

Mathematical Modeling and Simulation of Photovoltaic Power Source using Matlab/Simulink

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ABSTRACT: Photovoltaic (PV) model is used in a simulation study to validate the system design of a PV system. This paper presents a step-by-step (detailed modeling) procedure for the simulation of photovoltaic modules with numerical values, using Matlab/Simulink software package. The proposed model is developed based on the mathematical model of the PV module, which is based on that of an elementary PV solar cell employing One-diode equivalent circuit. A particular Polycrystalline PV module is selected for the analysis of the developed model. The essential parameters required for modeling the system are taken from datasheets. The output current and power characteristic curves highly depend on some climatic factors such as solar radiation and temperature, are obtained by simulation for the selected module with the output power of 250 W and discussed.

KEYWORDS: photovoltaic energy, PV Module, Modeling, Simulink model.

1 INTRODUCTION

Currently, the sources of energy and also the harmful increase in greenhouse present real problems of actuality. The additional danger is that excessive consumption of the natural resources stock reduces the reserves of this type of energy in a dangerous way for future generations, mainly with the industrial development. In order to preserve our natural living spaces and protect their resilience, a renewed compatibility would require a suitable form of alternatives energy sources that should be independent and easily accessible. Moreover, with industrial developments, the use of the power generation technology with renewable energy source is developing rapidly. The Renewable energy has an advance all over the world in the environment protection, since; it is clean, operating silently, long life time, low maintenance and absence of fuel cost and inexhaustible [1]-[2].

Among the renewable energy resources, the energy due to the photovoltaic (PV) effect can be considered the most essential and prerequisite sustainable resource because of the ubiquity, abundance, and sustainability of solar radiant energy. Regardless of the intermittency of sunlight, solar energy is widely available and is free. Recently, photovoltaic system is recognized to be in the forefront in renewable electric power generation.

PV module represents the fundamental power conversion unit of a PV generator system. The output characteristics of a PV module depend on the solar radiation, the cell temperature and the output voltage of the PV module. Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of maximum power point tracking (MPPT) for PV system applications.

Mathematical modeling of PV module is being continuously updated to enable researcher to have a better understanding of its working [3].

The main aim of this paper is to provide the reader with a step-by-step procedure for simulating PV module with subsystem blocks, with user-friendly icons and dialog in the same way as Matlab/ Simulink block libraries is developed. In chapter II, the equivalent circuit model of the PV module, the mathematical equations and the reference model providing

data for "Plus SW 240-255 Poly" [4] PV module of Solarworld for simulation, are presented. In chapter III, the Simulink model for the mathematical equations of the PV module and the simulation results are presented. Finally, brief conclusions are drawn in Section IV.

2 MODELING OF PV MODULE

2.1 EQUIVALENT CIRCUIT

A PV module consists of a number of solar cells connected in series and parallel to obtain the desired voltage and current output levels. Each solar cell is basically a p-n diode. As sunlight strikes a solar cell, the incident energy is converted directly into electrical energy without any mechanical effort.

For simplicity, the single-diode model [5] of Figure 1 is used in this paper. This model offers a good compromise between simplicity and accuracy with the basic structure consisting of a current source and a parallel diode.

The equivalent electrical circuit is shown in Figure 1. Series resistors R_s and parallel (shunt) R_p that limit the performance of the cell are added to the model to take into account the dissipative phenomena at the cell (internal losses) [6].

R_s : Series resistor, mainly due to losses by Joule effect through grids collection and to the specific resistor of the semiconductor, as well as bad contacts (Semi conductor, electrodes).

R_p : Parallel resistor, called 'Shunt' comes from the recombination losses mainly due to the thickness, the surface effects and the non-ideality of the junction.

