

# A STUDY ON MODELLING AND SIMULATION OF PHOTOVOLTAIC CELLS

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## Abstract

*This Paper presents a detailed study on the types of modelling of the PV Panel for simulation studies. The main concern of this study is to analyze the results and compare them under standard test conditions. PV systems are generally integrated with specific control algorithms in order to extract the maximum possible power. Hence it is highly imperative that the Maximum Power Point (MPP) is achieved effectively and thus we need to design a model from which the MPPT algorithm can be realized in an efficient way. Also other parameters should be taken into account for finding the best model for the use in simulation. It is very important to choose the appropriate model based on the application. The models used for study in this paper include the single diode model, two diode model and Simscape modelling. MATLAB/Simulink presents a powerful tool to study such systems. The work tests the accuracy of the models under different temperature and irradiance conditions. The two diode model is known to have better accuracy at low irradiance levels which allows for a more accurate prediction of PV system performance. Simscape, part of Simulink environment, has a solar cell block that makes building a PV model straightforward and much easier programming with full demonstration to all system details. On the basis of the study, the best model that can be used for simulation purposes can be selected. It is envisaged that the work can be very useful for professionals who require simple and accurate PV simulators for their design. All the systems here are modeled and simulated in MATLAB/Simulink environment.*

**Keywords:** PV cell, STC, MATLAB Simulink, Ideality Factor

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## 1. INTRODUCTION

There are two major problems presently that the world is presently facing i.e. energy crisis and climate change. The environmental issues are caused mostly by the over reliability on the fossil fuels as the prime energy source for everyday activities. The increasing energy consumption due to the development of the technology is another major issue in the world both the problems can be overcome at the same time by introducing renewable energy sources. They play a very healthy part in building a “greener” and more sustainable energy for the planet. The renewable energy sources are clean, economical, abundant and they do not cause harm to the environment by emitting harmful CO<sub>2</sub> gases. Solar energy, wind energy, hydro energy, geothermal energy, tidal energy and biomass are the sources of renewable energy. Out of all these energies, solar energy is the most reliable source since; sun is an infinite energy reservoir. The solar energy that hits the earth’s surface in one hour is equivalent to the energy consumed by all human activities in a year. The sunlight is converted into electricity by using the photovoltaic effect.

Photovoltaic effect is a phenomenon through which a collection of light-generated carriers by the P-N junction causes a movement of electron to the N-type side and holes to the P-type side of junction. This acts as a source of current. Due to the high cost of PV modules, optimal utilization of the available solar energy is imperative. This requires an accurate, reliable and comprehensive simulation

of the designed system before installation. PV cell modeling is a very important factor that affects the output of the PV cell. Temperature (T), Irradiance (G), have influence on the open circuit voltage (V<sub>oc</sub>) and short circuit current (I<sub>sc</sub>) which determine the power generation.

## 2. PV CELL MODELLING

The simplest way of representing the solar cell is the single diode model. It consists of a current source in parallel to a diode. The parameters required are short circuit current (I<sub>sc</sub>), open circuit voltage (V<sub>oc</sub>) and the diode ideality factor (a). The ideality factor of a diode is a measure of how closely the diode follows the ideal diode equation. Due to the presence of recombination losses, ideality factor other than ideal are produced. The basic model is improved for accuracy by introducing the series resistance (R<sub>s</sub>). It does not prove to be efficient under temperature variations. To overcome this drawback, an additional shunt resistance (R<sub>p</sub>) is included. This increases the parameters to a considerable level and the computations are increased. Although R<sub>p</sub> is added, the model fails under low irradiation conditions.

To improve the accuracy, the two diode model is introduced where another diode is included in parallel to the already prevailing current source and diode. The addition of the diode leads to complexity. All the parameters need to be estimated and thus requires large computational time. Although greater accuracy can be achieved by this model, it requires the computation of seven parameters namely

$I_{pv}, I_{o1}, I_{o2}, R_p, R_s, a_1$  and  $a_2$ . A three diode model of a solar cell has also been proposed taking into account the effect of large leakage current and also including the non-linearity of a solar cell.

Simscape is a tool provided by MATLAB which provides an environment for modelling and simulating physical systems spanning mechanical, electrical, hydraulic and other physical domains. Simscape components use physical connection to match the structure of the system being developed. Solar cell block in Simscape gives us a choice between two models containing eight parameters and five parameters respectively. In the latest version of MATLAB there is an option to set the number of series cells greater than one. This results in a more efficient simulation than if equations for each cell were simulated individually. Internally the block still simulates only the equipment for a single solar cell, but scales up the output voltage according to the number of cells.

