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# Modeling and Simulation of Solar Cell using Embedded MATLAB Simulink Tool

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***ABSTRACT:***
*The bountiful supply of sunlight has made the photovoltaic cell technology (converting sunlight into direct current) supreme among the diverse group of renewable energy resources available for electricity generation. This paper illustrates a typical modeling of a photovoltaic cell (SUNPOWER A300). Based on the single diode equivalent circuit, the model is implemented on using embedded MATLAB function block in SIMULINK, containing script, which accepts voltage as input, different irradiance and temperature as variable parameters and generate the I-V and P-V plots as output.*

***KEYWORDS:SUNPOWER- A300; Irradiance; Temperature; I-V and P-V curves***

## I. INTRODUCTION

Nowadays, the trend is to explore the renewable energy resources as much as possible as the stocks of non-renewable energy resources are under the apprehension of being fully exhausted within a next few hundred years. The bliss of the renewable resources is their sustainability, less maintenance cost, less or no production of the greenhouse or net carbon emissions and, last but not the least, considerably less noise pollution rendering minimal impact on the environment. Hydrogen and helium atoms are assumed to compose the main sequence star, the life-giving Sun, and the nuclear fusion of hydrogen nuclei into helium atoms serves as the source of the solar energy, the major among the five chief renewable energy resources-solar, water (hydro), wind, geothermal and biomass. 620 million metric tons of hydrogen atoms are fused each second in the core of Sun.

Photovoltaic cells are used to harvest the solar energy to produce direct current. The photons of light from the sun excite the electrons in the silicon cells to generate electric power. Although solar panels are capable of producing voluminous output (6%-amorphous silicon-based solar cell to 42.8% with multiple cells: 14-19% for commercially available multi- crystalline solar cells) [1], several critical factors like temperature, irradiance, shading, snow, etc. dominate the solar panel efficiency considerably. Generally, the assessment of the solar cell performance under Standard Test Conditions (STC with Irradiance=1000W/m$^2$ and Temperature=25°C) does not take into account existent geographical and meteorological conditions prevalent at the installation site. In order to anatomize the influence of these factors, modeling of PV cell is of paramount importance for real-time simulation. In solar cell R & D, computer-based modeling plays an integral role. [2]

## II. MODELING THE SOLAR CELL

A. Mathematical Model

An illuminated p-n junction acts as a solar cell. In its simplest (unconditional) configuration a solar cell is a current source placed in parallel with a diode, however, the model changes when the non-ideality factors especially the parasitic resistances (i.e. equivalent series and shunt resistances) are taken into account. Since the output of the current source varies directly with sunlight incident upon it, the solar cell is an inactive device during darkness resulting in zero voltage and current. This section briefly describes the single diode model of a solar cell and associated equations(Figure 1).

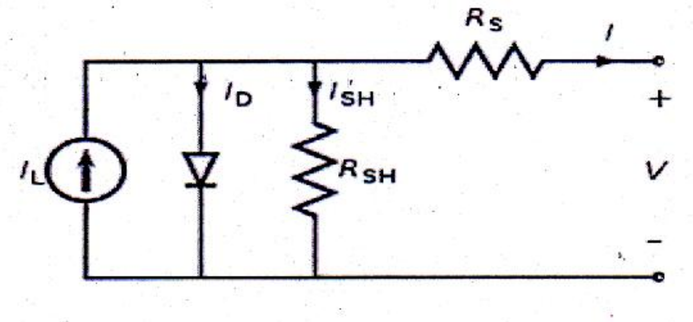


**FIGURE1: SINGLE DIODE MODEL WITH SERIES RESISTANCE$R_S$AND SHUNT RESISTANCE $R_{SH}$**

The Shockley diode equation can be stated as:

$$I_D = I_0(e^{\frac{qV_D}{nKT}} - 1)$$

$$I_D = I_0(e^{\frac{V_D}{nV_T}} - 1)$$

The output current, I= $I_L$-$I_D$ ,under ideal conditions neglecting the parasitic series and shunt resistances.

$$I = I_L - I_0(e^{\frac{qV_D}{nKT}} - 1)$$

With series resistance $R_S$

$$I = I_L - I_0(e^{\frac{q(V+IR_S)}{nKT}} - 1)$$

With series resistance $R_S$ and shunt resistance $R_{SH}$,

$$I = I_L - I_D - I_{R_{SH}}$$

$$I = I_L - I_0(e^{\frac{q(V+IR_S)}{nKT}} - 1) - (\frac{V + IR_S}{R_{SH}})$$

However $R_S$=0 in an ideal solar cell [3].In this paper, $R_{SH}$is neglected hence considering a moderately complex model with series resistance only [4].

The other equations involved can be listed as:

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

Where $G_{NOM}$ and$T_{1NOM}$ are the values of sun and temperature at standard test condition (i.e. $G_{NOM}$=1000W/m$^2$,$T_{1NOM}$=25°C)

$$I_L = I_L(T_1) + K_0(T - T_1)$$

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

$$I_0(T_1) = \frac{I_{SC}(T_1)}{(e^{\frac{qV_{OC}(T_1)}{nKT_1}} - 1)}$$

$$I_0 = I_0(T_1) \times (\frac{T}{T_1})^{\frac{3}{n}} e^{\frac{qV_g(T_1)}{nK(\frac{1}{T} - \frac{1}{T_1})}}$$