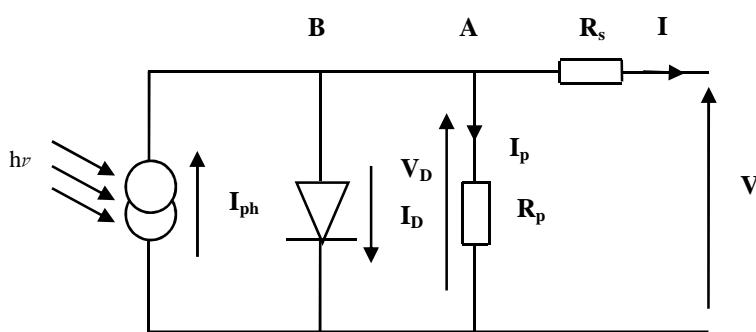


Fig.1. Equivalent circuit of real solar cell with R_s and R_p

2.2 EQUATIONS OF PV MODULE

PV cells are grouped in larger units called PV modules, which are further interconnected in a series-parallel configuration to form PV arrays. The following are the basic equations from the theory of semiconductors and photovoltaic that mathematically describe the I-V characteristic of the photovoltaic cell and module.

So, according to the law of Kirchhoff to the nodes A and B, we have:

$$I = I_{ph} - I_D - I_p \quad (1)$$

I_{ph} : is the light-generated current at the nominal condition (25°C and 1000W/m^2), it is linearly dependent on the solar radiation and is also influenced by temperature according to the following equation:

$$I_{ph} = [I_{SCR} + K_i (T_k - T_{ref})] \cdot \left(\frac{G}{1000} \right) \quad (2)$$

Where K_i : is the short-circuit current/ temperature coefficient of cell. T_k and T_{ref} : are the working temperature of cell and reference temperature respectively in $^\circ\text{K}$. G : is the solar radiation on the cell surface (W/m^2). I_p : Current through R_p . I_D : Diode Current, it is given by:

$$I_D = I_0 \left[\exp\left(\frac{qV_D}{AKT}\right) - 1 \right] = I_0 \left[\exp\left(\frac{q(V + R_s I)}{AKT}\right) - 1 \right] \quad (3)$$

Where, q: is the electron charge constant (1.6.10-19C), K: Boltzmann's constant (1.38.10-23J/K), T: Cell temperature (°K).

I_0 : is the saturation current of the diode and it is given by:

$$I_0 = I_{rs} \left[\frac{T}{T_r} \right]^3 \exp \left[\left(\frac{qE_{g0}}{AK} \right) \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \quad (4)$$

I_{rs} : is the reverse saturation current and it is given by:

$$I_{rs} = \frac{I_{SCR}}{\exp [qV_{OC}/N_s K A T] - 1} \quad (5)$$

Where A: is the ideality factor of the cell depends on recombination mechanisms in the space charge zone.

E_{g0} : is the bandgap energy of the semiconductor ($E_{g0} \approx 1.1$ eV for the polycrystalline Si at 25°C).

Replacing in equation (1) the equation (3), the characteristic equation becomes:

$$I = N_p I_{ph} - N_p I_0 \left[\exp\left(\frac{q(V + R_s I)}{N_s A K T}\right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (6)$$

Where N_p and N_s are, respectively, the number of parallel and series connections of cells in the given photovoltaic module ($N_p = 1$ and $N_s = 60$).

In the ideal case, R_s tends towards 0 and R_p to infinity. And in the real case, these resistors provide an assessment of the imperfections of the diode; considering that the resistance R_s has a low value, the slopes of the I-V characteristics are calculated at $I=0$ open circuit $V=0$ and respectively give the inverse of series and shunt resistance values.

2.3 REFERENCE MODEL

"Plus SW 240-250 Poly" PV Module of Solarworld is taken as the reference module for simulation and the data sheet details are given in Table1. A block diagram of the stage by stage model based upon the equations previously defined of PV model is represented in Simulink environment as given in Figures 2 to 6.

