Modeling and Simulation of Photovoltaic Cell using Single Diode Solar Cell and Double Diode Solar Cell Model

Tarana Afrin Chandel, Mohd Yusuf Yasin, Md Arifuddin Mallick

Abstract*: *Modeling and simulation of photovoltaic cells or PV cell is becoming important as it provides an easy platform to perform studies on photovoltaic cells and the design and analysis of the system based on photovoltaic cells. In this paper, we present our study of the ordinary photovoltaic module on the basis of one diode and two diode models. Studies are extended to solar cells as solar cells are similar to photodiodes. Performance of the solar cells may be described in terms of ideality factor (α), which decreases with temperature and is observed to affect the performance of the PV cell. PV systems exhibit better performance with diodes having higher values for α. In this paper, our efforts are to study the effects of α on Current and Power versus Voltage characteristics of the solar cells. MATLAB simulation of solar cell systems is a simple and elegant mechanism useful for designing and modeling the framework of the solar power plant.

Index Terms: I-V and P-V Curve, Modeling, Matlab/Simulink Software, Simulation, Solar PV Cell, Solar Cell Model.

I. INTRODUCTION

A solar cell converts electromagnetic radiations incident on the solar cell, directly into electric current [1]. Sun is the only source of the power on the earth surface and in the surrounding environment. The electromagnetic radiations from the sun are in the form of photons. The photon energy can be given by

$$E_{ph} = hf = \frac{hc}{\lambda} \text{ .... (i)}$$

Where *f* is frequency of radiations, λ their wavelengths, *h* the Plank's constant (6.626176 x 10-34 joule-seconds.) and c the speed of light ($3\text{x}10^8$ m/s). A solar cell uses these incident photons if their energies are equal to or greater than the band-gap energy associated with the semiconductor layers constituting the solar cell. The movement of electrons and holes through drift and diffusion can modify the process of generation and recombination through free electron and hole concentration [2]. Absorption of the photon energy causes free electron-hole pair generation, whereas their emission causes the electrons to move towards valance band thus initiating recombination of electron-hole (e-h) pair to take place. These generated electron-hole pairs produce charge, the presence of charge causes to establish an electric field in the bulk of the semiconductors of the solar cell [3]. The process of generation of electric current and voltages in the solar cell when it is exposed to sunlight is called photovoltaic effect. A photovoltaic cell is a semiconductor device which converts light energy into electric current at a fixed voltage [4]. Silicon based solar photovoltaic cell produces an open circuit voltage of 0.5 to 0.6 volt [5]. A cross-section of the solar cell is presented in figure1 which shows the photovoltaic effect. Thus photovoltaic effect on the basis of incident solar energy transduces the solar energy into electrical energy. Once electrical energy is available, the appearance of voltage and current is inevitable. The cross sectional view of solar cell is shown in fig1

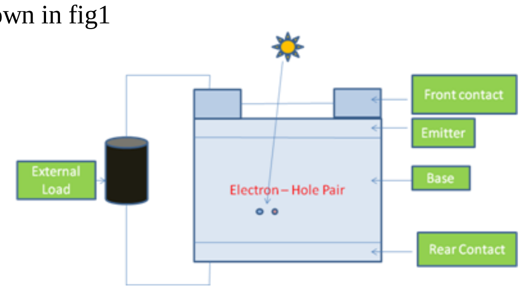

Fig 1: Cross sectional view of Solar Cell

Two different solar cell models are found useful to describe and simulate the electrical performance of the solar cell. These models are defined on the basis of the diode model along with the following parameters to define an electrical model of the solar cell. These parameters are usually five and are as follows: photo-current (I_{ph}) due to the transduced photon energy absorbed by the junction of the cell, series resistance (R_s) due to the semiconductor material layers through which current flows, diode reverse saturation current (I_o), parallel resistance (R_{sh}), is due to the current leakage under reverse bias condition and the ideality factor α is directly proportional to the rate of change of voltage dv with respect to thermal voltage V_t and logarithm ratio of dark current I_o to diode current I_d [6] [7].

