Modeling and Simulation of Photovoltaic module using MATLAB/Simulink

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Abstract
This paper presents modeling of Photovoltaic (PV) module using MATLAB/Simulink. The model is developed based on the mathematical model of the PV module. Two particular PV modules are selected for the analysis of developed model. The essential parameters required for modeling the system are taken from datasheets. I-V and P-V characteristics curves are obtained for the selected modules with the output power of 60W and 64W from simulation and compared with the curves provided by the datasheet. The results obtained from the simulation model are well matched with the datasheet information.

Keywords: Modeling, PV module, Simulation, MATLAB

1. Introduction

The concentration on the use of fossil fuels for energy supply is the main threat for the stability of the global climate system and our natural living conditions. To conserve our globe, the scientific community gave evidence that mankind has to decrease the green house gases emissions, mainly CO_2 and methane, by 60 - 70% as a minimum until the year 2050 [1]. In order not to harm our natural living spaces and threaten their resilience, a renewed compatibility would require a suitable form of energy alternatives sources that should be independent, easily accessible, and low in cost and should be environmentally clean.

Renewable energy, and in particular power generation from solar energy using Photovoltaic (PV) has emerged in last decades since it has the aforesaid advantages and less maintenance, no wear and tear. The main applications of PV systems are in either stand-alone systems such as water pumping, domestic and street lighting, electric vehicles, military and space applications [2-3] or grid-connected configurations like hybrid systems and power plants [4].

The main aim of this paper is to provide a reader with the fundamental knowledge on design and building the blocks of PV module based on the mathematical equations using MATLAB/Simulink. The principle and operation of the PV cell and the fundamental characteristics of PV cell are discussed in chapter II. In chapter III the mathematical model of the ideal PV cell and also the practical PV cell are described. The simulation model developed using MATLAB/Simulink and the results obtained are presented and discussed in chapter IV.

2. Operation and Characteristics of PV or Solar Cells

2.1 Principle of Operation of Solar Cell

An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity. The solar panels are mainly made out of semiconductor material and silicon being the most abundantly used semiconductor.Solar cells are connected in series to increase the output voltage. Similarly, the cells in parallel will yield a higher current. Series connected cells are called as PV modules and the interconnection series and parallel combination of solar cells is an array.

The operation of solar cells may be described from a PN junction where there are diffusion currents and drift currents for the direct and reverse polarization, respectively. Usually, the cells operate in reverse direction so that the current drift is desirable. When the PN junction is exposed to light, photons with energy greater than the gap of energy are absorbed, causing the emergence of electron-hole pairs. These carriers are separated under the influence of electric fields within the junction, creating a current that is proportional to the incidence of solar irradiation [5].

2.2 Characteristics of Solar Cell:

Solar cells naturally exhibit a nonlinear I-V and P-V

characteristics which vary with the solar irradiation and cell temperature. The typical I-V and P-V characteristics of solar cell are shown in figure 1.
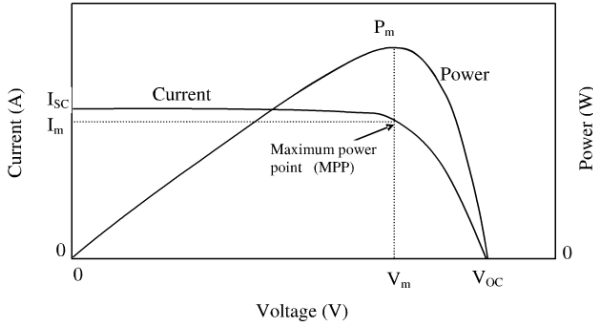

Figure 1. Characteristics of solar cell

The fundamental parameters related to solar cell are short circuit current (I_{SC}), open circuit voltage (V_{OC}), maximum power point (MPP), efficiency of solar cell and fill factor.

Short Circuit Current is the current corresponds to the short circuit condition when the impedance is low and it is calculated when the voltage equals to zero.

$$I\ (at\ V=0) = I_{sc} \tag{1}$$

I_{SC} occurs at the beginning of the forward-bias sweep and is the maximum current value in the power quadrant. For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation.