Table1. Electrical Characteristics data of PV module at STC

Parameters	Value (SW 250)
Maximum Power (Pmax)	250 Wp
Voltage at Maximum Power (Vmp)	30.5 V
Current at Maximum Power (Imp)	8.27 A
Open Circuit voltage (Voc)	37.6 V
Short Circuit current (Isc)	8.81 A
Cells per module	60
Area	1.676m ²

The performance of solar cell is normally evaluated under the standard test condition (STC), where an average solar spectrum at AM 1.5 is used, the solar radiation is normalized to 1000W/m², and the cell temperature is defined as 25 °C.

3 STEP BY STEP PROCEDURE FOR SIMULINK MODELING OF PV MODULE

3.1 SIMULINK MODELING FOR PV MODULE

In order to have a model to simulate the operation of our associated cells, we developed a model in Simulink package by using the equations given in previous section and the Solarworld "Plus SW 240-255 Poly" PV module is taken as reference

module. So, a block diagram of step by step model based on these equations is represented in Simulink environment as given in figures 2 to 6.

3.1.1 STEP 1

Detailed Simulink model of equation (2) of photocurrent I_{ph} is shown in Figure 2. The value of module short-circuit current is I_{SC} taken from the datasheet of the reference model as given in chapter II.

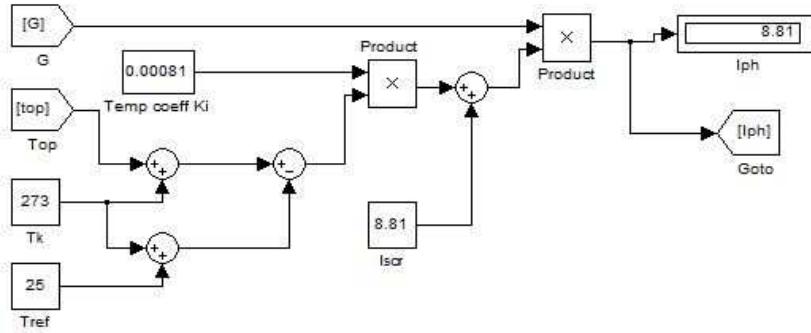


Fig.2. Block diagram for calculate light generated current (Photocurrent)

3.1.2 STEP 2

Detailed Simulink model of equation (5) of the reverse saturation current I_{rs} is shown in Figure 3. The value of module open-circuit voltage is V_{oc} taken from the datasheet of the reference model as given in table 1.

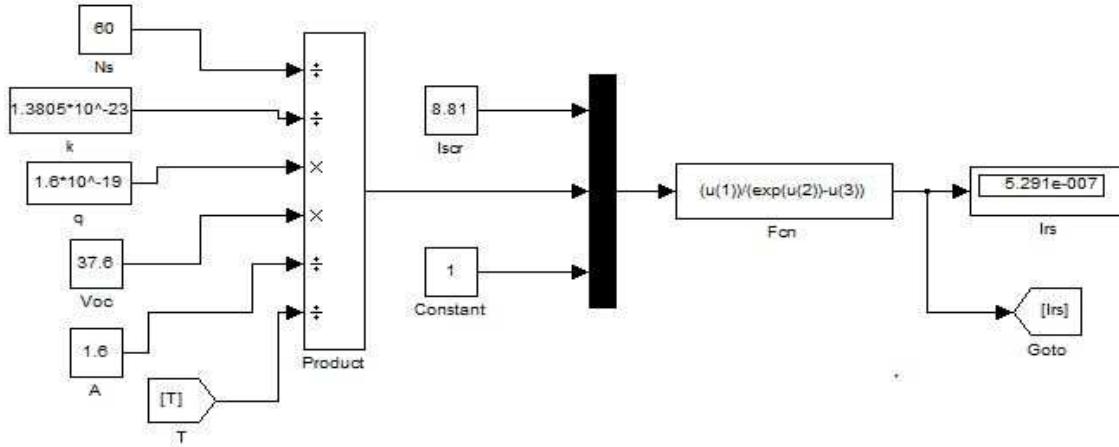


Fig.3. Block diagram for calculate Reverse saturation current.