### 3. SIMULATION PARAMETERS

A Single PV Cell is used for simulation for the study. The cells can be connected by increasing the number of cells in series and parallel based on the load requirement. The PV Cell specifications are as follows:

**Table -1:** PV Cell Specifications

PV CELL SPECIFICATIONS (0.8W)	
Open circuit voltage ( $V_{oc}$ )	0.541V
Short circuit voltage ( $I_{sc}$ )	1.464A
Voltage at maximum power ( $V_{mp}$ )	0.453V
Current at maximum power ( $I_{mp}$ )	1.28A
Maximum power ( $P_{max}$ )	0.58W

The parameters of the Single Diode and Two Diode models used for simulations are as follows:

**Table -2:** Parameters of the Single Diode and Two Diode Models

	SINGLE DIODE MODEL	TWO DIODE MODEL
$I_{sc}(A)$	1.464	1.464
$V_{oc}(V)$	0.38	0.54
$I_{mp}(A)$	1.36	1.29
$V_{mp}(V)$	0.32	0.45
$I_{O1}/I_{O}(A)$	$3.727*10^{-7}$	$2.46*10^{-6}$
$I_{O2}(A)$	-	$6.329*10^{-6}$
$R_s$	1e-3	1e-3
$a_1/a$	1	1.6
$a_2$	-	2.2
$K_i$	0.0017	0.0017

### 4. SINGLE DIODE MODEL

The characteristic curves of PV cell in simulation environment can be realized using the fundamental equations. A single PV cell is realized as a current source placed in parallel with a diode and the output current equation is given as:

$$I = I_{PV} - I_O \left[ e^{\frac{q(V+IR_s)}{akT}} - 1 \right] - \left[ \frac{V + IR_s}{R_p} \right] \tag{1}$$

Where,

$I_{pv}$ = photo voltaic current

$I_o$ =saturation current of the diode

$q$ =electron charge in coulombs

$=1.602*10^{-19}C$

$K$ =Boltzmann constant

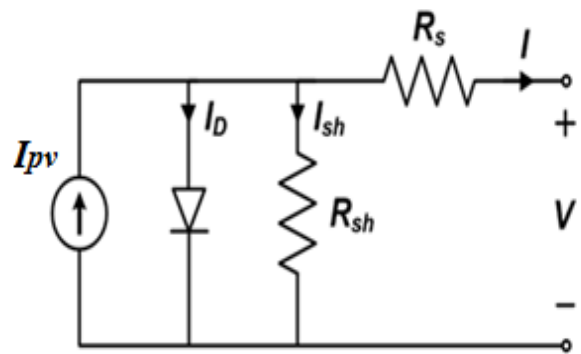
$=1.380*10^{-23} J/K$

$a$ =diode ideality factor

$R_s$ =series resistance

$R_p$ =parallel resistance

$T$ =Temperature in Kelvin



**Fig -1:** Equivalent Circuit of Single Diode Model

The photo voltaic current  $I_{pv}$  is a function of the irradiance ( $G$ ) and is formulated as:

$$I_{PV} = [I_{PV\_STC} + K_i \Delta T] \frac{G}{G_{STC}} \tag{2}$$

Where;

$I_{PV\_STC}$ =light generated current under standard test conditions (STC)

$\Delta T = T - T_{STC}$  (in kelvin)

$G$ = surface irradiance of cell ( $W/m^2$ )

$G_{STC} = 1000 W/m^2$

Irradiance under STC

$K_i$  = short circuit current coefficient

The diode saturation current  $I_o$  is given as:

$$I_o = I_{O\_STC} \left( \frac{T}{T_{STC}} \right)^3 \exp \left[ \frac{qE_g}{ak} \left( \frac{1}{T_{STC}} - \frac{1}{T} \right) \right] \tag{3}$$

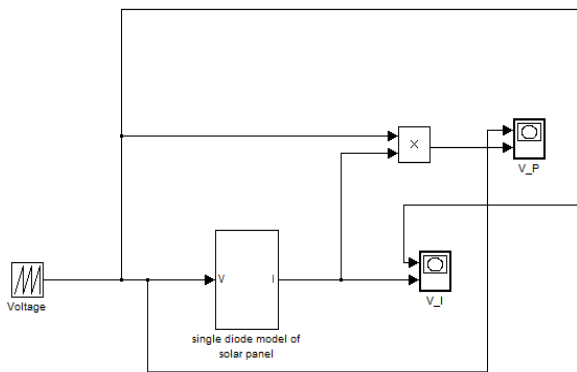
Where;

$I_{0,STC}$  = normal saturation current under standard test conditions (STC)

