

Modeling and Simulation of Photovoltaic Cells/Modules/Arrays

Basim Alsaid and Jafar Jallad

Electrical Engineering department, Palestine Technical University-Kadoorie, Tulkarm, Palestine

Abstract – The first purpose of this paper is to present a brief introduction to the behavior and functioning of a PV device and write its basic equation, without the intention of providing an in-depth analysis of the photovoltaic phenomena and the semiconductor physics. The introduction on PV devices is followed by the modeling and simulation of PV cell/PV module/PV array, which is the main subject of this paper. A MATLAB Simulink /PSIM based simulation study of PV cell/PV module/PV array is carried out and presented .The simulation model makes use of basic circuit equations of PV solar cell based on its behaviour as diode, taking the effect of sunlight irradiance and cell temperature into consideration on the output current I-V characteristic and output power P-V characteristic .A particular typical 50W solar panel was used for model evaluation, and results of simulation were compared with points taken directly from the data sheet and curves published by the manufacturers show excellent correspondence to the model.

Keywords – Modeling, Photovoltaic cell/ module /array, simulation, MATLAB/Simulink , PSIM

1. Introduction

A photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the photovoltaic (PV) cell. The photovoltaic module is the result of associating a group of PV cells in series and parallel and it represents the conversion unit in this generation system. An array is the result of associating a group of photovoltaic modules in series and parallel.

The obtained energy depends on solar radiation, the temperature of the cell and the voltage produced in the photovoltaic module. The voltage and current available at the terminals of a PV device may directly feed small loads .More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and the current at the load mainly to track the maximum power point of the device [1], [2] ,[3], [4], [5].

2. Solar Cell Modeling

Solar cells consist of a p-n junction fabricated in thin wafer or layer of semiconductors, whose electrical characteristics differ very little from a diode represented by the equation of Shockly [1], [2] ,[3], [4].

Thus the simplest equivalent circuit of a solar cell is a current source in parallel with a diode as shown in figure 1. The output of the current source is directly proportional to the light falling on the cell (photocurrent $I_{pv,cell}$) .So the process of modeling this solar cell can be developed based on (1), (2) and (3) :

$$I = I_{PV,CELL} - I_{diode} = I_{PV,CELL} - I_{0,CELL} \left[\exp\left(\frac{q * V}{\alpha * k * T}\right) - 1 \right] \quad (1)$$

Where:

- $I_{PV,cell}$ is the current generated by the incident light .
- I_{diode} is the Shockley diode equation.

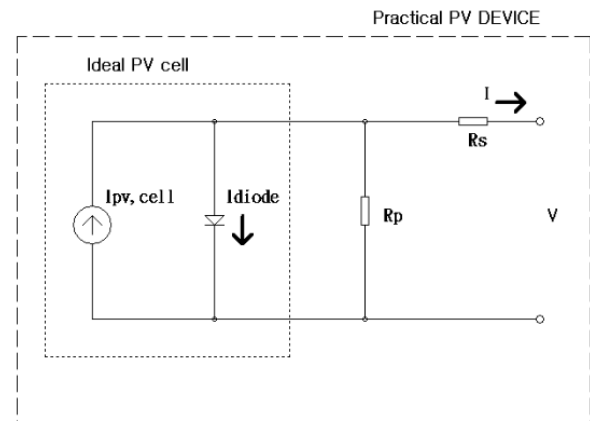


Figure 1. Equivalent model of a photovoltaic cell.

- $I_{0,cell}$ [A] is the reverse saturation or leakage current of the diode [A].
- q is the electron charge [$1.60217646 \cdot 10^{-19}$ C].
- k is the Boltzmann constant [$1.3806503 \cdot 10^{-23}$ J/K].
- T [K] is the temperature of the p-n junction.
- α is the diode ideality constant which lies between 1 and 2 for monocrystalline silicon. The basic equation (1) of the elementary PV does not represent the I-V characteristic of practical PV arrays. Practical modules are composed of several connected PV cells requires the inclusion of additional parameters R_s and R_p , with these parameters (1) becomes (2)

$$I = I_{PV} - I_0 \left[\exp\left(\frac{V + R_s * I}{V_t * \alpha}\right) - 1 \right] - \frac{V + R_s * I}{R_p} \quad (2)$$

The light-generated current of the module depends linearly on solar irradiation and is also influenced by temperature according to (3).

$$I_{PV} = (I_{PV,n} + K_I \Delta T) \frac{G}{G_n} \quad (3)$$

where K_I is the Temperature coefficient of I_{SC} , G is the irradiance (W/m^2) and G_n is the irradiance at standard operating conditions.