$$\alpha = \frac{dv}{V_t} \ln \frac{I_o}{I_d} \text{ .... (ii)}$$

Commonly used materials for solar cell are Silicon (Si) and Germanium (Ge). Other materials used to fabricate the solar cells are Copper-Indium-Gallium-Selenide (CIGS), Cadmium-Telluride (CdTe), Copper-Indium (CuIn), Cadmium Sulfide (CdS) and Gallium Arsenide (GaAs) [6]. There are two criteria which describe the performance of material, one is the open circuit voltage and another is the ideality factor [8] [9].

The ideality factor is also known as emissivity factor and describes the behavior of the p-n junction on the basis of the charge recombination in the space charge region. The ideality factor may vary over the range 1≤ α ≤ 2 for a

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single diode model or the model containing more parallel connected diodes. However, value of α is 2 for more than one diode due to the increasing recombination of charge carriers occurs in the space charge region. Ideality factor is also affected by impurity and defects and also when recombination deviates from the bulk-hetero-junction solar cells.

Basically the ideality factor indicates the type of charge recombination that take place in the diode. Ideal diodes have an ideality factor 1 whereas non ideal diodes, the ideality factor deviates as it is to involve more recombination due to a single recombination mechanism or multiple mechanisms responsible for recombination. Si and Ge diodes have ideality factor 1 and 1.4 respectively. In diodes having an ideality factor 1, the minority carrier recombination is said to be band to band type, i.e. low level injection in the bulk area of the device [10]. Solar cell diode current equation is given in eq (iii) where α defines ideality factor [11]

$$I = I_L - I_o\left(e^{\left(\frac{V_d}{\alpha V_t}\right)} - 1\right) \quad \text{……………………………} \quad \text{(iii)}$$

Ideality factor in the diode changes if the recombination deviates from bulk area. Diodes with ideality factor 2, recombination takes place just because of high level injection form band to band by both the charge carriers (two carriers limits the recombination). Many researches are carried out with ideality factor 1 [12][13][14]. The current-voltage or I-V characterstic performance of solar cell is affected as ideality factor increases from 1 to 2. The ideality factor of diode helps to indicate the effect of trap assisted recombination of carriers in the solar cell. Fig 2 shows the carrier recombination mechanism in semiconductor devices. Three types of recombination mechanisms are reported by the researchers viz a viz. Band to Band, Trap assisted and Auger recombination [15]. These mechanisms are explained by Fig 2 and Fig 3.

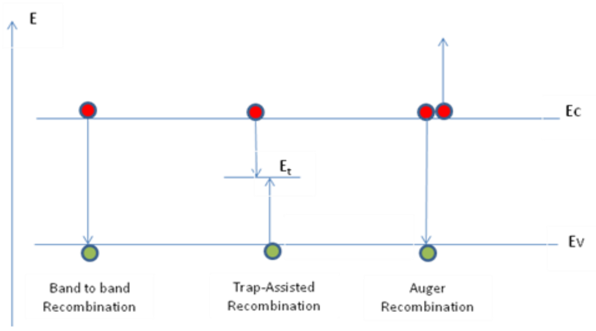

Fig 2: Mechanism of recombination in semiconductor material

Radiative or band to band recombination process dominates the bandgap semiconductor. The space solar cell are made of direct bandgap materials (GaAs) and hence radiative recombination occurs. Terrestrial solar cells are made from indirect bandgapmaterials like silicon. In such a case the radiative recombination is very week and is usually neglected. The main features of radiative recombination are (i) an electron and hole pairs directly recombine and hence releases a photon. (ii) The photon energy is equal to the band gap energy as shown in figure 3a. Schockley Read Hall or SRH recombination occurs in materials which are imperfect in their crystal structures. These meterials exhibit the following recombination processes (i) an elctron or a hole is trapped by the energy in the forbidden energy region which is due to the defects in the crystal lattice (ii) Electron and hole achieve the same energy before it is re-emited thermally into the conduction band and get recombine as shown in figure 3b. Because of above reason it has an effective recombination near mid gap energy level.