Open Circuit Voltage is the voltage when the open circuit occurs and there is no current passing through the cell. The Open circuit voltage is calculated when the voltage equals to zero.

$$V\ (at\ I=0) = V_{oc} \tag{2}$$

V_{OC} is also the maximum voltage difference across the cell for a forward-bias sweep in the power quadrant. $V_{oc}= V_m$ for forward-bias power quadrant. The open circuit voltage can be expressed as:

$$V_{oc} = \frac{AkT_c}{q}\ ln\left(\frac{I_{pv}}{I_s}\right) \tag{3}$$

where, I_{pv} is the light generated current (it is directly proportional to the solar irradiation), I_s is the

saturation or leakage current of the diode, q is the electron charge [1.60×10^{-19} ^OC], k is the Boltzmann constant [1.38×10^{-23} J/K], T_C is the cell operating temperature (^OK) and A is the ideality constant of diode.

Both k and T_C should have the same temperature unit, either Kelvin or Celsius. The ideality constant varies depends on PV technology [6]. Ideality constant of different PV technology is presented in Table I.

Table 1: Ideality constant (A) for PV technology

Technology	Ideality Factor
Si-mono	1.2
Si-poly	1.3
a-Si:H	1.8
a-Si:H tandem	3.3
a-Si:H triple	5
CdTe	1.5
CIS	1.5
AsGa	1.3

Maximum Power Point is the operating point at which the power is maximum across the load.

$$P_m = V_m I_m \tag{4}$$

where, V_m is the maximum voltage and I_m is the maximum current.

Efficiency of solar cell is the ratio between the maximum power and the incident light power.

$$\eta = \frac{P_m}{P_{in}} \times 100 \tag{5}$$

P_{in} is taken as the product of the solar irradiation of the incident light $(G=\lambda/1000)$, measured in W/m^2, with the surface area (A_c) of the solar cell in m^2.

$$Pin = G.\ A_c \tag{6}$$

Fill Factor (FF) is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (P_t) that would be output at both the open circuit voltage and short circuit current together

$$FF = \frac{P_m}{V_{oc}I_{sc}} \tag{7}$$

Typical fill factors range from 0.5 to 0.82. The fill factor diminishes as the cell temperature is increased.

3. Mathematical model of PV cell

The ideal photovoltaic cell is shown in figure 2. The mathematical equation for I-V characteristics of the ideal cell is given by equations (8), (9) [7].
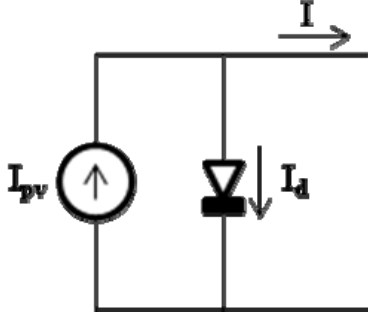

Figure 2. Equivalent circuit of Ideal PV Cell

$$I = I_{pv} - I_d \tag{8}$$

where, I_d is the Shockley equation and it can be expressed as

$$I_d = I_s \left\{ exp\left(\frac{q}{AkT_c}\right) - 1 \right\} \tag{9}$$

A general mathematical description of I-V output characteristics for a PV cell has been studied for over the pass four decades [8]-[10]. The equivalent circuit of solar cell comprised of a current source connected in anti-parallel with the diode, series resistance of the cell R_S and the shunt resistance of the cell R_{sh} is shown in figure 3. Based on figure 3, the output current of the solar cell can be calculated as

$$I - I_{pv} - I_d - I_{Rsh} \tag{10}$$

$$I = I_{pv} - I_s \left\{ exp\left(\frac{q}{AkT_cN_s}V + IR_s\right) - 1 \right\} - \frac{V + IR_s}{R_{sh}} \tag{11}$$

where, N_S is number of cells in series for a PV module.

The light generated current of the solar cell is mainly depends on the solar irradiation level and its working temperature, which is expressed as

$$I_{pv} = [I_{sc} + K_I(T_c - T_r)].G \tag{12}$$

where, I_{SC} is the short-circuit current of cell at 25°C and 1000W/m^2, K_I is the short-circuit current temperature co- efficient of cell, T_c and T_r are the working temperature of cell and reference temperature respectively in ^OK.