3.1.3 STEP 3

Detailed Simulink model of equation (4) of the output current of PV module I of the single-diode model presented in Figure 1 is shown in Figure 4. The module operating temperature, reference temperature, and module reverse saturation current are taken as inputs.

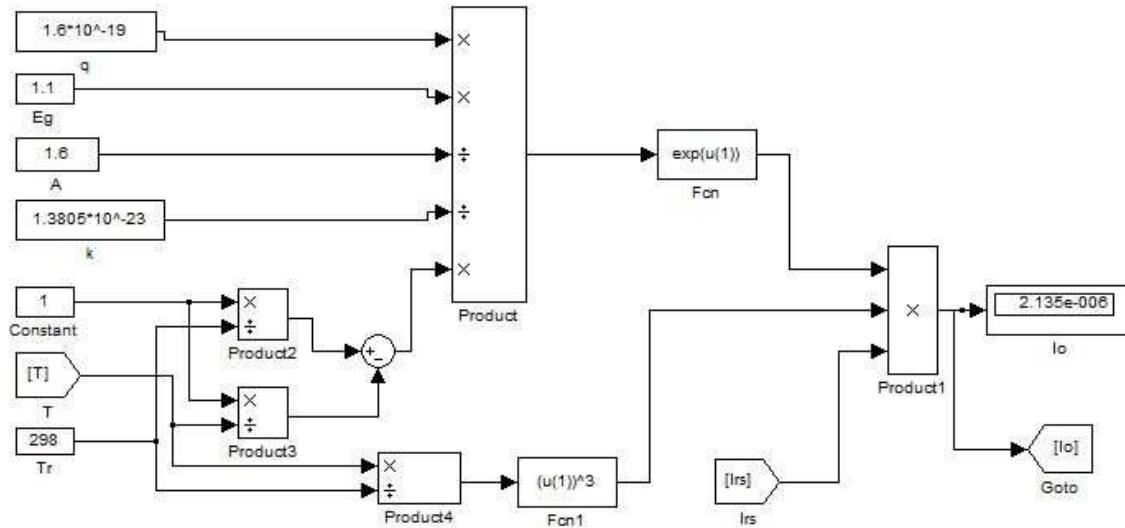


Fig .4. Block diagram for calculate Saturation current.

3.1.4 STEP 4

The basic equation that describes the output current of PV module I of the single diode model presented in figure1 is given by the equation (6).

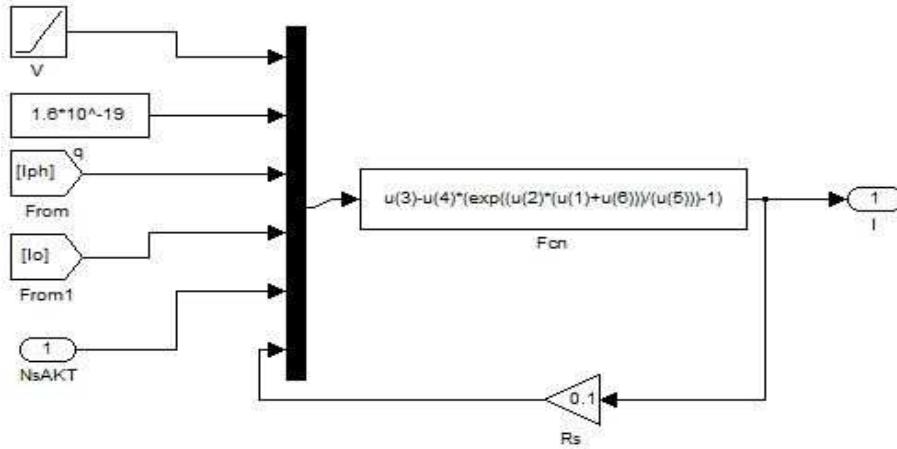
The parallel resistance has its greatest effect when the voltage is lowest, that is, when the current passing through the diode of the equivalent circuit is very small. The effect of parallel resistance, when it is sufficiently small, is to reduce the open-circuit voltage and the fill factor [7]. The short-circuit current is not affected by it.