$$X_V = I_0(T_1)\frac{q}{nKT_1} e^{\frac{qV_{OC}(T_1)}{nKT_1}} - \frac{1}{X_V}$$

$$R_S = -\frac{dV}{dI_{V_{OC}}} - \frac{1}{X_V} \quad (5)$$

**TABLE-I**
**CHARACTERISTIC PARAMETERS**

| SYMBOL | DESCRIPTION | UNIT |
|---|---|---|
| $I_D$ | Diode current | Ampere(A) |
| $I_0$ | Reverse saturation bias current (or scale current) | Ampere(A) |
| I | Output current | Ampere(A) |
| $I_L$ | Photon current corresponding to a particular irradiance level and given temperature, varying directly with irradiance level | Ampere(A) |
| $I_{SC}$ | Short circuit current | Ampere(A) |
| $I_{MAX}$ | Maximum current at MPP | Ampere(A) |
| q | Charge of an electron (1.602 X $10^{-19}$Coulombs) | Coulombs |
| K | Boltzmann Constant(1.38 X $10^{-23}$J/K) | Joule/Kelvin(J/K) |
| n | Ideality factor of the diode (typically varies between 1 and 2(however it can be more), based on the fabrication process and semiconductor material. It is set to 1 for an ideal diode. | - |
| $V_T$ | Thermal voltage (approximately 25.85mV at 300K) | Volts(V) |
| $V_D$ | Voltage across the diode | Volts(V) |
| $V_{OC}$ | Open circuit voltage | Volts(V) |
| $V_{MAX}$ | Maximum voltage at MPP | Volts(V) |
| $T_1$ | Normalized temperature(=25 °C at STC) | Kelvin (K) |
| T | Working temperature in Kelvin. | Kelvin (K) |

| | | |
|---|---|---|
| $R_S$ | Series resistance is the equivalent resistance in contacts, metal grids as well as the resistance encountered (internal losses) by the current flow in the p-n layers of the semiconductor material | Ohm |
| $R_{SH}$ | Shunt resistance that corresponds to the leakage current of p-n junction | Ohm |
| G | Number of Suns | Watt/metre$^2$(W/m$^2$)<br>(At STC, G=1Sun = 1000 W/m$^2$) |
| $K_0$ | Current/Temperature coefficient | Ampere/Kelvin[A/K] |
| Vg | Voltage of the Crystalline Silicon | Electron volt [eV] |
| $dV/dI_{Voc}$ | dV/dI coefficient at Voc | Ampere/Kelvin[A/V] |
| $P_{MAX}$ | Maximum power at MPP | Watts |
| MPP | Maximum Power Point | - |
| FF | Fill Factor | - |
| STC | Standard Test Condition | - |
| A | exposed PV cell area | cm$^2$ |

The abecedarian parameters characterizing the solar cell are:

1. Short circuit current($I_{SC}$)
2. Open circuit voltage ($V_{OC}$)
3. Maximum power point (MPP)
4. Efficiency of PV cell (η)
5. Fill Factor (FF)

Where $I_{SC}$ is the maximum value of current (equal to the photon current for very small values of series parasitic resistance) under short circuit conditions, $V_{OC}$ (ranging from 500-650 mV roughly) is the most attainable voltage under open circuit condition (zero current). The maximum cell current ($I_{SC}$, under short circuit condition) and the maximum cell voltage ($V_{OC}$, under open circuit condition) do not occur simultaneously and hence maximum output power ($P_{MAX}$ ) that can be delivered to the connected load by the PV cell is not equal to product of $I_{SC}$ and$V_{OC}$. The maximum power output $P_{MAX}$ is expressed as the product of $I_{MAX}$ (Current at Maximum Power Point) and $V_{MAX}$ (Voltage at Maximum Power Point), which are much less than $I_{SC}$ and $V_{OC}$ respectively. Efficiency is the ratio of PV cell output to the input light power and is denoted as

$$\text{Efficiency} = \frac{P_{OUT}}{P_{IN}} = \frac{P_{MAX}}{G} = \frac{I_{MAX}V_{MAX}}{GA} = \frac{I_{MAX}V_{MAX}}{1000A}$$

The ratio between the product of current and voltage corresponding to the maximum power point to the product of short circuit current times the open circuit voltage is termed as Fill Factor. This parameter conveys the idea about the cell quality and typically ranges between 0.7-0.8 for good cells.

$$FF = \frac{I_{MAX}V_{MAX}}{I_{SC}V_{OC}}$$

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B. Current-Voltage (I-V) Curve for a solar Cell:

Solar cell I-V and P-V characteristic curves offer an elaborate delineation of the input-output analysis of the cell and therefore important in determining the cell output and solar efficiency. Relating to the equation $I = I_L - I_D - I_{RSH}$ ,the I-V Curve of a solar cell shows an inverse relation between output current decreasing from maximum value i.e. the short circuit current to zero as we sweep the voltage from zero to its maximum value that is the open circuit voltage. I-V plot is shown in Figure 2A.

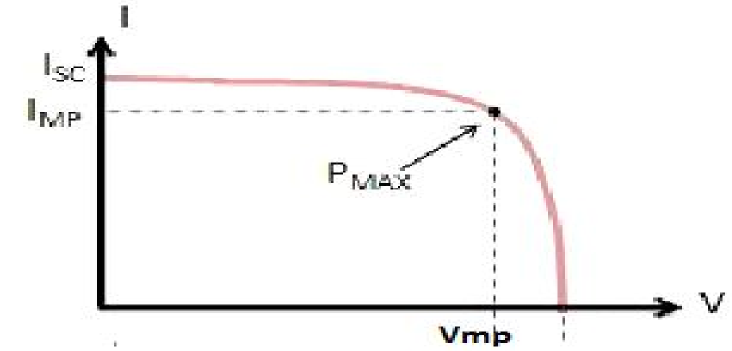


**FIGURE 2(A) I-V PLOT**

C. Power -Voltage (P-V) Curve for a solar Cell:

In any DC electrical circuit, Power (P) in Watts (W) = The Current in Amperes (A) X the Voltage in Volts (V) i.e. W = V X A. Thus the P-V curve is the measure of the different valuesof output power (product of current and voltage from I-V curve) corresponding to respective voltage levels.P-V plot is shown in Figure 2B.