$T_{STC}$  = temperature under standard test conditions

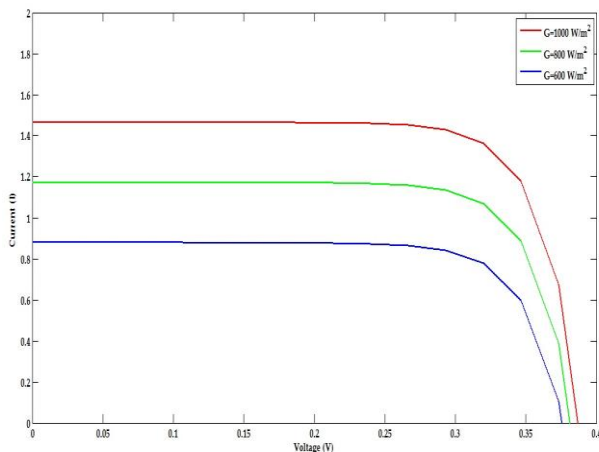
$E_g$  = band gap energy of the semiconductor

The Matlab/Simulink implementation of the single diode model is as follows:

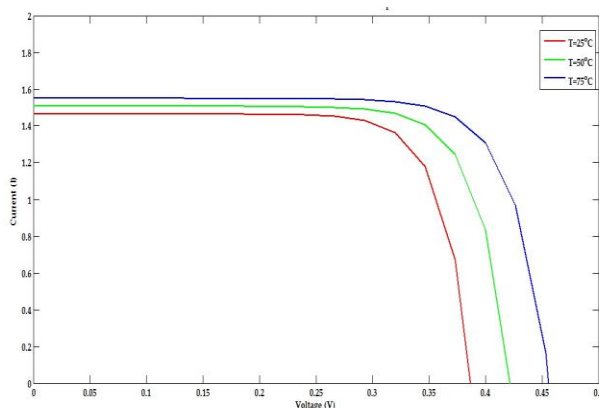


**Fig -2:** Single Diode Model Matlab/Simulink Implementation

The PV Characteristics under Varying Irradiance and Temperature for a single diode model are shown below:

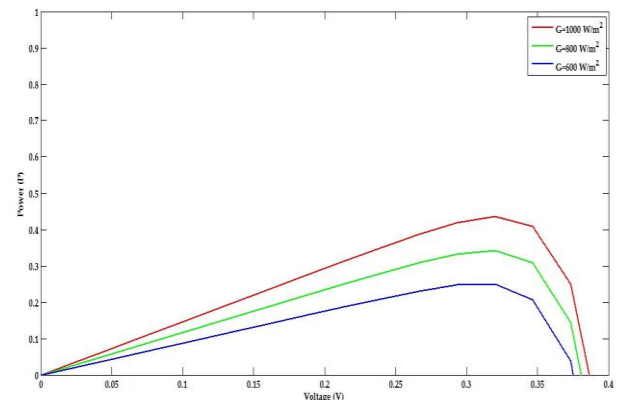


**Fig -3:** V-I Curve under varying Irradiance

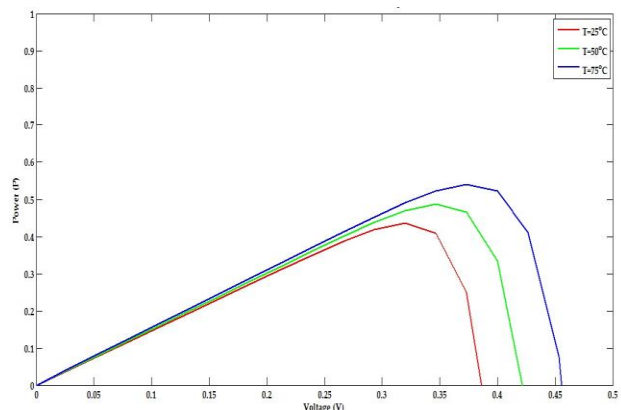


**Fig -4:** V-I Curve under varying Temperature

The Irradiance values given to the solar cell are  $1000\text{W/m}^2$ ,  $800\text{W/m}^2$ ,  $600\text{W/m}^2$  and the  $I_{sc}$  values vary proportionately. The Temperature values given are  $25^\circ\text{C}$ ,  $50^\circ\text{C}$ ,  $75^\circ\text{C}$  and the  $V_{oc}$  values vary with the temperature.



