

## Modeling and Simulation of Solar Photovoltaic module using Matlab/Simulink

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**Abstract:** This paper presents the circuit model of photovoltaic (PV) module. Simulation and modeling is done using MATLAB/ Simulink software package. The proposed model is user friendly and can be used as a common platform for both applied physics scientist and power electronics engineers. A detailed modeling procedure is presented. The designed model is verified by using STP255-20/Wd PV module. The IV and PV characteristics are simulated at different temperature and irradiance conditions and the results are verified. The proposed model is very simple fast and accurate. The designed model can be used for analysis of PV characteristics and for simulation of maximum power point tracking algorithms.

### I. INTRODUCTION

Energy is required for large number of purposes. Traditional energy is used from coal, natural gas, oil and nuclear energy. But they are exhaustible and polluting. So we need to find an alternate source which is renewable energy source. This can be more extensively used in many applications. Solar energy is a good option and the electricity produced is clean, long lasting, no moving parts, less maintenance and silent. It has experienced a remarkable growth for the past two decades in its widespread use from standalone and utility interactive PV systems [1, 2]. The increase in a number of photovoltaic system installed all over the world brought the need for proper supervision and control algorithms as well as modelling and simulation tool for researcher and practitioners involved in its application is very mandatory.

The modelling and simulation of PV have made a great transition and play a vital role in power generation. Simple circuit models have been proposed in literature [3, 4]. Even though they are interesting, they are very tedious complicated and impractical. Thus because of numerical challenges, an accurate and comprehensive design of PV system in MATLAB Simulink model is proposed. In this paper modelling is limited to simulation of PV module characteristics.

In section II, a simple circuit with detailed circuit modelling of PV module is presented for the design of PV system. In section III, physical equations governing the PV module are presented. A Simulink model is developed for each equation of PV module. In section IV, the numerical result for different temperature and irradiance conditions is presented. Section V presents the discussion and conclusion of the modelling process.

### II. BASIC CIRCUIT AND MATHEMATICAL MODEL

A PV module consists of number of solar cells connected in series and parallel as per the requirement. When solar light falls on PV cell, light energy is converted to electrical energy without any moving parts. The transmitted light is absorbed within the semiconductor, by using this light energy to excite the free electrons from the low energy status to an unoccupied higher energy level. These excess electron hole pairs contribute to the flow of current.

A general mathematical description of I-V output characteristics for a PV cell has been researched and analysed for the past four decades. Such an equivalent based circuit based model is mainly used for the Maximum power point tracking techniques (MPPT) [5, 6]. Authors [7, 8, 9] discussed about solar power extraction.

The equivalent circuit of the general model which consists of a photon current, a diode, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the flow of current is shown in Fig. 1. The current ( $I_{pv}$ ) - voltage ( $V_{pv}$ ) equation of a solar cell is given by:

$$I_{pv} = I_{ph} - I_s \left[ e^{\left\{ \frac{q \cdot (V + I \cdot R_s)}{A \cdot K \cdot T} \right\}} - 1 \right] - (V + I \cdot R_s) / R_{sh} \quad (1)$$

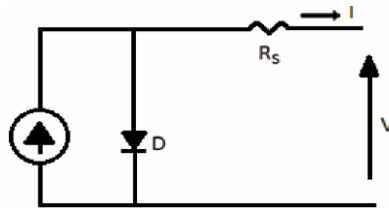


Fig.1. Solar cell model using single diode

The light generated current depends both on irradiance and temperature. It is measured at some reference conditions. Thus,

$$I_{ph} = \{I_{sc} + K_i * (T-25)\} * \lambda \tag{2}$$

Where

- $I_{ph}$  is a light generated photon current,
- $I_s$  is a cell saturation of dark current,
- T Cell temperature in Celsius
- K Boltzmann's constant,  $1.38 * 10^{-19}$  J/K
- q Charge of electron,  $1.6 * 10^{-23}$  C
- $K_i$  Short circuit current temperature coefficient at  $I_{sc}$
- $\lambda$  Solar irradiation in Watts/m<sup>2</sup>
- $I_{sc}$  Short circuit current at 25° C
- $E_g$  Band gap energy for silicon
- A Ideality factor
- $T_{nom}$  Reference temperature in Celsius
- $I_s$  Cell saturation current at  $T_{nom}$
- $R_{sh}$  Shunt resistance in  $\Omega$
- $R_s$  Series resistance in  $\Omega$

Equation (1) is not adequate to describe the cell behavior when subjected to environmental conditions especially at low voltage. So the circuit model is modified by additional parallel resistance ( $R_{sh}$ ). This is shown in figure2. In the proposed model, a current source  $I_{ph}$  which depends on solar radiation and cell temperature, a diode in which the reverse saturation current( $I_d$ ) depends mainly on the operating temperature, a series resistance( $R_s$ ) and a shunt resistance( $R_{sh}$ ) which takes in account the losses in PV cell.