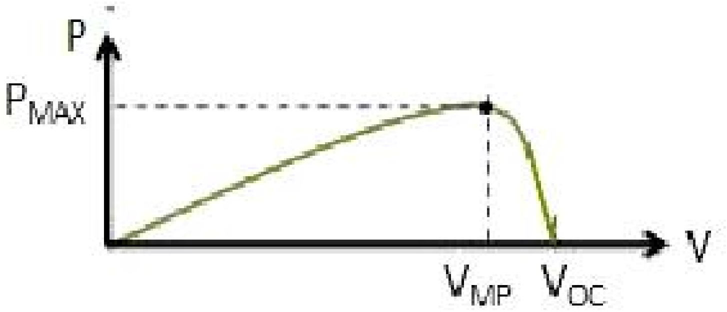


**FIGURE 2(B) P-V PLOT**

D. Effect of irradiance and temperature on solar cell as environment variables:

Solar cell efficiency refers to that portion of sunlight that is converted into electricity via photovoltaic effect. Temperature and ambient irradiance widely dominate the solar cell efficiency and their variation throughout the day result in different I-V and P-V characteristics.

Short circuit current starts at a maximum value at zero voltage, remains fairly constant at low voltages and falls rapidly at a voltage close to 0.5V(close to open circuit voltage when $I_{SC} = 0$ ). $I_{SC}$ relying on the solar

insolation, sun's light spectrum and solar cell geometry (i.e. area and characteristics of material) though evince a linear variation with ambient irradiation as more electron-hole pairs are created, its variation with temperature (positive temperature coefficient) is marginal (roughly 0.05% increase with every °C).

Neglecting the parasitic resistances,

$$I = I_L - I_0 (e^{\frac{qV_D}{nKT}} - 1)$$

Under open circuit conditions, I=0,$V_D$=$V_{OC}$

$$V_{OC} = \frac{nKT}{q} \ln(\frac{I_L}{I_0} + 1)$$

This equation clearly indicates that $V_{OC}$ is widely controlled by the dark saturation current. The reverse saturation current of the diode, is not constant for any given device but varies widely with working temperature, T. For every 10 °C temperature rise, $I_0$doubles itself. The inverse relationship makes $V_{OC}$exhibit a negative temperature coefficient (roughly around -0.35%/°C or -2.2mV/°C ) as the rate of photon generation increases, intrinsic semiconductor band gap shrinks,[6] and temperature increase results in an increase in $I_0$.Although $V_{OC}$ depends on manufacturing techniques, its logarithmic variation with irradiance (though positive coefficient) is not that significant.

Moreover, both $I_{SC}$ and $V_{OC}$ have positive coefficient and power output escalates with increasing irradiance. But as the decrease in $V_{OC}$ results in less maximum theoretical power**[6]** $P_{MAX}$= $I_{SC}$ X $V_{OC}$ with same $I_{SC}$ temperature adversely affects the solar cell output(as for each degree rise in temperature above 25°C the cell output decreases by 0.25% for amorphous cells and about 0.4-0.5% for crystalline cells).

Thus the obtainable maximum power is more on sunny days with low temperature. Non-silicon temperature insensitive solar cells are preferred more so that the temperature can be kept close to 25°C [7]**.**Figure 3A shows the I-V plot and Figure 3B shows the P-V plot at different irradiance levels and 25°C .Figure 4A shows the I -V plot and Figure 4B shows theP-V plot at different temperature levels and 1Sun [10].