The use of simplified circuit model in this paper makes this model suitable for power electronics designers who are looking for an easy and effective model for simulation of photovoltaic devices with power converters. The value of parallel resistance R_p is generally high and hence neglected to simplify the model as given in (7).

The series resistance R_s (0.1Ω) is the sum of several structural resistances of the PV module and its influence is stronger especially near the maximum power point region. In this paper simplification of equation is done by excluding R_p . So, equation (6) for the current output of PV module can be modified as:

$$I = N_p I_{ph} - N_p I_0 \left[\exp\left(\frac{q(V + R_s I)}{N_s A K T}\right) - 1 \right] \quad (7)$$

The solution for (7) involves iteration and requires solving of algebraic loop in Simulink. To avoid this problem, the functional models are used in PV research for modeling of PV module. The iterative Matlab/Simulink model of the output current I is shown in figure5.

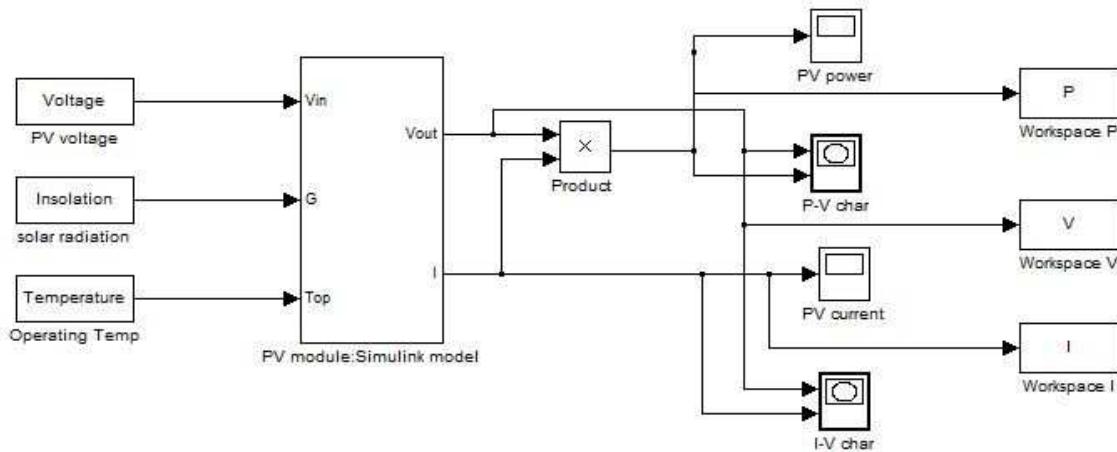
**Fig.5. Block diagram for calculate Output current.**

3.1.5 STEP 5

All the above blocks are interconnected to get Simulink model of I for the PV module. This model takes solar radiation, operating temperature, and Voltage V as inputs and calculates I .

V is varied from 0 to 37.6V.

Simulink model of I is simulated with the setup shown in Figure 6.

**Fig.6. Simulink model of PV module**

4 SIMULATION RESULTS AND DISCUSSIONS

4.1 CALCULATION OF PHOTOCURRENT

The module photocurrent I_{ph} of the photovoltaic module depends linearly on the solar radiation and is also influenced by the temperature according to the equation (2). Table 2 gives the values of photocurrent for different values of solar radiation and temperature.