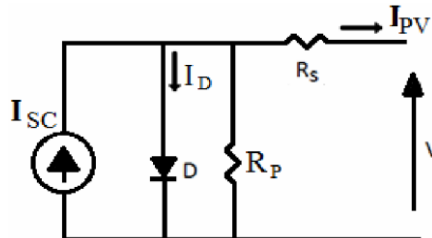


Fig.2. Single diode model with Rsh

$$I_{pv} = N_p * I_{ph} - N_p * I_s \left[ e^{\left\{ \frac{q * (V/N_s + I * R_s / N_p)}{A * K * T} \right\}} - 1 \right] - (V * N_p / N_s + I * R_s) / R_{sh} \tag{3}$$

Where

- $N_p$  number of parallel cells
- $N_s$  number of series cells

The reference values are taken from the PV module manufacturers datasheet for specified operating condition such as STC(standard test conditions) for which the irradiance is 1000W/m<sup>2</sup>. The reverse saturation current( $I_{rs}$ ) is given by

$$I_{rs} = I_{scr} / [e^{(q * V_{oc} / N_s * K * A * T)} - 1] \tag{4}$$

Where

- $I_{scr}$  short circuit current

The saturation current varies with temperature with cubic power.

$$I_s = I_{rs} * (T/T_r)^3 * [ e^{-\{ E_g * (T - T_r) / (A * V_t * T_r) \}} ] \quad (5)$$

Shunt resistance is inversely related with shunt leakage current to the ground. In general, the PV efficiency is insensitive to variation in shunt resistance. Small change in series resistance will significantly affect the PV output power.

A procedure based on Simulink model to determine the values to these parameters is proposed. The analysis and evaluation of these model parameters at real condition of irradiance and temperature of the PV module are then determined as per initial values.

### III. DEVELOPED SIMULINK MODEL

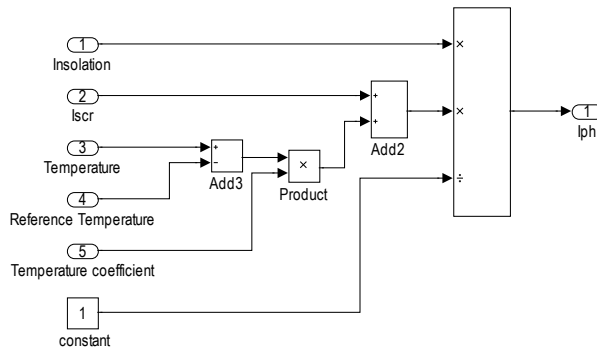
A polycrystalline solar module STP 255-20/Wd is taken as reference module to carry out the study. This module is used for the utility side applications. The electrical characteristics of this module is given in the Table-1 which is taken from the datasheet of the manufacturer.

**Table -1** Electrical specification of STP 255-20/Wd

Specifications	Variable	Values
Maximum power at STC	Pmax	255W
Optimum operating voltage	Vmp	30.8V
Optimum operating current	Imp	8.28A
Open circuit voltage	Voc	37.6V
Short circuit current	Iscr	8.76A
Module efficiency	η	15.7%
No. of series cells	Rs	60
No. of series cells	Rsh	1

Note: Electrical specifications are under test conditions of irradiance 1000 W/m<sup>2</sup>, spectrum of 1.5 air mass and cell temperature of 25°C.

The various stages of development of Simulink model are shown. The subsystem of photon generated current will take Temperature (T), Insolation (λ), Short Circuit Current (Isc) as input. The subsystem is implemented in Fig. 3 using equation 1. The value of I<sub>scr</sub> module short circuit current is taken from the datasheet of the reference model.



**Fig. 3.** Subsystem of photon generated current

I<sub>ph</sub> for different values of irradiance and temperature is shown in Table-2.

**Table -2** I<sub>ph</sub> for various irradiance and temperature

S.No	Irrad. KW/m <sup>2</sup>	Value of I <sub>ph</sub> (A)				
		25°C	40°C	60°C	80 °C	100 °C
1	1	8.76	8.78	8.82	8.85	8.88
2	0.8	7.00	7.02	7.05	7.08	7.11
3	0.6	5.25	5.2	5.29	5.31	5.33
4	0.4	3.5	3.51	3.52	3.54	3.55
5	0.2	1.75	1.75	1.76	1.77	1.77

The subsystem of reverse saturation current is implemented in Fig. 4 using equation 4. It will take short circuit current, temperature, open circuit voltage, number of series cells.