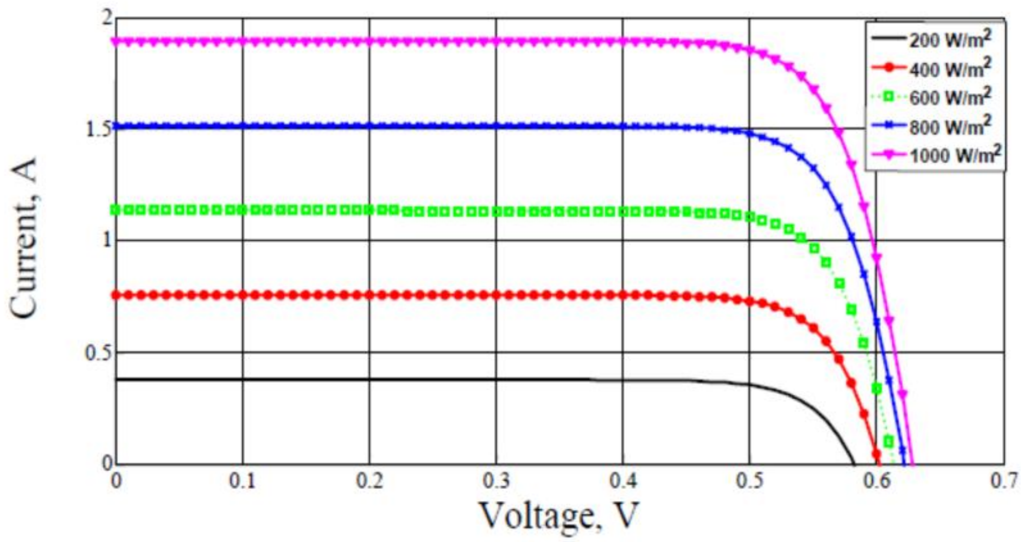


**FIGURE 3A:I-V PLOT AT DIFFERENT IRRADIANCE LEVELS AND 25°C**

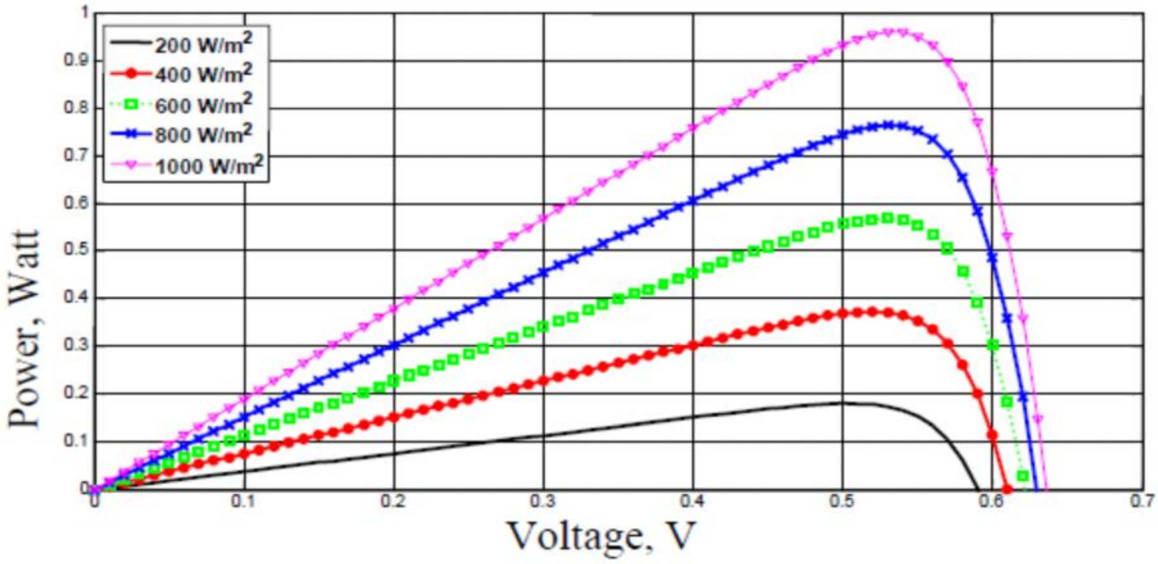


**FIGURE 3B:P-V PLOT AT DIFFERENT IRRADIANCE LEVELS AND 25°C**

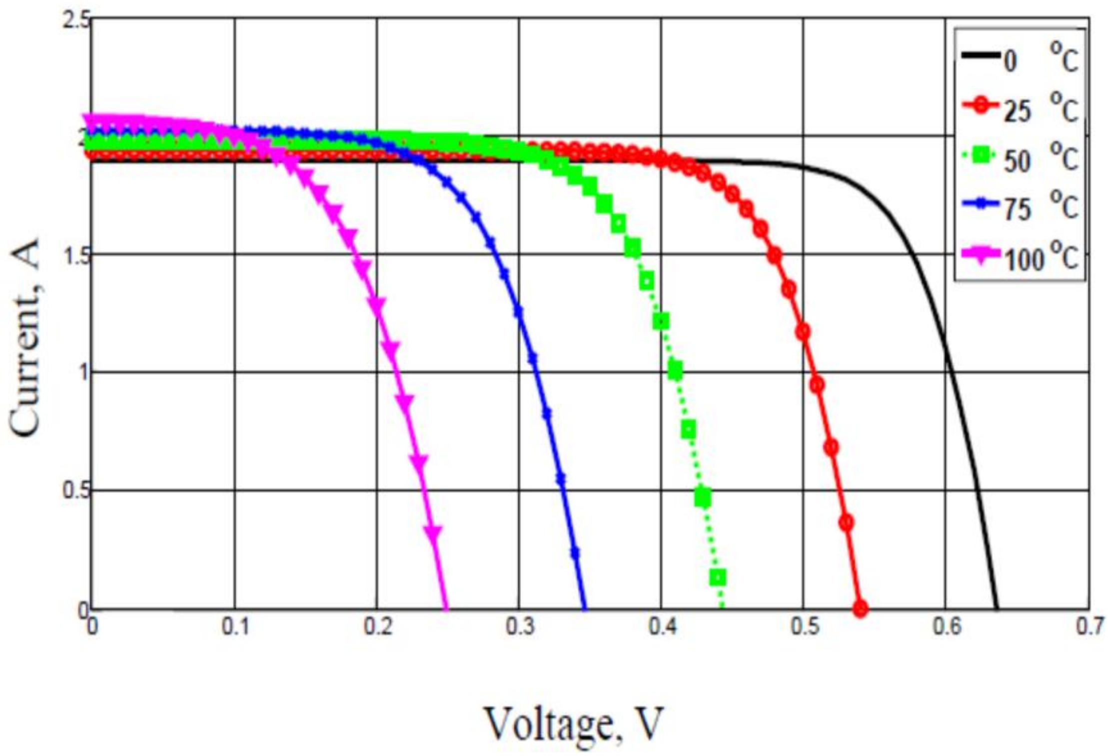


**FIGURE4A:I-V PLOT AT DIFFERENT TEMPERATURE LEVELS AND 1 SUN**

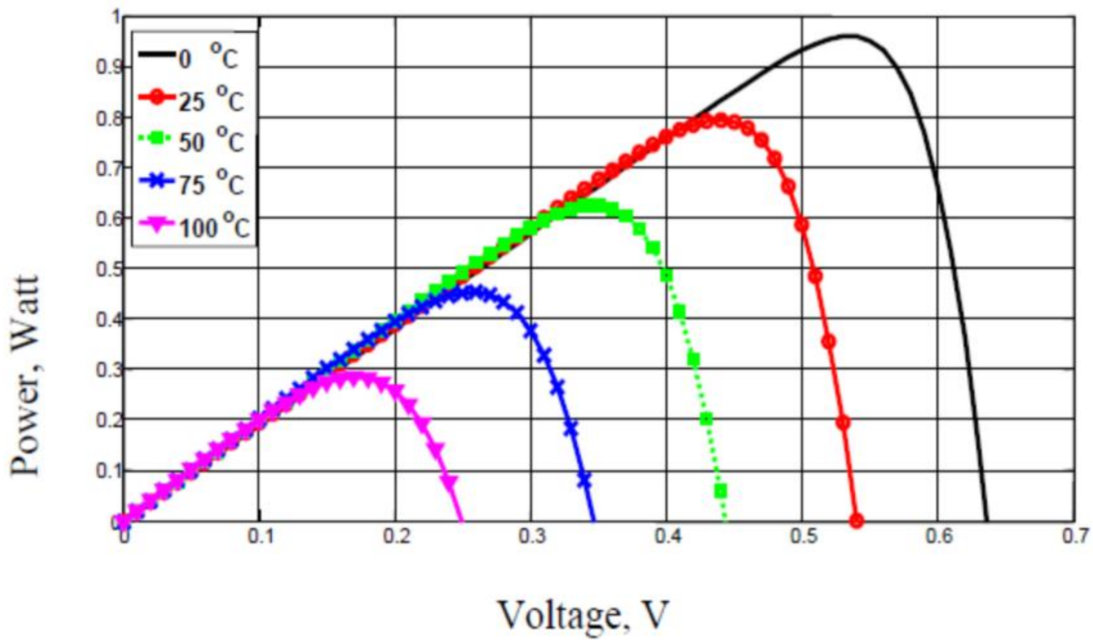


FIGURE4B:P-V PLOT AT DIFFERENT TEMPERATURE LEVELS AND 1 SUN

**TABLE-II**

**MONTHLY AVERAGE GLOBAL HORIZONTAL IRRADIANCE (in KWhr/m2/day) AND AVERAGE TEMPERATURE (°C) VARIATION OF KOLKATA**

| MONTH | IRRADIANCE (in KWhr/m$^2$/day) | IRRADIANCE(in Suns) | AVERAGE TEMPERATURE(°C) |
|---|---|---|---|
| **January** | **4.27** | **0.17792** | **20.1** |
| February | 5.17 | 0.21542 | 23 |
| **March** | **6.00** | **0.25** | **27.6** |
| April | 6.58 | 0.27417 | 30.2 |
| **May** | **6.48** | **0.27** | **30.7** |
| June | 5.10 | 0.2125 | 30.3 |
| **July** | **4.60** | **0.19162** | **29.2** |
| August | 4.52 | 0.18833 | 29.1 |
| **September** | **4.70** | **0.19583** | **29.1** |
| October | 4.50 | 0.1875 | 28.2 |
| **November** | **4.65** | **0.19375** | **24.9** |
| December | 4.17 | 0.17375 | 20.8 |

NOTES:*Conversion Formulas used: 1 KWhr/m$^2$/day = 41.67W/m$^2$ =0.041667 Suns and 1 Suns= 1000W/m$^2$

*The above six entries appearing in bold are used in real-time modeling and simulation.

*Monthly Average Global Horizontal Irradiance (in KWhr/m2/day) of Kolkata, West Bengal, India, Latitude: 22.55, Longitude: 88.35 are taken as reference. Annual Average: 5.06 kWh/m2/day [Source: NREL].Temperature reference is drawn from Yr – Weather statistics for Kolkata, West Bengal (India)