**Fig -5:** P-V Curve under varying Irradiance



**Fig -6:** P-V Curve under varying Temperature

## 5. TWO DIODE MODEL

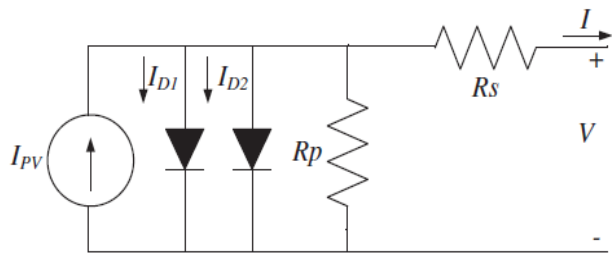
The single diode model was formulated based on the assumption that recombination loss in the depletion region is absent. In a practical solar cell, the recombination loss must be taken in to account and thus this leads to a more definite model known as the two diode model. The output current equation is given as:

$$I = I_{PV} - I_{D1} - I_{D2} - \left( \frac{V + IR_s}{R_p} \right) \tag{4}$$

Where  $I_{D1}$  &  $I_{D2}$  are the diode currents of the two diodes respectively given as:

$$I_{D1} = I_{01} \left[ \exp\left(\frac{q(V + IR_s)}{a_1 kT}\right) - 1 \right] \tag{5}$$

$$I_{D2} = I_{02} \left[ \exp\left(\frac{q(V + IR_s)}{a_2 kT}\right) - 1 \right] \tag{6}$$



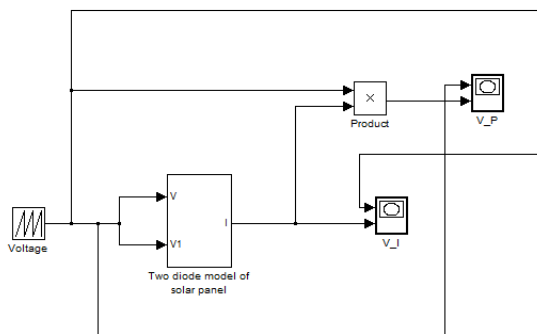
**Fig -7:** Equivalent Circuit of Two Diode Model

$I_{O1}$  &  $I_{O2}$  are saturation current of the two diodes respectively. The simplified equations to determine the diode saturation currents are as follows:

$$I_{O1} = I_{O2} = \frac{(I_{SC\_STC} + K_i \Delta T)}{\exp\left[\frac{V_{oc\_STC} + K_v \Delta T}{\{(a_1 + a_2)/p\} * V_T}\right] - 1} \quad (7)$$

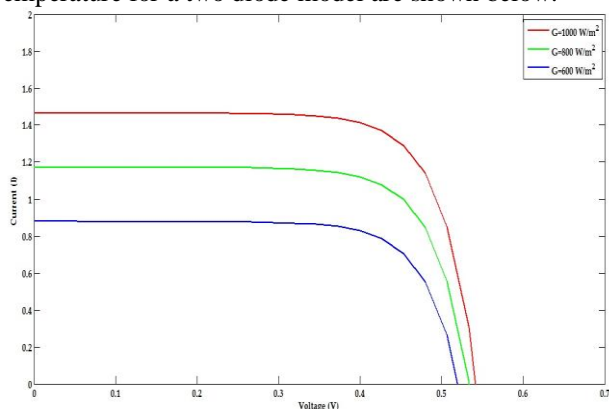
The diode ideality factors  $a_1$  and  $a_2$  represent the diffusion and recombination current component. The two diode models produce more precise results at lower irradiance levels.

The Matlab/Simulink implementation of the two diode model is as follows:

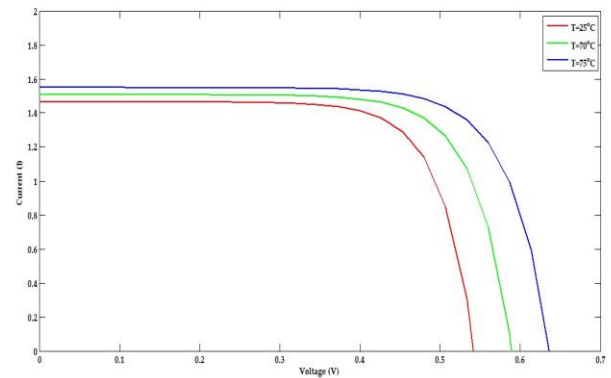


**Fig -8:** Two Diode Model Matlab/Simulink Implementation

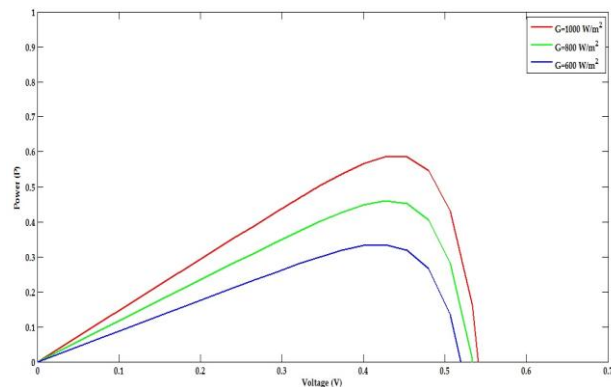
The PV Characteristics under Varying Irradiance and Temperature for a two diode model are shown below:



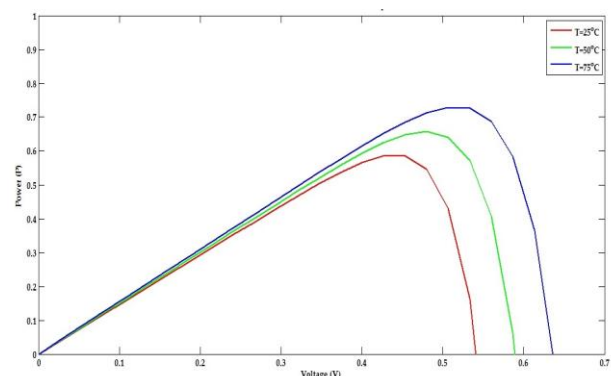
**Fig -9:** V-I Curve under varying Irradiance



**Fig -10:** V-I Curve under varying Temperature



**Fig -11:** P-V Curve under varying Irradiance



**Fig -12:** P-V Curve under varying Temperature

The Irradiance values given to the solar cell are  $1000\text{W/m}^2$ ,  $800\text{W/m}^2$ ,  $600\text{W/m}^2$  and the  $I_{sc}$  values vary proportionately. The Temperature values given are  $25^\circ\text{C}$ ,  $50^\circ\text{C}$ ,  $75^\circ\text{C}$  and the  $V_{oc}$  values vary with the temperature.

## 6. SIMSCAPE MODELLING

The solar cell block in the Simscape environment represents a solar cell current source. The model includes the following components:-

- Solar-induced current
- Temperature dependence

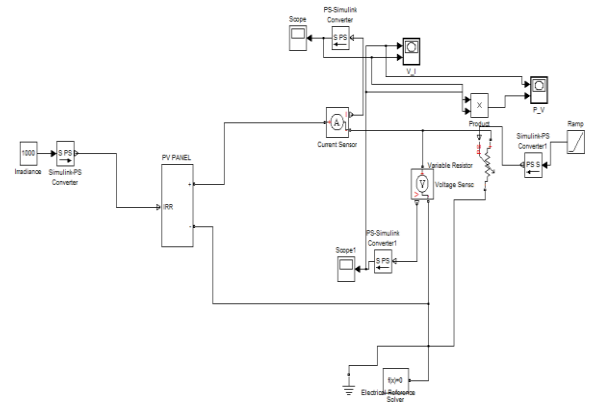
The block has the following ports:-

- $I_r$  Incident irradiance
- + Positive electric voltage
- - Negative electrical voltage

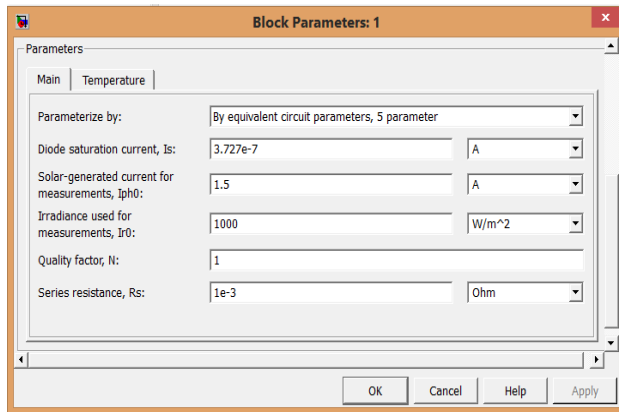


**Fig -13:** Solar cell model in Simscape

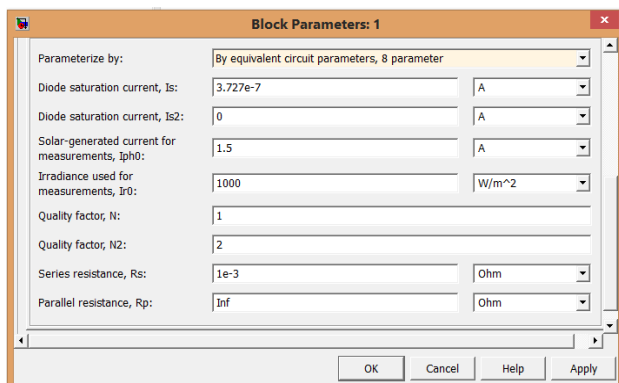
The solar cell in electronics represents single solar cell as a parallel current source ( $I_{ph}$ ) an exponential diode  $D$  and a shunt resistance ( $R_p$ ) that are connected in series with a resistance ( $R_s$ ). The mathematical equations used in the single diode and two-diode model are applicable for the Simscape model as well.