Table2. *I_{ph}* for various solar radiation and temperature

S. no.	Solar Radiation (W/m ²)	Value of I _{ph} (A)				
		0°C	25°C	50°C	75°C	100°C
1	1000	8.79	8.81	8.83	8.851	8.871
2	700	6.153	6.167	6.181	6.195	6.21
3	500	4.395	4.405	4.415	4.425	4.435
4	300	2.637	2.643	2.649	2.655	2.661
5	100	0.879	0.881	0.883	0.8851	0.8871
6	0	0	0	0	0	0

4.2 CALCULATION OF REVERSE SATURATION CURRENT

Module reverse saturation current varies with temperature as shown in Table 3.

Table3. *I_{rs}* for various temperature

S. no.	Temperature (°C)	Module reverse saturation current (A)
1	0	0.5291 * 10 ⁽⁻⁰⁰⁶⁾
2	25	2.135 * 10 ⁽⁻⁰⁰⁶⁾
3	50	6.941 * 10 ⁽⁻⁰⁰⁶⁾
4	75	19.05 * 10 ⁽⁻⁰⁰⁶⁾
5	100	45.67 * 10 ⁽⁻⁰⁰⁶⁾

4.3 CALCULATION OF SATURATION CURRENT

The module saturation current I_0 varies with the temperature as shown in Table 4.

Table4. *I₀* For various Temperature

S. no.	Temperature (°C)	Module saturation current (A)
1	0	0.03515 * 10 ⁽⁻⁰⁰⁶⁾
2	25	2.135 * 10 ⁽⁻⁰⁰⁶⁾
3	50	7.001 * 10 ⁽⁻⁰⁰⁵⁾
4	75	0.001414
5	100	0.01937

It is clearly derived from equation (1) through (6) that the PV module exhibits a highly nonlinear radiation and temperature dependence I-V and P-V characteristic curves.

4.4 SOLAR RADIATION EFFECTS ON PV MODULE CHARACTERISTICS

The response of a PV cell at different levels of solar radiation and at constant temperature 25°C Shows that solar radiation has a significant effect on the short-circuit current (Fig. 7), while the effect on the voltage in open circuit is quite low. Regarding the power, we can clearly see the existence of the maximum on the power curves (Fig. 8) corresponding to the Maximum Power Point Pmax. When the solar radiation is high, the cell generates more power.

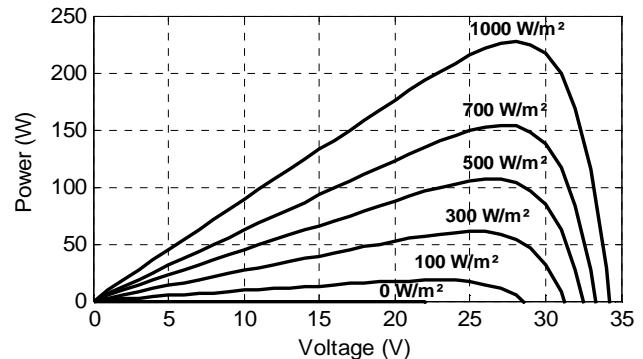
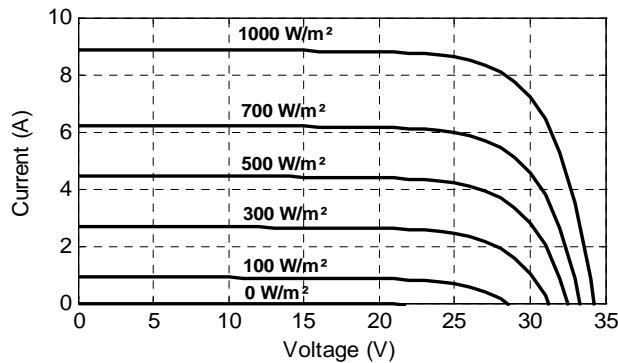


Fig.7. I-V characteristic - variable solar radiation - constant temperature (25°C), Fig.8. P-V characteristic - variable solar radiation - constant temperature (25°C)

As we can see in the figures above, the current and the power increase are highly affected by the solar radiation. The table below can sum up this.