In auger recombination three carriers are involved. Electron and holes recombine and this energy is released to third carries instead of releasing this energy as photon or heat as shown in fig 3c. Auger recombination occurs at high carrier concentation as they are heavily doped. In silicon solar cell, auger recombination limits the lifetime of carriers and effecting the efficiency of solar cell.

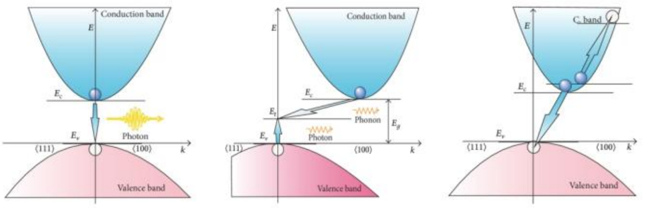

Fig 3: Recombination properties in semiconductors materials based on optically induces free carrier absorption [15] (a) Band to Band Recombination (b) Trap-assisted recombination. (c) Auger Recombination

The ideality factor decreases with increasing temperature and affects the performance of photovoltaic cell. Diodes with ideality factor 2 gives more accurate performance of photovoltaic system. To analyze the performance of I-V and P-V Characteristic of diode with 2 ideality factor, having two diodes connected in parallel, we have designed a model and simulated it using Matlab Simulink Software R2013a.

Solar panels are formed by fabricating numbers of solar cell connected in series and parallel. These cells determine the maximum power of the panel. The power in solar cell/panel is measured in watt/m2, which depend on the irradiance of sun. The commercial silicon solar cell generates 0.5<Vo<0.6 volts and 28<Io<35 mA [16]. In the commercially available panel, the area of a single solar cell is 34.5 mm2. In this case taking max voltage and current of solar cell (polycrystalline), power output is 21 mW, and power density is 600W/m2. This value corresponds to the commercial solar cell having efficiency 15% available in the market.

II. MODELING OF PHOTOVOLTAIC CELL

To analyze the maximum power of solar photovoltaic system we require an authentic model, so the model is designed and simulated by MATLAB Simulink.. The solar cell block in SimElectronics module under simulink on the MATLAB platform represents a single photo-active diode in parallel with a current source (Iph), a series resistance (Rs) and a parallel resistance (Rsh) [17][18]. An ideal equivalent circuit of the photovoltaic module is shown in fig 4(a).

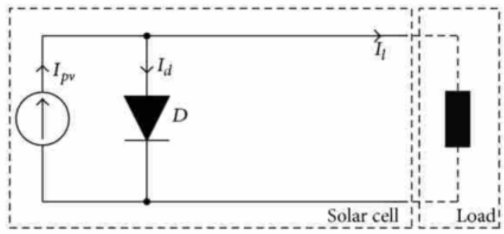

Fig 4a: Ideal solar cell model

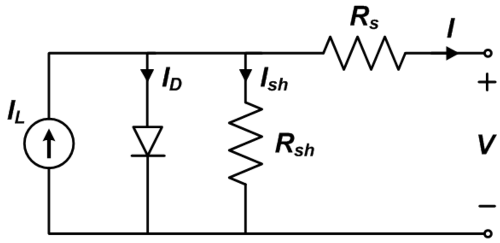

Fig 4b: Equivalent circuit of single diode solar cell

The output current of figure 4a is given by the equation given below

$$I = I_{ph} - I_d \text{ .... (iii)}$$

Where $I_d = I_o\left(e^{(\frac{V_d}{\propto V_t})} - 1\right)$

Hence, equation (iii) becomes as shown below

$$I = I_{ph} - I_o\left(e^{(\frac{V_d}{\propto V_t})} - 1\right) \text{ .... (iv)}$$