## III. RESULTS AND ANALYSIS

The Sunpower A300 is chosen for modeling and simulation due to its sweeping applications in the field of photovoltaics.The SIMULINK models of a specific solar cell, Make SUNPOWER, Model A-300 (shown in Fig:5(a) and (c)) have been developed which consists of an embedded MATLAB function(solar) with multiple inputs as variable irradiance and temperature. The input subsystem is shown in Fig:5(b) and (d).The embedded MATLAB function extensively make use of the equations for PV cell represented by single diode model as mentioned in section II. The voltage as an input to PV cell is varied from 0- 0.65V using ramp block and passed to embedded MATLAB function block containing MATLAB script with fixed value characteristic constants (mentioned in TABLE-III).The six constant blocks are used for passing the average irradiance value and average temperature corresponding to months starting from January to December interleaved with two months as per TABLE-II. The plot of short circuit current, current and power with voltage for each value of irradiance are obtained at the scope (shown in fig- I-V plot and P-V plot). Similarly, the plot of short circuit current, current, and power with voltage for each value of temperature are obtained at the scope (shown in fig- I-V plot and P-V plot). The purpose of using embedded MATLAB function block instead of Simscape blocks under SIMULINK is that the same Simulink model can be used for simulation of any other PV cell with a mere change in MATLAB script and with different values of characteristic parameters**.**Figure 5A shows the Simulink model for variable irradiance, 5B shows the Input irradiance subsystem, 5C shows the Simulink model for variable temperature and 5D shows Input temperature subsystem.