The diode saturation current of the cell varies with the cell temperature, which is expressed in [11] as,

$$I_s = I_{rs} \left(\frac{T_c}{T_r}\right)^3 exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_c} - \frac{1}{T_r}\right)\right] \tag{13}$$

where, I_{rs} is the reverse saturation current of a cell at a reference temperature and a solar irradiation, E_g is the band gap energy of the semiconductor used in the cell (Eg ≈1.12 eV for the polycrystalline Si) at 25 ^OC [11].
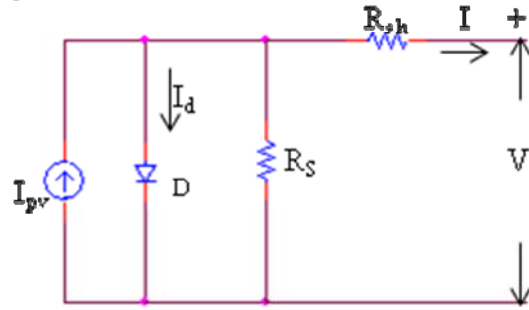

Figure.3 Equivalent circuit of solar cell

The reverse saturation current of a cell I_{rs} is

$$I_{rs} = \frac{I_{sc}}{exp\left(\frac{q}{AkT_cN_s}V_{oc}\right) - 1} \tag{14}$$

The work proposed in [12] claims that the only two unknowns in equation (11) are R_S and R_{sh}, and it may be found by making the maximum power calculated from I-V curve of the model ($P_{m,m}$) equal to the maximum power obtained from the experiment i.e., the power given in the datasheet ($P_{m,e}$) and solving the resulting equations for Rs, using iteration method by slowly increasing the value of Rs from zero. (i.e.,) the iteration starts with Rs=0. The equation which satisfies $P_{m,m} = P_{m,e}$ is given as,

$$R_{m,m} = V_m \left\{ \frac{I_{pv} - I_s \left[exp\left(\frac{q}{AkT_c N_s} V_m + I_m R_s \right) - 1 \right]}{-\frac{V_m + I_m R_s}{R_{sh}}} \right\} = R_{m,e}$$

(15)

$$R_{sh} = V_m (V_m + I_m R_s) / \left\{ V_m I_{pv} \left[exp\left(\frac{V_m I_{pv} - q}{AkT_c N_s} V_m + I_m R_s \right) - 1 \right] \right\}$$
$$- R_{m,e}$$

(16)

4. Modeling and Simulation of PV Module

The blocks of the model are developed using MATLAB /Simulink based on Equation (11).The Solarex MSX60/MSX64 PV modules are chosen for modeling. The typical electrical characteristics of both MSX60 and MSX 64 are given in table 2. These modules consist of 36 polycrystalline silicon solar cells electrically configured as two series strings of 18 cells each [13].

The blocks developed using MATLAB/simulink for the PV module is shown in figures 4, 5, 6 and 7. The values of R_S and R_{Sh} are calculated using equations (15), (16) and the optimum values which satisfies $P_{m,m}=P_{m,e}$ are R_S = 0.1 Ω and R_{Sh} =161.344Ω

The I-V characteristics and P-V characteristics curves obtained from the simulation for MSX 60 and MSX 64 PV modules at T_c=25°C (298.15 °K) and G=1 are presented in figures 8, 9, 10 and 11. The guaranteed minimum output power of MSX 60 module is 58W and MSX 64 module is 62W [13]. The output obtained from the model exactly matches with the data provided by the datasheet for both I-V characteristics and P-V characteristics of MSX 60 and MSX 64.

5. Conclusion

A PV module model based on the mathematical model of solar cell is developed using MATLAB/Simulink blocks. The essential input parameters such as V_m, I_m, V_{oc}, I_{sc}, N_S, K_I, T_c and G are taken from the manufacturers datasheet for the typical 60W and 64W modules selected for analysis. The I-V and P-V characteristics outputs are generated using the developed model for the selected modules and the obtained results are well matched with the datasheet information.