Where $V_t = \frac{kT}{q}$ = 26mV at room temperature

V_d = Forward bias voltage of diode

I_{ph} = Current generated due to irradiation,

I_o = The dark saturation current of diode

V_t = Thermal voltage of diode

q = Charge carrier, 1.6 x10^{-19} C

K = Boltzman Constant, 1.3865 x 10^{-23}

T = Temperature in Kelvin

α = Ideality Factor

$$I_{ph} = I_L$$

III. MODELING MATHADOLOGY

This work is based on the modeling techniques depending on the PV model: one diode model and two diode model.

A. Ideal PV cell and I-V Characteristics in Dark and Light Condition

A Single solar cell can be modeled by a current source, a single diode and two resisters as shown in fig 4(b). This single diode model of the solar cell has current which can be given by

$$I_d = I_o\left(e^{(\frac{V_d}{\propto V_t})} - 1\right) \text{ ....(v)}$$

Io is called the dark or reverse saturation current, V_d is forward bias voltage of PV cell created by photon.

The Ideal Model of single PV cell and its I-V curve in dark and light condition is shown in figure 4a & fig 5 respectively. For low value of diode voltage V_d close to zero, the diode current is simply a dark saturation current, few nanoampere, lower values depends upon temperature [18] [19][20]. As voltage increases above 0.6 volt current rises exponentially very rapidly.

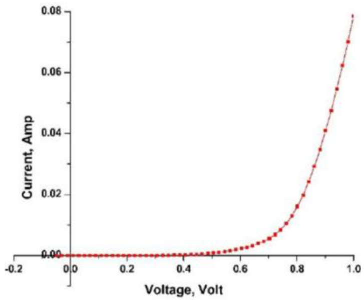

Fig 5: IV Curve in dark and light condition

IV. SOLAR CELL MODELING

Although many equivalent circuit models have been developed and proposed over the past four decades to describe the solar cell's behavior, only two models are used practically. In this section the two common models are briefly presented

A. Single Diode PV Cell Model

Photon or light energy generate charge carrier or electron-hole pair and p-n junction collects these charges and spreads them so that the current flowing in the external circuit is enabled and also by the process of photovoltaic effect, forward bias voltage occurs[21]. This leads to a single diode model shown in fig 6 [22]. Photon related current is modeled by a current source I_{ph}. This current is diverted in forwarded bias diode I_d and the remaining current comes out to the external circuit. We also model the parasitic resistance, R_{sh} represent the leakage resistance and R_s represent physical resistance in the contact as well as the semiconductor layer.

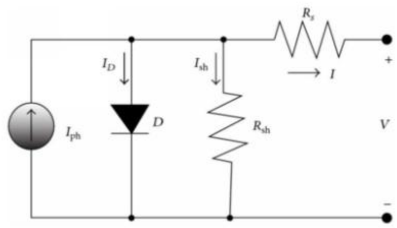

Fig 6: Single diode PV Cell Model

$$I = I_{ph} - I_d - R_{sh} \text{ .... (v)}$$

$$I = I_{ph} - I_o\left(e^{(\frac{V_d}{\propto V_t})} - 1\right) - \left[\frac{(V + I\,R_{sh})}{R_{sh}}\right] \text{..(vi)}$$

B. Simulation of PV Cell with Single Diode Model

In order to simulate this model we use a single solar, a current sensor and a voltage sensor is connected in series and in parallel to the solar cell respectively. These sensors are further connected to P-S- simulink converter which converts the physical signal to the simulink output signal. The output of both the P-S simulink converter is connected to the display to monitor current and voltage respectively. The output of voltage and current PS simulink is given to the product block which is further connected to display for monitoring output power. By varying the P-S simulink constant for different values of irradiation we get different value of voltage, current and power. . Simulation is done with the resistor value of 19 ohm. Fig 7 shows the simulink model of single diode PV cell and simulation result is shown in table 2.