The diode saturation current I_0 dependence on temperature can be expressed as shown in (4).

$$I_0 = I_{0,n} \left(\frac{T_n}{T} \right)^3 \exp \left[\frac{q^* E_g}{\alpha^* k} \left(\frac{1}{T_n} - \frac{1}{T} \right) \right] \quad (4)$$

E_g is the band gap energy of the semiconductor and $I_{0,n}$ is the nominal saturation current expressed by (5)

$$I_{0,n} = \frac{I_{SC,n}}{\left[\exp \left(\frac{V_{OC,n}}{V_{t,n} * \alpha} \right) - 1 \right]} \quad (5)$$

From (4) and (5) I_0 can be expressed as shown in (6).

$$I_0 = \frac{I_{SC,n} + K_I \Delta T}{\exp \left(\frac{V_{OC,n} + K_V \Delta T}{V_{t,n} * \alpha} \right) - 1} \quad (6)$$

Where $V_{OC,n}$ is open circuit voltage, $I_{SC,n}$ is the short circuit current, $V_{t,n}$ is the thermal voltage, T_n is the temperature at standard operating conditions. $V_t = Ns * kT/q$ is the thermal voltage of the module with Ns cells connected in series. [Cells connected in parallel increase the current and cells connected in series provide greater output voltages]. If the module is composed of N_p parallel connections of cells the photovoltaic and saturation currents may be expressed as: $I_{pv} = I_{pv,cell} * N_p$, $I_0 = I_{0,cell} * N_p$. In (2) R_s is the equivalent series resistance of the array (unknown) and R_p is the equivalent parallel resistance (unknown), so they have to be calculated. Equation (2) originates the I-V curve seen in figure 2, where three remarkable points are highlighted:

- open- circuit (V_{oc} , 0),
- short circuit (0, I_{sc}),
- maximum power point (V_{MP} , I_{MP}).

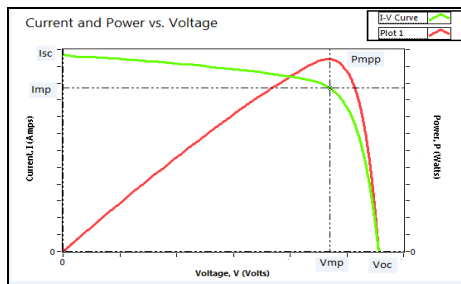


Figure 2. Characteristic I-V, P-V curve of a practical photovoltaic device.

2.1. Open-circuit

This point is obtained when the terminals of the module are disconnected. The module presents a voltage called (V_{OC}) expressed analytically using (7).

$$V_{OC} = \frac{\alpha^* k^* T}{q} \ln \frac{I_{PV}}{I_0}; I_{PV} > I_0 \quad (7)$$

2.2. Short-circuit

The terminals of the module are connected with an ideal

conductor, through which flows a current called (I_{SC}). In this situation, the voltage between module terminals is zero.

$$I_{SC} = I_{PV} = K * G \quad (8)$$

where K is a constant.

2.3. MPP

Here the voltage versus current product is maximum. V_{MP} is related to V_{OC} through the relation (9):

$$V_{MP} \approx 0.8 * V_{OC} \quad (9)$$

And I_{MP} is related to I_{SC} through the relation (12) :

$$I_{MP} \approx 0.9 * I_{SC} \quad (10)$$

The best conditions, are the "standard operating conditions" happen at Irradiance equal to 1000W/m^2 , cells temperature equals to 25°C , and spectral distribution (Air Mass) AM is equal to 1.5.

3. Modeling of Photovoltaic Module by Matlab Simulink and Psim

MSX-50 solar array PV module, pictured in figure 3, is chosen for a MATLAB and Psim simulation model. The module is made of 36 multi-crystalline silicon solar cells in series and provides 50W of nominal maximum power. Table 1 shows its electrical specification and figure 4 shows its I-V characteristics from data sheet.

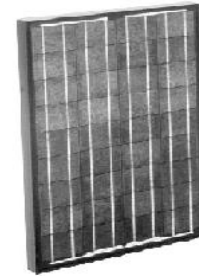


Figure 3. Picture of MSX-50 Photovoltaic Modules.

Table 1, Electrical characteristics data of the MSX-50 solar at 25°C , 1.5AM , 1000W/m^2 , taken from the datasheet

Electrical Characteristics	
Maximum Power (Pmax)	50W
Voltage at Pmax (Vmp)	17.1V
Current at Pmax (Imp)	2.92A
Open-circuit voltage (Voc)	21.1V
Short-circuit current (Isc)	3.17A
(K_I) Temperature coefficient of Isc	$(0.065 \pm 0.015) \% / ^\circ\text{C}$
(K_V) Temperature coefficient of Voc	$-(80 \pm 10) \text{mV} / ^\circ\text{C}$
NOCT	$47 \pm 2^\circ\text{C}$

4. Rs and Rp Calculation

R_s and R_p are calculated iteratively. The goal is to find the values of R_s and R_p that makes the mathematical P-V curve peak coincide with the experimental peak power at the (V_{MP} , I_{MP}) point. The value of R_s and R_p are reached when the iteration stopped for Pmax calculated is equal to Pmax estimated. The iterative method gives the solution $R_s = 0.235 \Omega$ and $R_p = 350.90396 \Omega$. Figure 6 and figure 11 show the I-V characteristic at standard conditions where V_{MP} , I_{MP} , V_{OC} and I_{SC} values are shown using the calculated

values of R_s and R_p .[4]