Table 2. Electrical Characteristics of MSX 60/MSX 64 PV Module

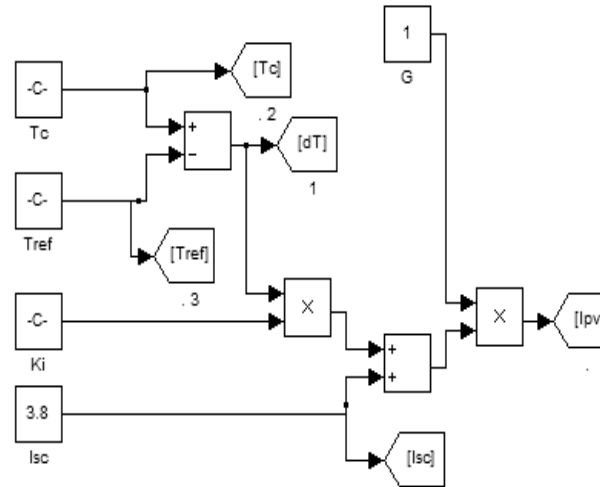| Description	MSX 64	MSX 64
Maximum Power (Pm)	64 W	60W
Voltage @ Pmax (Vm)	17.5 V	17.1A
Current at @ Pmax (Im)	3.66A	3.5A
Guaranteed Minimum Pm	62W	58W
Short Circuit current (Isc)	4.0a	3.8A
Open Circuit voltage (Voc)	21.3A	21.1A
Temperature co-eff of Voc	-(80±10) mV/°C	
Temperature co-eff of Isc	(0.065±0.15) %/°C	
Temperature co-eff of power	-(0.5±0.05) %/°C	
NOCT2	47±2 °C	

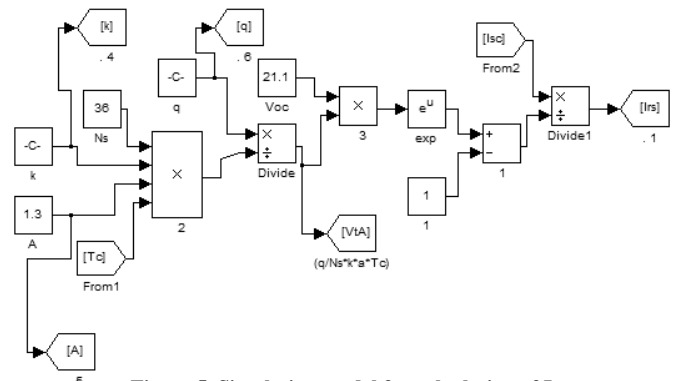**Figure 4. Simulation model for calculation of I_{pv}**

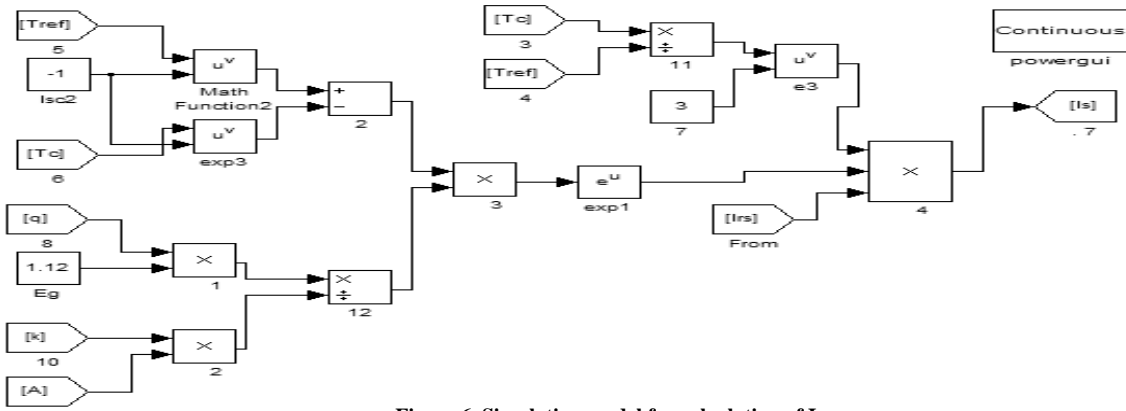**Figure 5. Simulation model for calculation of I_{rs}**