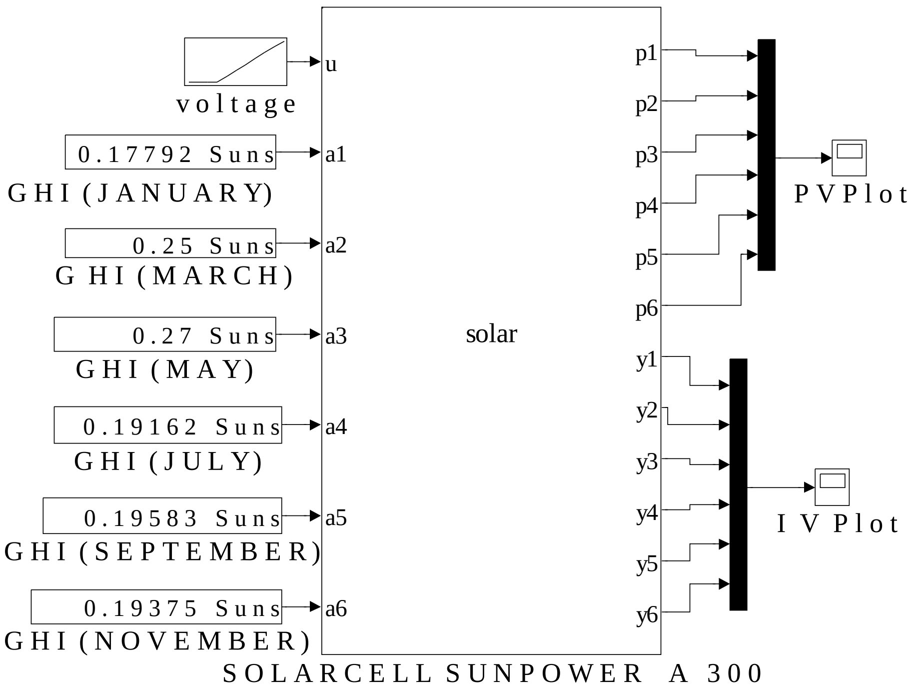


**FIGURE 5A:SIMULINK MODEL FOR VARIABLE IRRADIANCE**

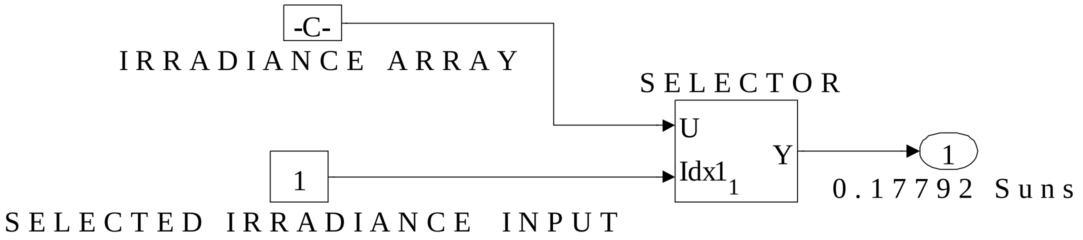


**FIGURE 5B: INPUT IRRADIANCE SUBSYSTEM**

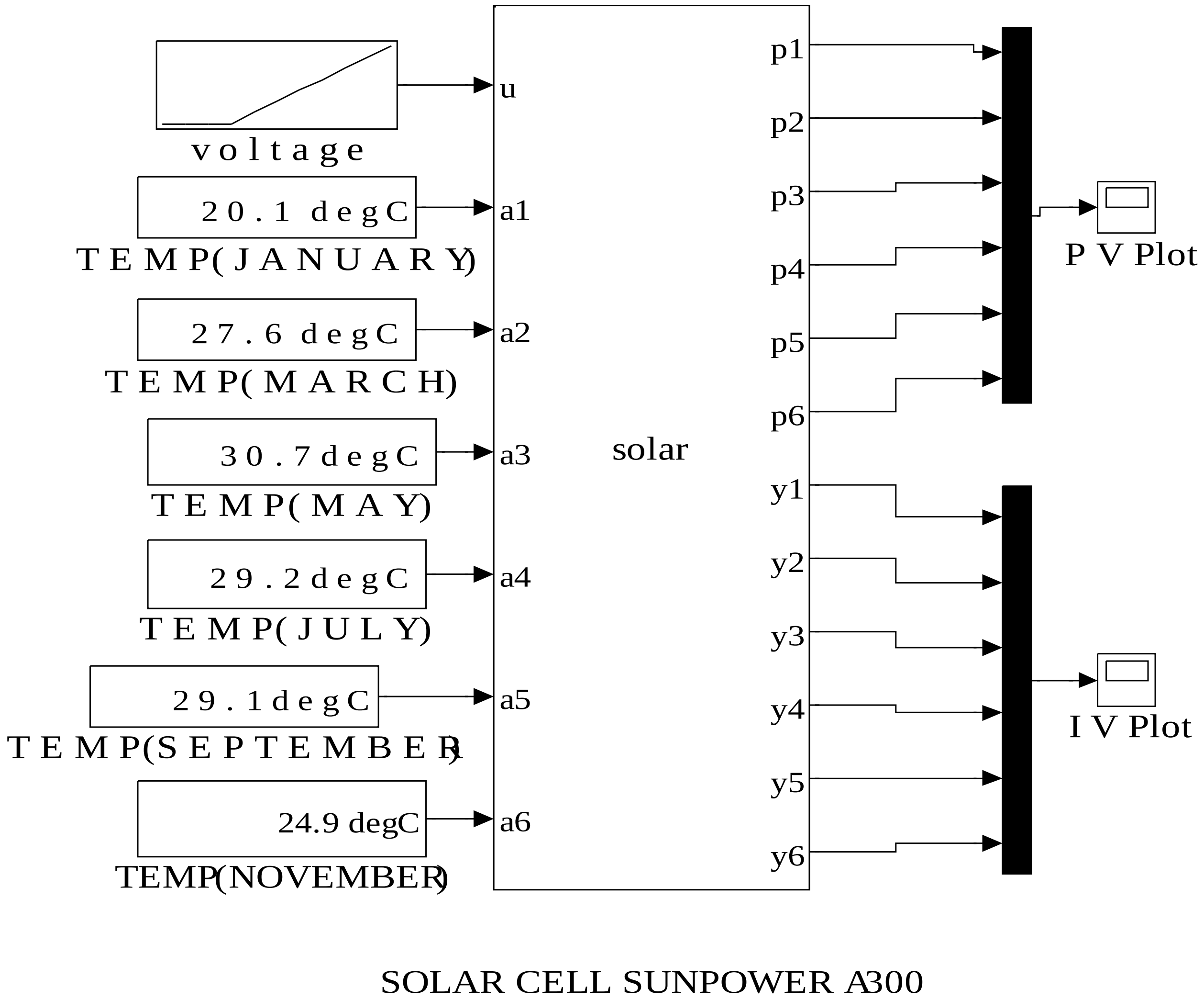


**FIGURE 5C:SIMULINK MODEL FOR VARIABLE TEMPERATURE**

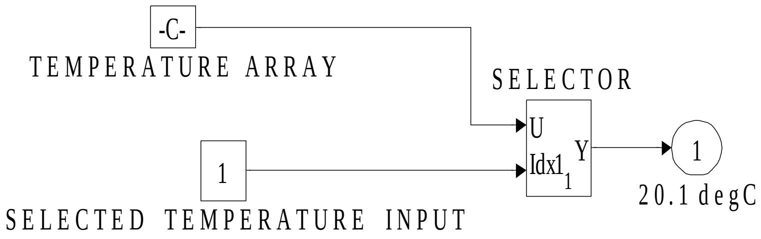


**FIGURE 5D: INPUT TEMPERATURE SUBSYSTEM**

**TABLE – III**

| PARAMETER | SYMBOL | VALUE |
|---|---|---|
| Open Circuit Voltage | $V_{OC}$ | 0.665 V |
| Short Circuit Current | $I_{SC}$ | 5.75 A |
| Maximum Power Voltage | $V_{MAX}$ | 0.560 V |
| Maximum Power Current | $I_{MAX}$ | 5.35 A |
| Rated Power | $P_{RATED}$ | 3.0 W |
| Efficiency | η | 20.0% minimum |
| Temperature Coefficient of Voltage | -1.9 mV / ºC | |
| Temperature Coefficient of power | -0.38 % / ºC | |