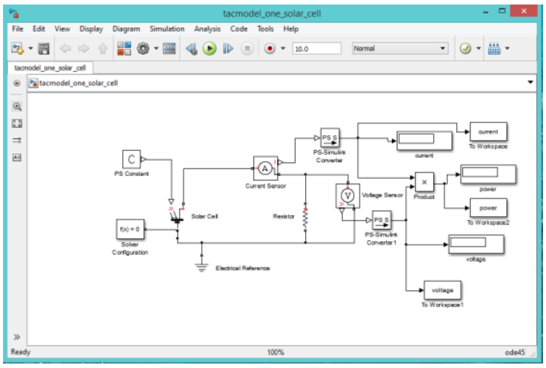

Fig 7: Simulink Model of Single Diode PV Cell

Single diode model is not efficient. Besides it has certain serious limitations which may be the efficiency of the solar cell. The efficiency of single solar cell is mainly dependent on

1. **Emissivity of solar cell:** The ideality factor is 1 for single solar cell as recombination of charge carriers take place from band to band and hence efficiency is limited.
2. **Thermalisation:** When photon energy E is greater than band gap energyE_g, excites the carriers in the conduction band, thus the absorbed photon energy equal to band gap energy, hence affecting the output.

Due to low efficiency of single solar cell model, we moved toward two diode solar cell model.

V. TWO DIODE PV CELL MODEL

Two diodes model is the modified version of the single diode model as shown in fig 8. The second diode D2 is in parallel with first diode D, which will affect the recombination [21]. This effect is shown on the performance of power in photovoltaic cell.

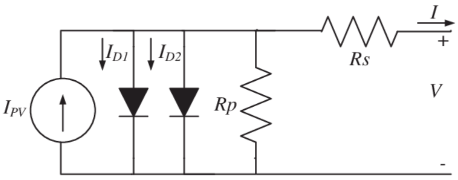

Fig 8: Two Diode PV Cell Model

. The solar cell metal contacts and the semiconductor material bulk resistance are represented by a resistor connected in series (R_s) with the cell R_{sh} shunt resistance ground the leakage current in reverse bias condition [23]. The series and shunt resistors are connected in the same manner as in single diode model. The current in diode D_1 (I_{d1}) shows the carrier recombination saturation current across the surface trap area with an ideality factor (α) = 1 whereas the current in diode D_2 (I_{d2}) shows the carries recombination saturation current across the p-n junction of the solar cell with an ideality factor (α) = 2 [24]. Now the output current will be

$$I_{load} = I_{ph} - I_{d1} - I_{d2} - I_{sh} \quad \ldots\ldots \text{(vii)}$$

$$I = I_{ph} - I_{o1}\left(e^{\left(\frac{V+I*R_s}{\alpha 1 V_t}\right)} - 1\right) - I_{o2}\left(e^{\left(\frac{V+I*R_s}{\alpha 2 V_t}\right)} - 1\right) - \left[\frac{(V_p + I * R_s)}{R_{sh}}\right]$$

……….. (viii)

With low temperature and high irradiation two diode model will give better electrical performance with high precision [24].

A. Simulation of Two PV Cell with Two Diode Model

In order to simulate this model we use two solar cells connected in parallel, a current sensor and a voltage sensor is connected in series and in parallel to the solar cell respectively. These sensors are further connected to P-S-simulink converter which converts the physical signal to the simulink output signal. The output of both the P-S simulink converter is connected to the display to monitor current and voltage respectively. The output of voltage and current PS simulink is given to the product block which is further connected to display for monitoring output power. By varying the P-S constant for different values of irradiation we get different value of voltage, current and power. . Simulation is done with the resistor value of 19 ohm. Fig 9 shows the simulink model of two diode PV cell and simulation result is shown in table 3.