Table5. MPP under solar radiation variation (at constant temperature 25°C)

Solar radiation (W/m ²)	P _{mpp}	I _{mpp}	V _{mpp}
0	0	0	0
100	18.09	0.8812	28.5
300	60.84	2.648	31.3
500	106.4	4.414	32.5
700	153.9	6.18	33.3
1000	227.1	8.829	34.2

4.5 TEMPERATURE EFFECTS ON PV MODULE CHARACTERISTICS

The temperature is an important parameter in the behavior of solar cells. The temperature has also an influence on the characteristic of a PV generator. Fig. 9 and 10 show the variation of the characteristics of a PV module at different levels of temperature and at a given solar radiation. So, we can clearly see that the temperature has a very important effect on the open circuit voltage and a no remarkable effect on both the short circuit current (Fig. 9) and the power of the module (Fig. 10). When the temperature is low, the cell generates more power.

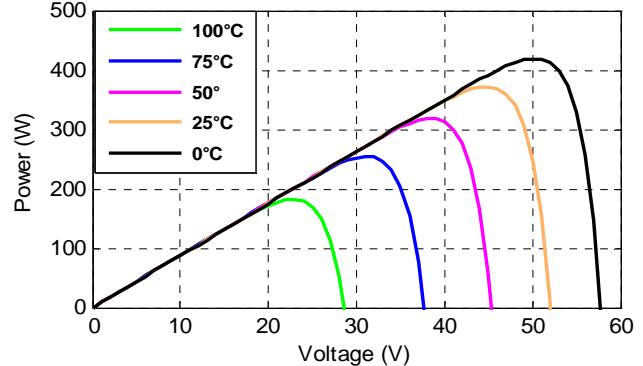
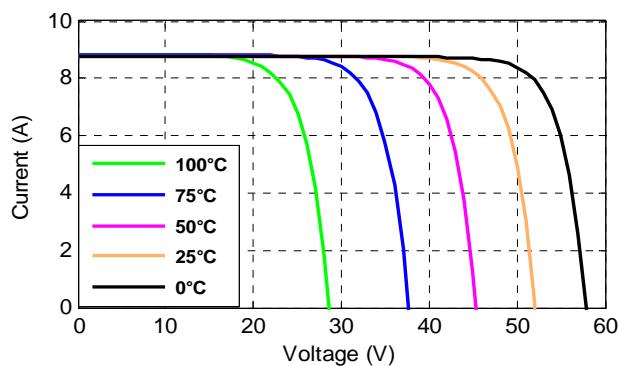


Fig. 9. I-V characteristic - constant solar radiation - variable temperature, Fig. 10. P-V characteristic - constant solar radiation - variable temperature

As we can see in the figures above, the voltage and the power increase are highly affected by the temperature. The table below can sum up this.

Table6. MPP under Temperature variation (at constant solar radiation 1000W/m²)

Temperature (°C)	P _{mpp}	I _{mpp}	V _{mpp}
0	419.3	8.749	57.82
25	371.1	8.769	52
50	317.3	8.79	45.33
75	254.7	8.81	37.6
100	181.8	8.83	28.51

5 CONCLUSIONS AND PERSPECTIVES

In this work, we presented the step-by-step procedure for modeling the PV module. This mathematical modeling procedure serves as an aid to induce more people into photovoltaic research and gain a closer understanding of I-V and P-V characteristics of PV module. Since a precise knowledge of these characteristic curves is required to study photovoltaic systems in an efficient manner. The essential parameters are taken from the datasheet for the typical 250Wp module selected for analysis. The simulation of the module based on mathematical equations using Matlab/Simulink environment showed that the Current-Voltage and Power-Voltage characteristic curves are highly influenced by temperature and solar radiation. The following of this work is based on optimizing the performance of PV modules using commands and techniques to minimize the influence of these meteorological parameters.

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