**TYPICAL ELECTRICAL PERFORMANCE OF SUNPOWER A-300 SOLARCELL (MONO CRYSTALLINE SILICON)**

*Data are given at STC: Illumination 1000W/m$^2$, Temperature: 25°C and spectrum of light AM 1.5.**[8]**

The I-V Plot under variable irradiance (0.17792S-0.27S) shows a significant increase in$I_{SC}$ from 1.043A to 1.572A.$V_{OC}$also increases marginally from 0.47V to 0.57V. At fixed temperature (here 30.7°C), increase in Suns from 0.17792S to 0.27S increases$I_{MAX}$from 0.977A to 1.475A and $V_{MAX}$ (marginally) from 0.51-0.52V. Hence the power output$P_{MAX}$ burgeons- P-V curves ranging from 0.4983W at 0.17792Suns to 0.767W at 0.27Suns. Therefore, at any fixed temperature, with the increase in irradiance the short circuit current, maximum current and voltage (at MPP) increase and hence the maximum output power gets augmented.

Figure 6A show the I-V Plots of SUNPOWER A300 solar cell under variable irradiance (monthly variation) and 6B show the P-V Plots of SUNPOWER A300 solar cell under variable irradiance (monthly variation).

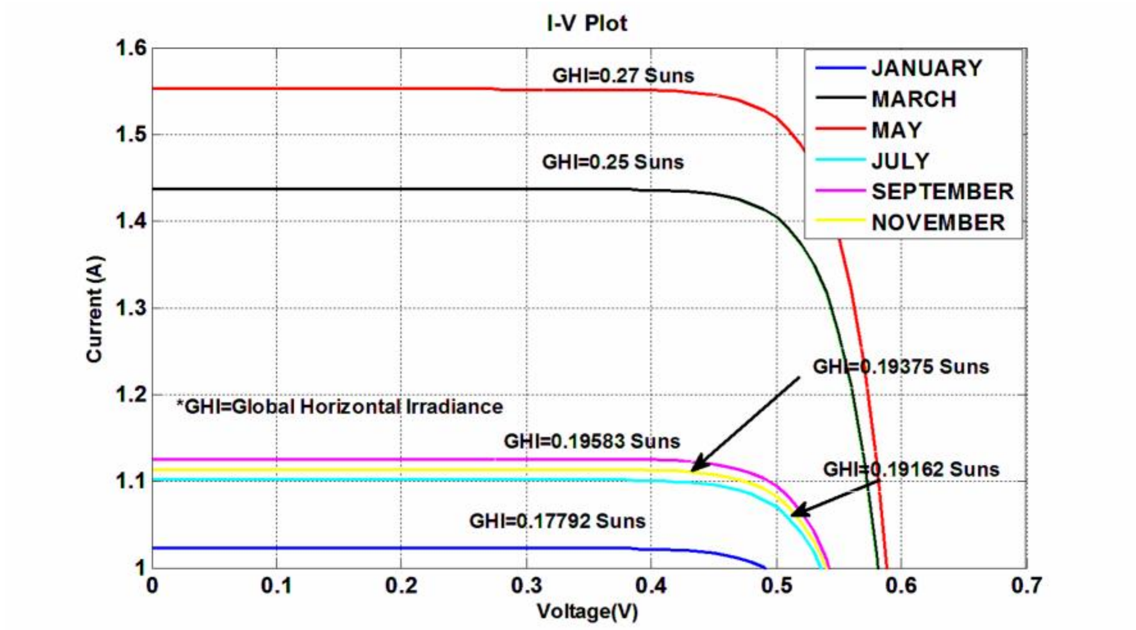


**FIGURE 6A: I-V PLOTS OF SUNPOWER A300 SOLAR CELL UNDER VARIABLE IRRADIANCE**

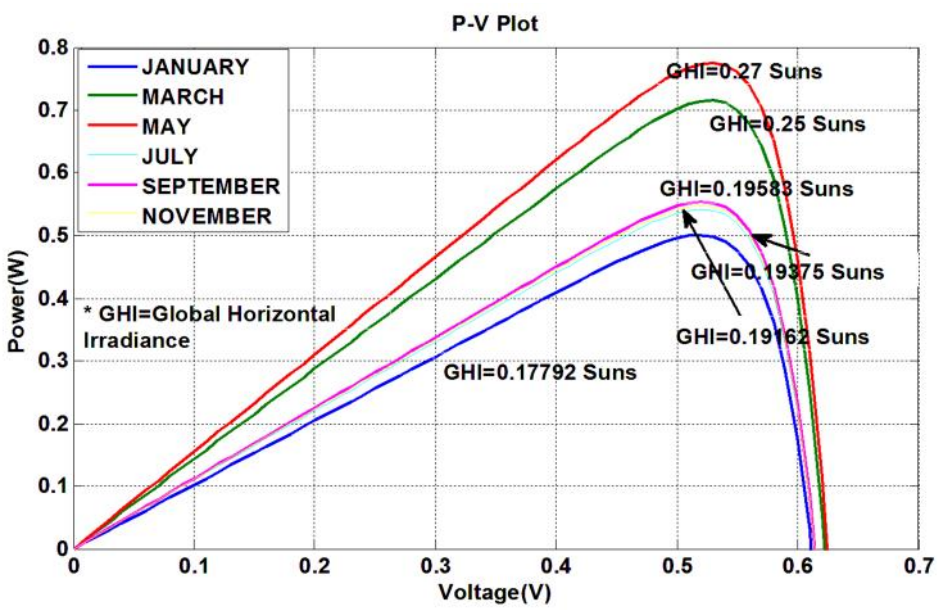


**FIGURE 6B: P-V PLOTS OF SUNPOWER A300 SOLAR CELL UNDER VARIABLE IRRADIANCE**

The I-V Plot under variable temperature (20.1°C-30.7°C) exhibits that with increasing temperature and fixed irradiance of 1 Suns, the short circuit current increases nominally from 5.73A at 20.1°C to 5.775 A at 30.7°C but the open circuit voltage decreases from 0.545V to 0.505V. The increase in °C results in decrease in power output (3.1W at 20.1°C to 2.75 W at 30.7°C).Therefore at fixed Suns, temperature increase leads to a marginal increase of both the short circuit current and the maximum current at MPP, but the open circuit voltage and

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hence the maximum voltage decreases thus affecting the total cell output $P_{MAX}$ causing it to ebb.Figure 6C show the I-V Plots of SUNPOWER A300 solar cell under variable temperature (monthly variation), 6D show the P-V Plots of SUNPOWER A300 solar cell under variable temperature (monthly variation).