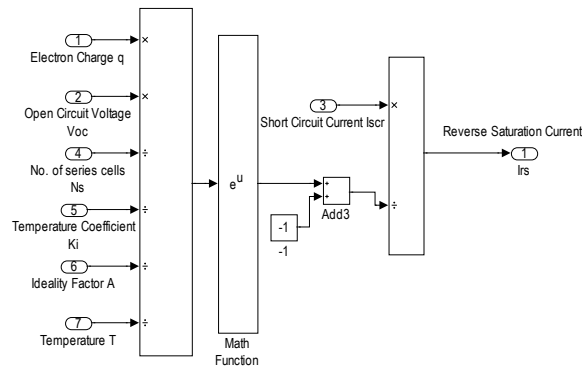


Fig.4. Subsystem of reverse saturation current.

The subsystem of saturation current is implemented in Fig.5. Using the equation 5. Module reverse saturation current varies with temperature as shown in Table 3.

Table -3 Irs for various temperature

S.No	Temperature °C	Reverse saturation current (A)
1	25	2.11*10e-6
2	40	4.38*10e-6
3	60	10.47*10e-6
4	80	22.68*10e-6
5	100	45.29*10e-5

The subsystem of module saturation current is that varies with the cell temperature is given in equation 5 and is simulated in fig. 5

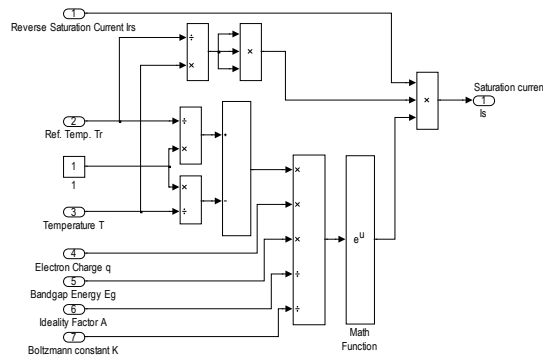


Fig.5. Subsystem of module saturation current.

The module saturated current is calculated for various temperatures is given in Table 4.

Table -4 is for various temperatures

S.No	Temperature °C	Module saturation current (A)
1	25	2.11*10e-6
2	40	1.83*10e-5
3	60	2.43*10e-4
4	80	2.43*10e-3
5	100	1.90*10e-2

The subsystem of output current  $I_{pv}$  is given by equation 3 and is simulated with the model as shown in fig. 6. The  $V_{pv}$  is the open circuit voltage as given in datasheet of the manufacturer. The value of series is given small value as the power rating is high. The value of shunt resistance is given some higher value. The effect of parallel resistance is to reduce the open circuit voltage and fill factor. Short circuit current is not affected by it. The solution for the equation 3 includes many iterations and need for algebraic loop in Simulink. To eradicate this problem, the Simulink functional models are being for modelling procedure.

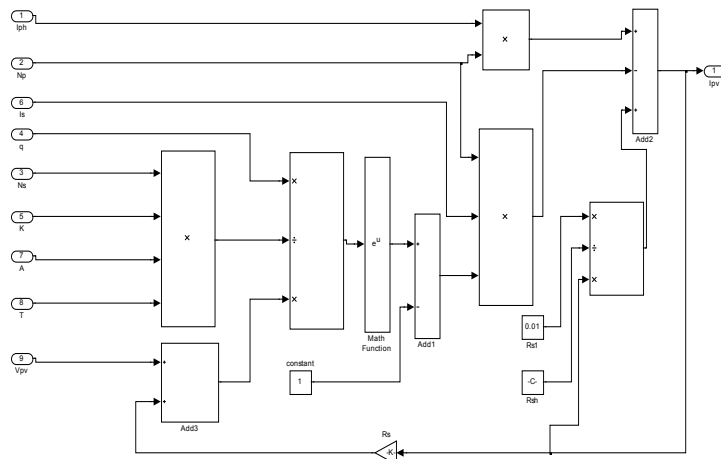


Fig.6. Subsystem of module output current.

This simplified design is more comfortable for power electronics engineer who are in search of fast and effective model for the simulation of PV modules.

All the above models are interconnected and final model is developed which takes irradiance, operating temperature, output current and output voltage. Fig. 7 & 8 shows the final model.

