point shifts and settles on the maximum power point ‘M’ on the I-V curve as shown in the Fig. 8. At this point $V=V_m$, $I=I_m$ and $P=P_m$.

Other required parameters are obtained from the datasheet in Table I. The tool is capable of calculating the optimal load resistance for different temperature and irradiance levels given as inputs by the user. The simulated results are summarized in Table V.

TABLE V
SIMULATION RESULTS FOR OPTIMAL LOAD RESISTANCE

G(W/m^2), T_c=25°C	R’(Ohm)	T_c(°C), G=1000W/m^2	R’(Ohm)
200	0.3034	-5	0.0753
400	0.1566	10	0.0710
600	0.1089	25	0.0668
800	0.0827	40	0.0628
1000	0.0668	55	0.0588
		70	0.0551
		85	0.0514

The results show that larger the solar irradiation and cell temperature, the lesser is the value of the required optimal load resistance (R').

V. CONCLUSION

A resourceful tool for mono-crystalline silicon PV cell characterization for varying temperature and irradiance levels using LabVIEW software was developed and presented in this paper. The tool takes the specifications in the manufacturer’s data sheet as inputs from the user and facilitates analysis of variations in the output characteristics of the PV cell for the desired temperature and irradiance conditions given as inputs by user on the LabVIEW front panel. The presented tool was validated using the KL156MB2 mono-crystalline solar cell datasheet. The tool is flexible for simulation of any mono-crystalline PV cell of any size from any manufacturer. The simulation results are obtained from the tool on a single-click event.

Another important feature of the developed model is that it is capable to calculate and present the value of the optimal load resistance to derive the maximum power from the solar cell under the given irradiation and temperature conditions. This feature enables the maximum power point tracking for the given PV cell.

Panel designers can make use of this tool for the cell characteristics comparison. The tool presented in this paper can also be extended for the simulation of the PV panels and arrays. The advantages of using LabVIEW as a tool for simulation due to its graphical programming style and a user-friendly interface are apparent.

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