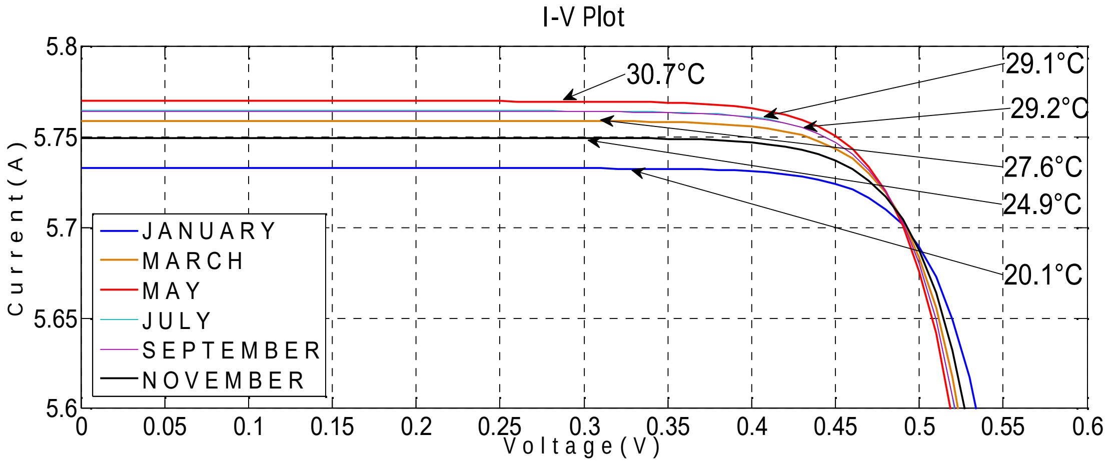


**FIGURE 6C: I-V PLOTS OF SUNPOWER A300 SOLAR CELL UNDER VARIABLE TEMPERATURE**

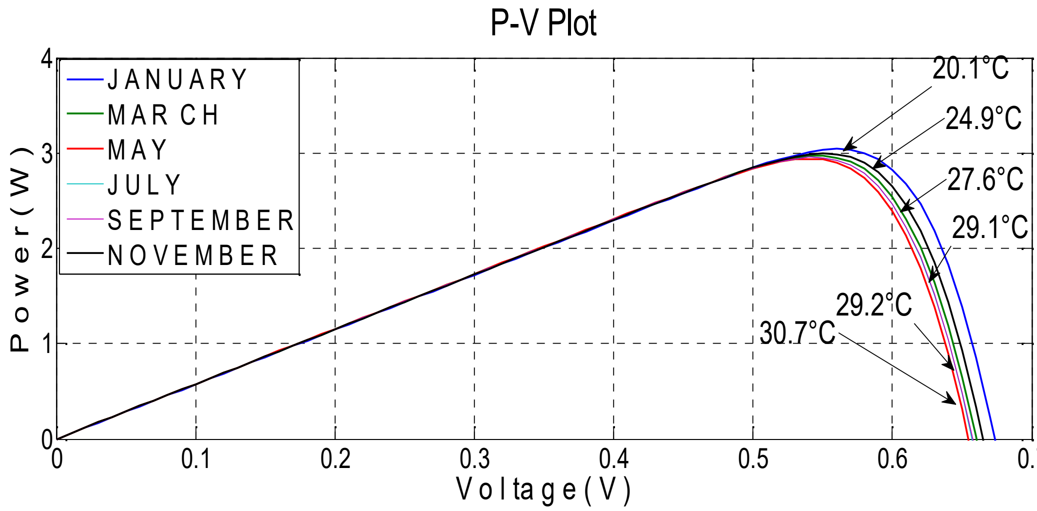


**FIGURE 6D: P-V PLOTS OF SUNPOWER A300 SOLAR CELL UNDER VARIABLE TEMPERATURE**

## IV. CONCLUSION

The future will witness the quotidian demands for electricity by various domestic and commercial appliances, types of equipment being satiated by solar panels.[9] It will also prove extremely well suited for remote regions with no electricity. Hence it calls for careful examination of the effects of the factors directly influencing the solar panel efficiency. The present work is mainly focused on studying and analyzing the effect of irradiance and surrounding temperature on the performance of the solar cell. Simulation models and result analysis is a highly competent approach for observing the behavior of the solar cell as field tests not only require substantial investment, it is primarily contingent on the state of the atmosphere. The present article discusses a single-diode model, of characteristic constants of SUNPOWER A300 solar cell as the reference, which gives

acceptable results in various conditions within less iteration and is the most suitable model used for simulating electrical behavior of PV module system for planning purposes in power system field. The real- time modeling and simulation with the help of MATLAB script and SIMULINK can be taken as a rudimentary and also speedy tool for determining the various environmental conditions' effect on I-V characteristics and P-V characteristics. It can be concluded the output current is mainly affected by ambient irradiance change, while the temperature changes dominate the output voltage [10].An alternative way of simulation could be the use of Simscape blocks in SIMULINK. This article is the very basic step of analyzing the solar cell performance under the variable meteorological conditions of Kolkata and ultimately aims to develop a comparative study using SIMULINK approach to determine the suitability of the different commercially available PV cells in this megacity. The analysis method used in the present work can also be adopted to determine the performance of a solar cell arrays under partial shading condition.

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