**Fig -16:** Simscape modelling of a PV cell



**Fig -14:** 5-parameter model

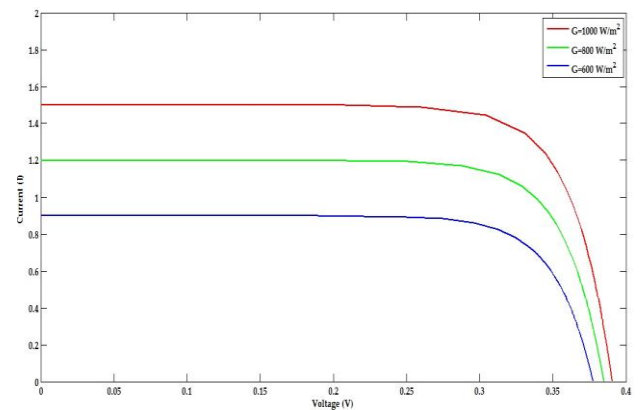


**Fig -15:** 8-parameter model

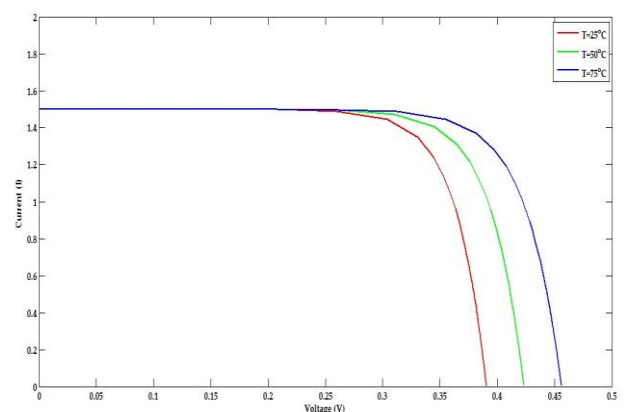
The block can be parameterized in terms of short-circuit current and open-circuit voltage. This block allows enclosing one of the two models: a model with eight parameters and a model with five parameters. It is assumed that the impedance of  $R_p$  is infinite and the saturation current of the second diode is zero. The model with five parameters allows optimization of this block according to the equivalent circuit model parameters or by short circuit current and open circuit voltage.

### 6.1 Simscape Single Diode Modeling (5-Parameter Model)

The PV Characteristics under Varying Irradiance and Temperature for a one diode model implemented in Simscape are shown below:



**Fig -17:** V-I Curve under varying Irradiance



**Fig -18:** V-I Curve under varying Temperature

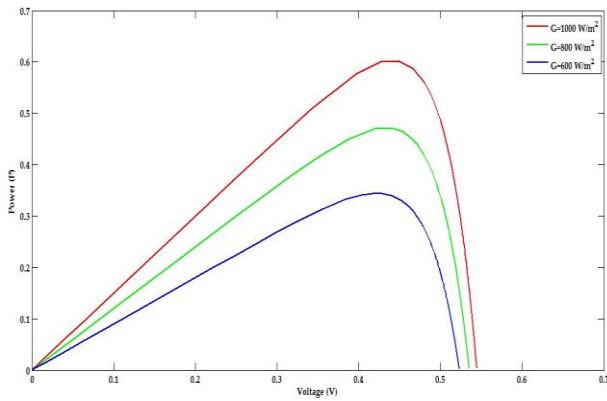


Fig -19: P-V Curve under varying Irradiance

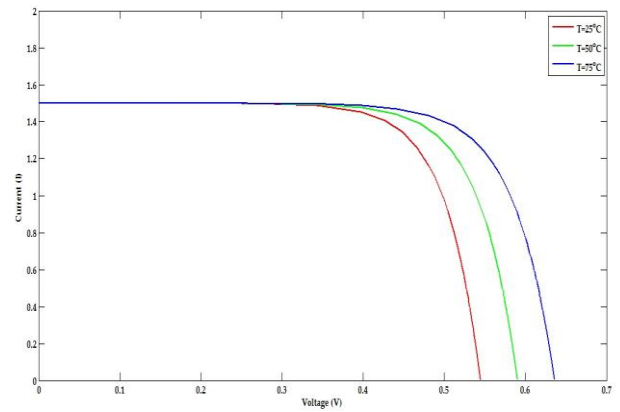


Fig -22: V-I Curve under varying Temperature

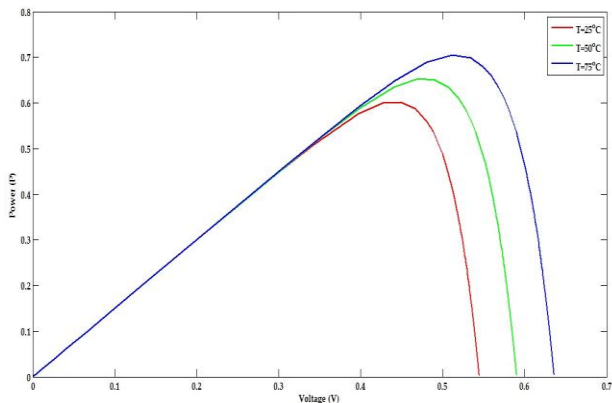


Fig -20: P-V Curve under varying Temperature

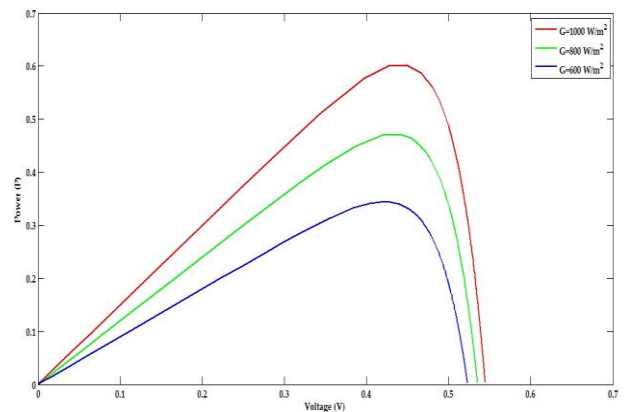


Fig -23: P-V Curve under varying Irradiance

## 6.2 Simscape Two Diode Modeling (8-Parameter Model)

The PV Characteristics under Varying Irradiance and Temperature for a two diode model implemented in Simscape are shown below:

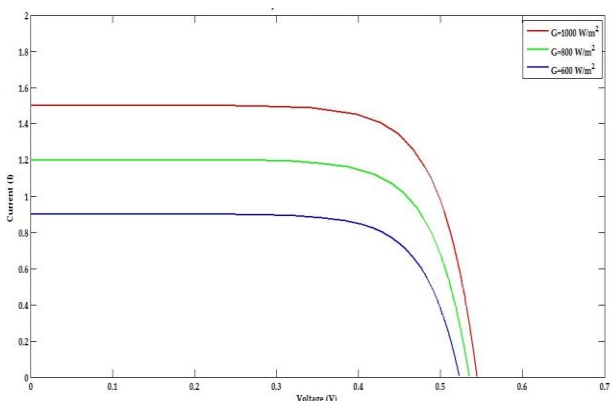


Fig -21: V-I Curve under varying Irradiance

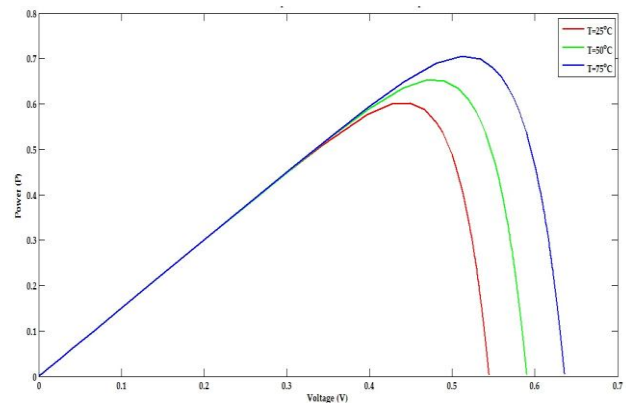


Fig -24: P-V Curve under varying Temperature

The Irradiance values given to the solar cell are  $1000\text{W/m}^2$ ,  $800\text{W/m}^2$ ,  $600\text{W/m}^2$  and the  $I_{sc}$  values vary proportionately. The Temperature values given are  $25^\circ\text{C}$ ,  $50^\circ\text{C}$ ,  $75^\circ\text{C}$  and the  $V_{oc}$  values vary with the temperature.