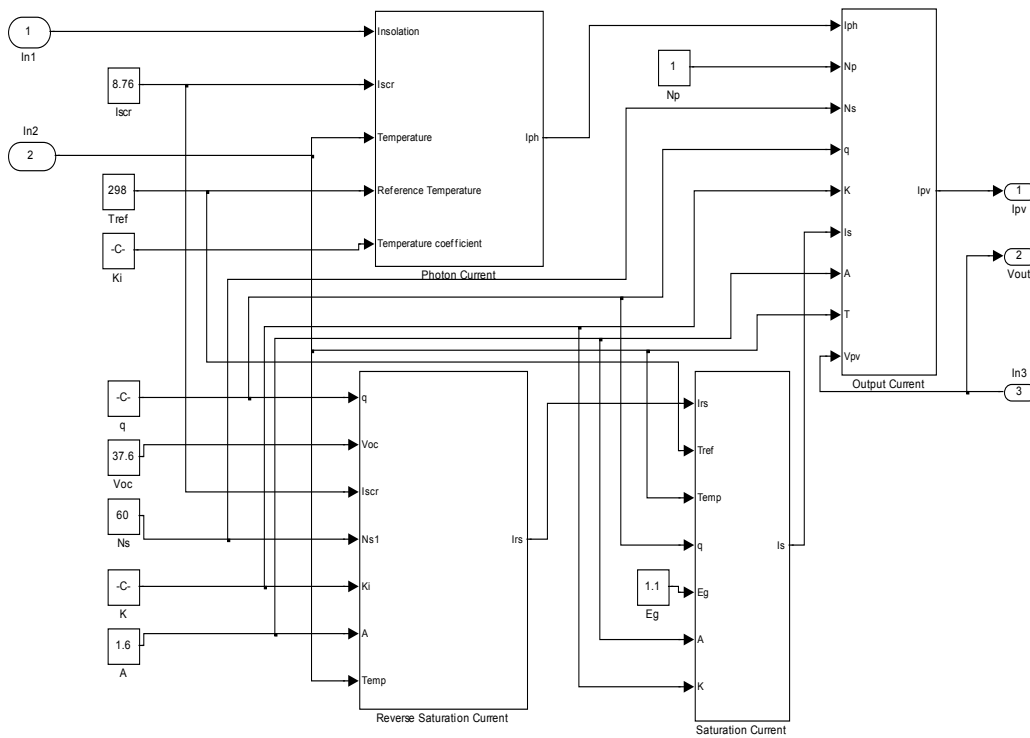


Fig. 7. All models interconnected

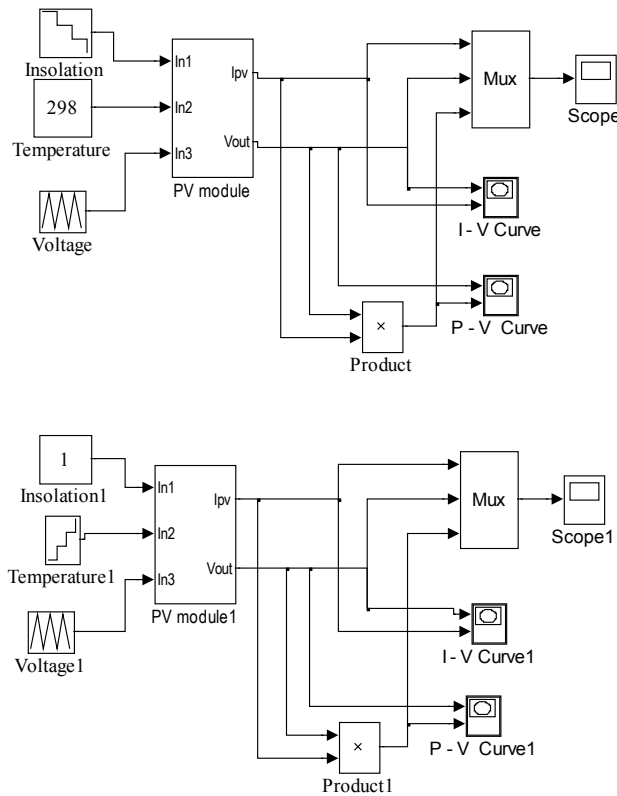


Fig. 8. The final model which gives output voltage and current for varying irradiance and temperature

#### IV. Simulation Results

The PV module taken for modelling is STP255-20/Wd. The developed model is implemented for the above module and evaluated. The evaluation is done using the equations developed in the previous sections. The chosen module provides the output power of 255W maximum nominal and has 60 series cells. The technical specifications are listed in the table 1. The PV and IV characteristics are modeled and simulated for the chosen module using the developed equations and models. Fig. 9 and fig. 10 shows the PV and IV characteristics of module under varying irradiance at constant temperature respectively.