The parameters considered for the simulation of PV cell model is mentioned in table1. At the time of I-V curve fitting, superposition is conducted to two diodes to simulate the dark features of solar cell

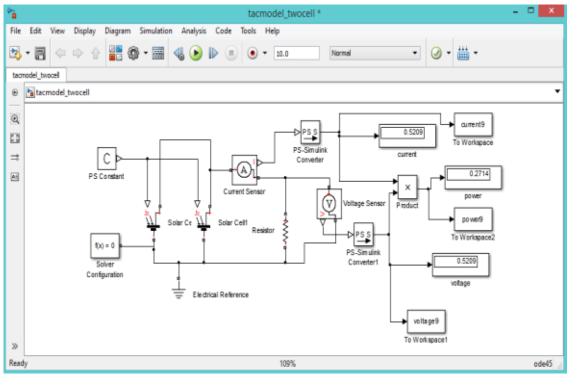

Fig 9: Simulink Model of Two Diode PV Cell

I_{s1} is used to denote the recombination saturation current flowing through the body area or the surface trap level, and corresponding n=1; I_{s2} is made to denote recombination saturation current flowing through p-n junction or crystal boundary depletion region, and the corresponding n=2. Thus the I-V curve can be interpreted.

B. Parameters used for modeling and Simulation of the PV cell

The parameters required for modeling and simulation of PV Cell is shown in table I.

Table I: Parameters required for modeling and simulation of PV Cell

S.N	Parameters for solar model	Temperature dependent Parameters
1	Isc=7.46 A	First order temperature coefficient for Iph, TIPH1=0 1/K
2	Voc= 1.0 V	Energy gap EG=1.1eV
3	Ideality facto r=1.5	Temperature exponent for Is, TXIS1=3
4	Rs= 0 ohm	Temperature exponent for Rs, TRS1 =0
5	Irradiance used for measurements, Ir = 1 - 1000 (W/m^2)	Measurement temperature=25 C
6	-	Simulation temperature=25 C

VI. IDEALITY FACTOR

Ideality factor in other words is known as emissivity factor in which p-n junction behavior is described on the basis of the recombination of charge carriers in the space charge region. Ideality factor ranges from 1 for single diode model to 2 for more than one diode model as recombination of charge carriers increases in space charge region. Ideality factor is also affected by impurity and defects increases [20]. The ideality factor α is obtained from the dark current. The equation for dark current in the diode is given by equation (i) which is also shown below

$$I_d = I_o\left(e^{\left(\frac{q(V+I*Rs)}{\alpha kT}\right)} - 1\right) \ldots\ldots\ldots\ldots\ldots \text{(ix)}$$

Considering dark I-V characteristic, neglecting $I * Rs$ and taking the logarithm of above equation, we get

$$\alpha = \frac{dv}{V_t}\, ln\, \frac{I_o}{I_d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(x)}$$

Thus, ideality factor (α) is directly proportional to the dark I-V characteristic.

VII. SIMULATION RESULTS

A. Simulation Result for Single Solar Cell Model

The photocurrent depends on the irradiation intensity at the particular instant and the temperature. In our modeling the radiation were varied (in W/m^2 1000, 900, 800, 700, 600, 500, 400, 300, 200 and 100) and the temperature was kept constant at 25^o C. I-V curve for different irradiation intensity (W/m^2) on a single solar cell is shown in figure 10. For same irradiation intensity the P-V Curve is shown in figure 11 for s single solar cell model. Effect on Power due to change in Irradiation at temperature 25^o C is shown in table II

Table II: Effect on Power due to change in Irradiation at temperature 25^o C (One solar cell model)

Irradiation (w/m$^{2)}$	Current (A)	Voltage (V)	Power (W)
1000	0.03157	0.5998	0.01894
900	0.03136	0.5958	0.01868
800	0.03112	0.5912	0.01840
700	0.03084	0.586	0.01808
600	0.03053	0.580	0.01771
500	0.03016	0.570	0.01728
400	0.0297	0.564	0.01678
300	0.02911	0.5531	0.01610
200	0.02828	0.5372	0.01519
100	0.0261	0.5098	0.01360

In figure 11, the simulation graph shows nonlinear output, and observed that the current is constant up to 0.5 volt for different values of irradiation intensity. This shows that till 0.5 volt it was an open circuit voltage.