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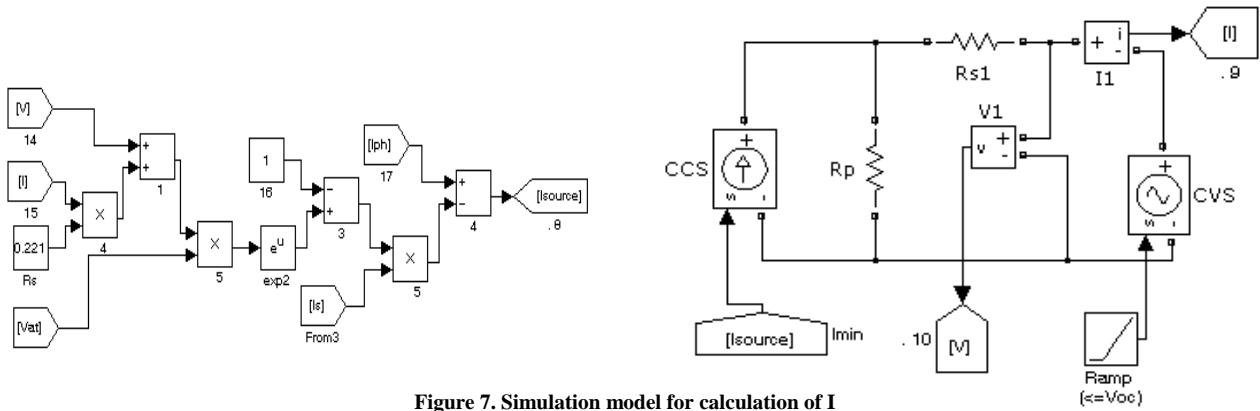**Figure 6. Simulation model for calculation of I_S**
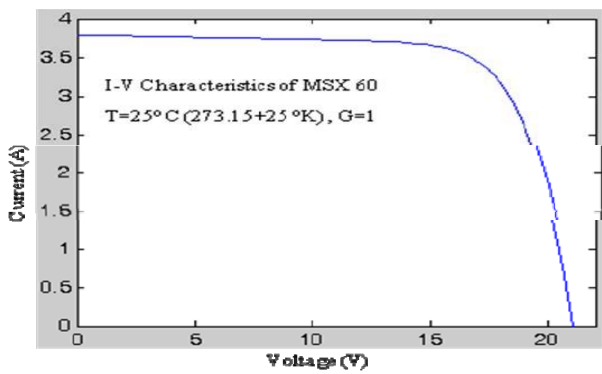

Figure 7. Simulation model for calculation of I

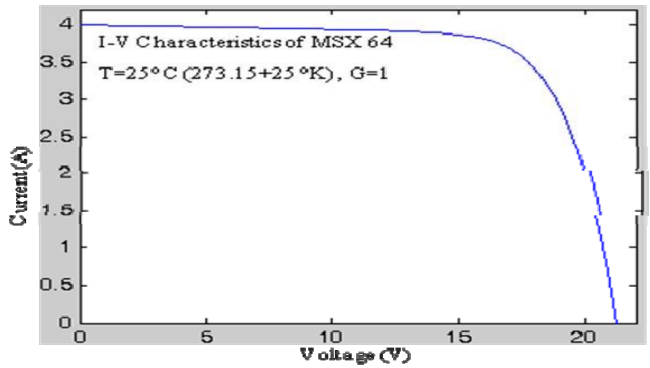**Figure 8. Simulation results of I-V characteristics of MSX60 at T_C=25 ^{o}C and G=1**

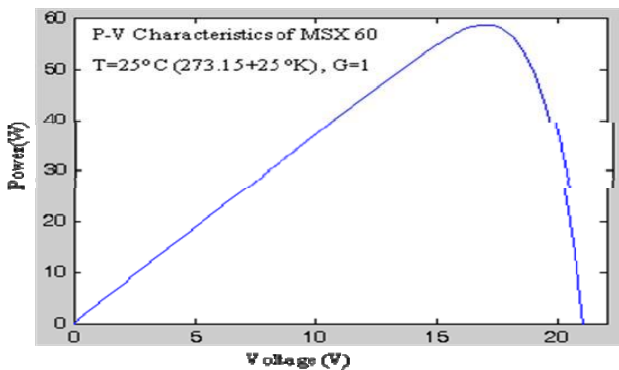**Figure 10. Simulation results of I-V characteristics of MSX64 PV at T_C=25 ^{o}C and G=1**

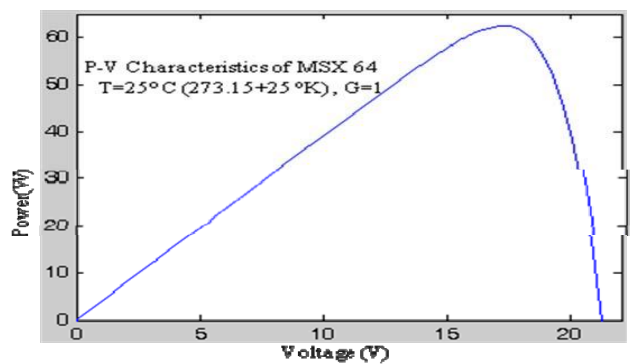**Figure 9. Simulation results of P-V Characteristics of MSX60 at T_C=25 ^{o}C and G=1**

Figure 11. Simulation results of P-V characteristics of MSX64 at T_C=25 C and G=1

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