**Table 6.2. I-V Curves with various Irradiance levels**

I - V Curves	Temperature in Kelvin	Irradiance level in KW/m <sup>2</sup>
I	298	1
II	298	0.8
III	298	0.6
IV	298	0.4

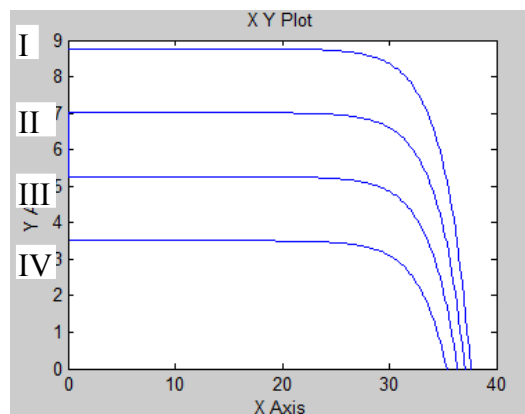


Fig. 9 IV characteristics under varying irradiance at constant temperature (298K)

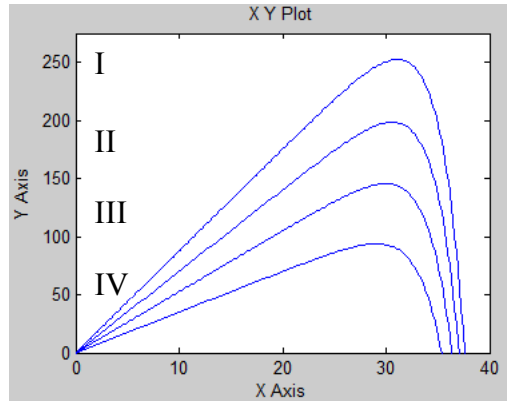


Fig. 10 PV characteristics under varying irradiance at constant temperature (298K)

Fig. 11 and fig. 12 shows PV the IV characteristics of module under varying temperature at constant irradiance respectively. From the characteristics, it is observed that there is an optimum operating point called maximum power point. This point changes with temperature and irradiance. This point increases with irradiance and decreases with temperature. [7]. Hence for any given PV voltage and power, the corresponding insolation can be estimated

**Table6.3. I-V Curves with various temperature levels**

I - V Curves	Irradiance level in KW/m <sup>2</sup>	Temperature in Kelvin
I	1	293
II	1	313
III	1	333
IV	1	353

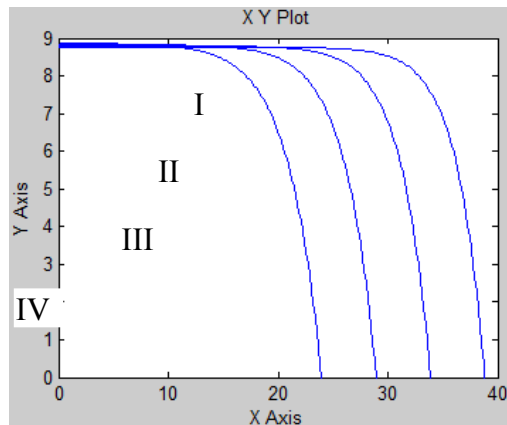


Fig. 11 IV characteristics under varying temperature at constant irradiance (1KW/m<sup>2</sup>)

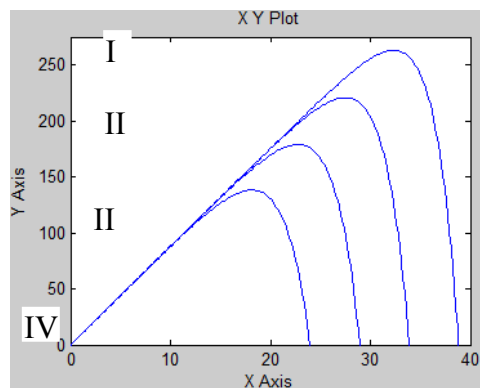


Fig. 12 PV characteristics under varying temperature at constant irradiance (1KW/m<sup>2</sup>)

In the developed model, PV and IV characteristics exactly matches the characteristics of the original module.

## V. ANALYSIS AND CONCLUSION

A PV module is developed and modelled using Matlab/Simulink. From the model, it is understood that the output current is function of solar irradiance. From the equation developed, output voltage is the function of diode junction voltage. This depends on material property. The developed PV model is verified with the available module. The model can be used for the analysis in the area of solar photovoltaic conversion system and MPPT technologies. The reason for using Simulink is that the entire system can be studied as it can simulate both the PV module and the associated power electronics.

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