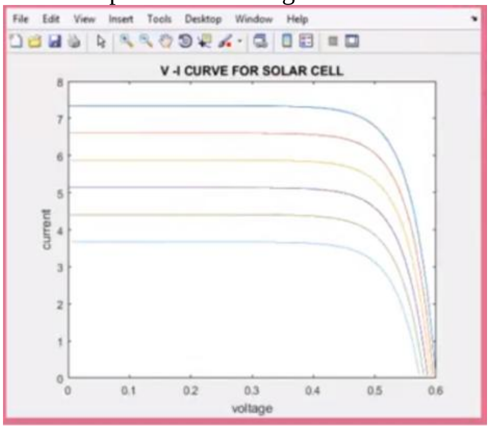

Figure 10: I-V Curve of Single Solar Cell Model

In fig 11 we observe different values of maximum power for different values of irradiation. For the irradiation of 1000 W/m^2 observe maximum power point and for 100 W/m^2 observe the lowest maximum power point.

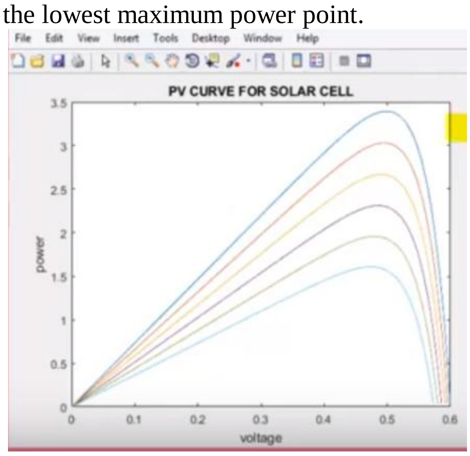

Fig 11: P-V Curve of Single Solar Cell model

B. Simulation Results for Two Solar Cells Model

We observed that as the irradiation intensity is decreasing, power of the solar cell is also decreasing, which is shown in Table III.

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Table III: Effect on Power due to change in Irradiation at temperature 25° C (Two solar cells)

Irradiation (w/m^2)	Current (A)	Voltage (V)	Power (W)
1000	0.03296	0.6263	0.02065
900	0.03275	0.6222	0.02038
800	0.03257	0.6177	0.02008
700	0.03224	0.6127	0.01975
600	0.03193	0.6066	0.01936
500	0.03155	0.5995	0.01892
400	0.03193	0.59091	0.01838
300	0.03110	0.5747	0.01769
200	0.03051	0.5797	0.01674
100	0.02968	0.05649	0.01517

The above table is represented in excel shown in fig 12 which shows relation between Current-Voltage Vs Irradiance

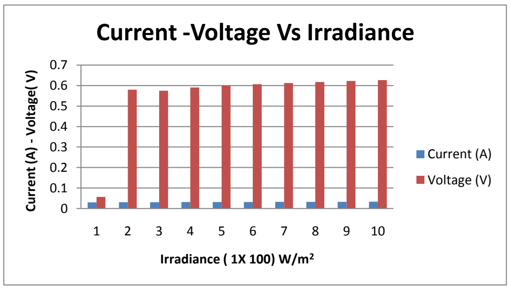

Fig 12: Relation between Current-Voltage Vs Irradiance

Relation between Voltage-Power Vs Irradiance is shown in Fig 13

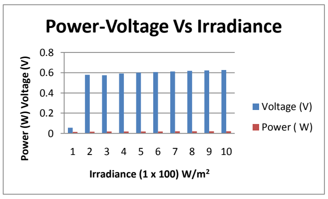

Fig 13: Relation between Voltage-Power Vs Irradiance

VIII. COMPARATIVE ANALYSIS BETWEEN SINGLE AND DOUBLE DIODE SOLAR CELL

Comparative analysis of single and double diode for same irradiation (W/m^2) shows that power of double diode solar cell is more than single diode which can be seen from table IV