## 7. RESULTS AND DISCUSSIONS

In order to compare various PV models, a small scale PV cell of 0.8 watts is considered. The four models i.e., mathematical modeling of single diode and two diode model and the Simscape modeling of the single diode and two diode model are simulated and their PV Characteristics are plotted in the Matlab/Simulink environment. The Comparison of the PV Characteristics are shown in the below figure:



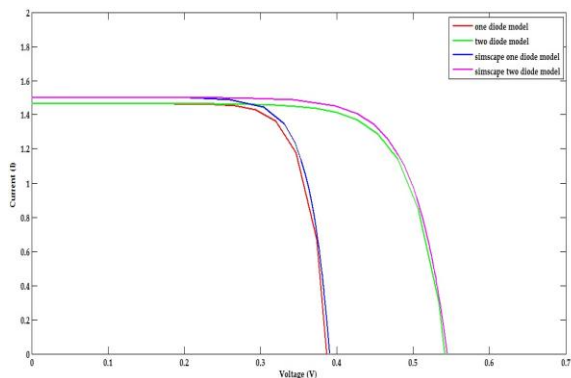


Fig -25: V-I Curves for  $G=1000W/m^2$  and  $T=25^\circ C$

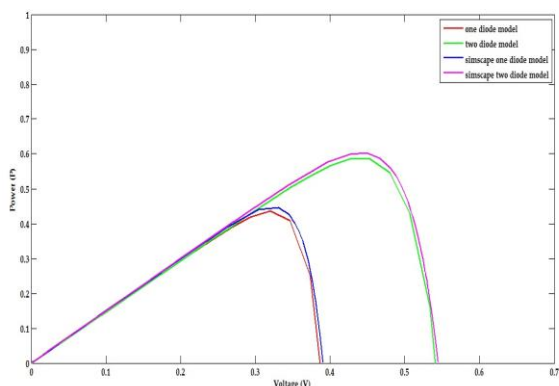


Fig -26 P-V Curves for  $G=1000W/m^2$  and  $T=25^\circ C$

It can be observed from Fig 25 and Fig 26 that the two-diode model gives a better precise output under temperature and irradiation variation, with respect to the single-diode model. This is observed as the single diode models were built on the assumption that the recombination losses were absent in the depletion region, which is not applicable in real solar cell especially at low voltages. The observed difference between the power generated from the single diode and the two diode models is 0.13W under STC. It was also found from the plots that PV Simscape model is a more precise tool to simulate the PV systems. The difference between the Simscape modelling and the Mathematical modelling of 0.02W under STC. The Simscape based Solar cell focuses mainly on the dynamic output of the solar cells. Thus, it is clear that Simscape yields more accurate results than the Mathematical modeling of the PV Cell. The results can be observed from the Tables 3-4.

Table -3: Comparison between One Diode and Two Diode models under varying Temperature and Irradiance conditions

Irradiance (G) $W/m^2$	One diode model			Two diode model		
	$V_{oc}$	$I_{sc}$	$P_{max}$	$V_{oc}$	$I_{sc}$	$P_{max}$
1000	1.333	1.464	0.435	1.333	1.464	0.585
800	1.333	1.171	0.342	1.333	1.171	0.460
600	1.333	0.878	0.249	1.333	0.878	0.335
<b>Temperature (T) and <math>G=1000 W/m^2</math></b>						
25°C	1.333	1.464	0.435	1.333	1.464	0.585
50°C	1.333	1.506	0.487	1.333	1.506	0.657
75°C	1.333	1.549	0.540	1.333	1.549	0.729

Table -4: Comparison between 5-parameter and 8-parameter models in SIMSCAPE under varying Temperature and Irradiance conditions

Irradiance (G) $W/m^2$	Simscape one diode model			Simscape two diode model		
	$V_{oc}$	$I_{sc}$	$P_{max}$	$V_{oc}$	$I_{sc}$	$P_{max}$
1000	0.390	1.500	0.445	0.544	1.500	0.6021
800	0.384	1.200	0.351	0.535	1.200	0.4713
600	0.377	0.900	0.258	0.523	0.900	0.3444
<b>Temperature (T) and <math>G=1000 W/m^2</math></b>						
25°C	0.390	1.500	0.445	0.544	1.500	0.6021
50°C	0.423	1.500	0.485	0.590	1.500	0.6529
75°C	0.456	1.500	0.522	0.636	1.500	0.7046

### 8. CONCLUSION

Simulation tools are very mandatory for developing and handling mathematical simulations for handling mathematical simulations for analyzing the behavior of PV Systems. They embolden the process of progressing the study of new systems like power converters, inverters etc., for reducing cost and time. In this paper, a study on the various mathematical modeling of PV array is discussed. The models discussed are single diode model, two diode model and Simscape modeling of the 8-parameter and 5-parameter model. It can be revealed from the results that the Simscape modelled Solar cells i.e., the single diode and two diode model has comparably better accuracy than the formulated models. The appropriate modeling of the solar cells can facilitate proficient work in the area of MPPT even under varying atmospheric conditions.

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## BIOGRAPHIES



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