Table IV: Comparison of Power between one diode solar cell and two diode solar cells model for same irradiation and same temperature T= 25°C

Irradiation (W/m^2)	One Diode Solar Cell Power (W)	Two Diode Solar Cell Power (W)
1000	0.01894	0.02065
900	0.01868	0.02038
800	0.01840	0.02008
700	0.01808	0.01975
600	0.01771	0.01936
500	0.01728	0.01892
400	0.01678	0.01838
300	0.01610	0.01769
200	0.01519	0.01674
100	0.01360	0.01517

In fig 14, comparison of power between single diode PV cell and double diode PV cell shows that two diode PV has more output power. Blue color line shows power for single diode PV cell model and green color line shows power for two diodes PV cell model.

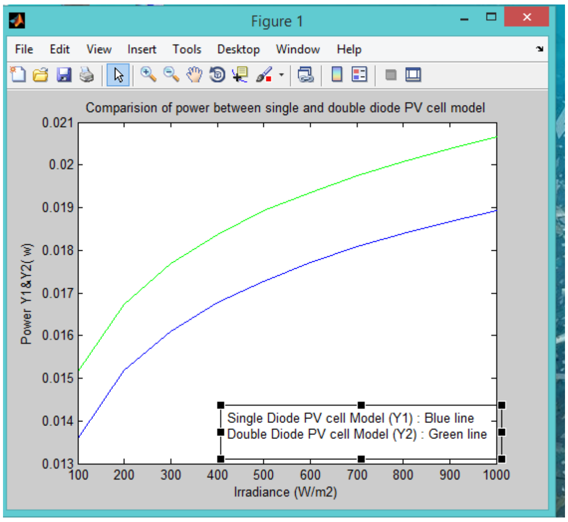

Fig 14: Variation of Power between Single and Double Diode PV Cell

IX. CONCLUSION

In this work, we pursue our studies of the one diode and two diode models to represent the solar cell assemblies. Simulation is carried out on MATLAB/ SIMULINK. We observe the importance of the ideality factor in our studies. Ideality factor for single solar cell is 1 where as for two solar cell is 2 i.e. $1<\alpha<2$. Power in one diode solar cell decreases as ideality factor increases above1.2 where power increased in two diode solar cells as ideality factor increases from 1 to 1.2 and remains constant till α attains a maximum value of 2. From fig 10, the simulation graph shows nonlinear output, and observed that the current is constant up to 0.5 volt for different values of irradiation intensity. This shows that till 0.5 volt it was an open circuit voltage. In figure 11 we observe different values of maximum power for different values of irradiation. For the irradiation of 1000 W/m^2 observed maximum power point and for 100 W/m^2 observe the lowest maximum power point. In fig 14 we observed the power in two diode photovoltaic model is enhanced as compared to single diode photovoltaic model. With reference to citation 16, in the commercially available panel, the length and width of single solar cell is 2.6 cm and .015 cm having an area of 0.345 cm^2. In this particular case the voltage and current of solar cell (polycrystalline) is considered as 0.6 Volt and 0.035A respectively.

From the above mentioned values of voltage and current the power is found to be .0210 W/m2. This value corresponds to the commercial solar cell having efficiency 15% available in the marketThus, from the simulation result we find that the two diode solar cell model gives more accurate result as compared to single cell model. we conclude the maximum power point is directly dependent upon the radiation intensity and ideality factor of the diode solar cell.

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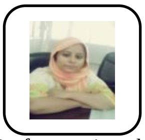

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