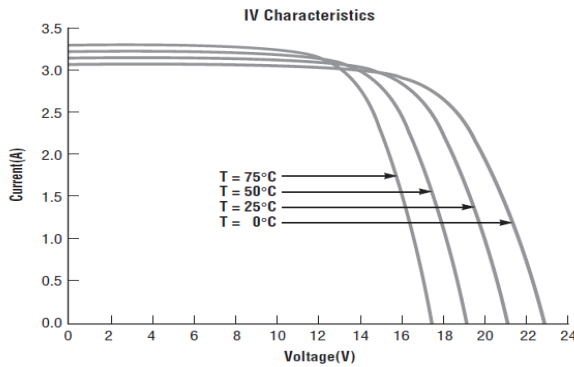


Figure 4. I-V characteristics at 1000W/m², from data sheet with different temperatures

5. Simulation in Simulink and Psim

5.1. PV Module simulation with Psim simulator

Figure 5 shows the modeling circuit of the PV module by Psim, it is composed of the PV panel used, current, voltage and power measurements. Irradiance and temperature are the inputs that are used to show the effects of their variation on the output characteristics. Figure 6 shows the result of simulation, the I-V and P-V characteristics at constant temperature ($T=25^\circ\text{C}$) and constant irradiance of (1000W/m²). The simulation shows the three remarkable points $V_{oc}=21.1\text{V}$, $I_{sc}=3.17\text{A}$ and maximum power point ($P_{max}=50\text{W}$, $V_{MP}=17.1\text{V}$, $I_{MP}=2.9\text{A}$) which are very closed to the values given by the datasheet. Figure 7 shows the effect of temperature variation (25°C , 50°C , 75°C) on the I-V characteristics for constant irradiance of (1000W/m²), also this simulation gives excellent results if these curves are compared with the curves given by the manufacturer shown in figure 4. Figure 8, shows the effect of irradiance variation (1000, 800, 600, 400) W/m² at constant temperature ($T=25^\circ\text{C}$) on V-I characteristic which is very closed to the real data.[4]

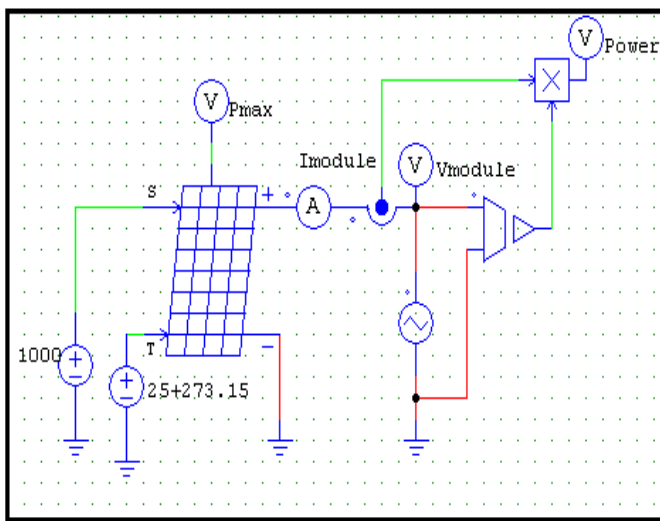


Figure 5. PV module model in PSIM.

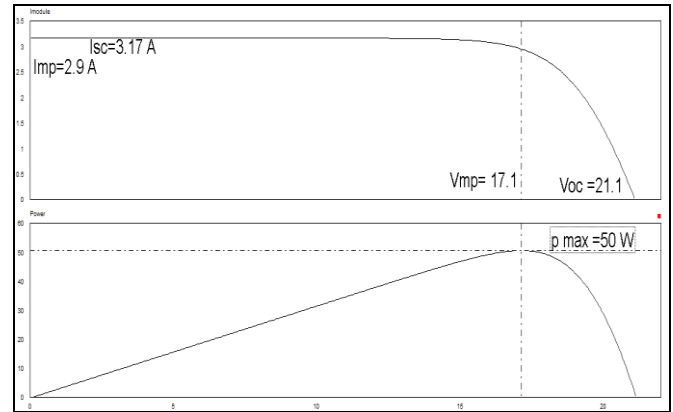


Figure 6. I-V ,P-V characteristics at $T=25^\circ\text{C}$, irradiance=1000W/m², after calculation of R_s and R_p , by PSIM.

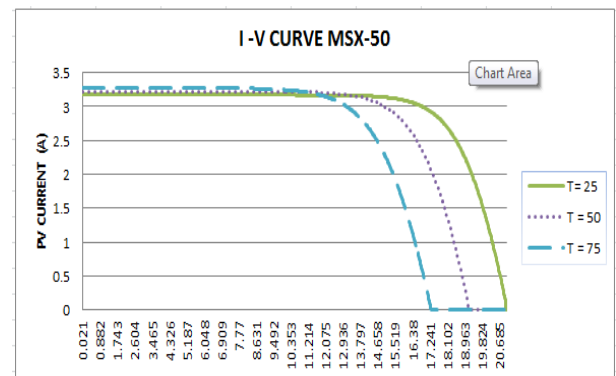


Figure 7. I-V characteristics at 1000W/m², by PSIM with different temperatures.

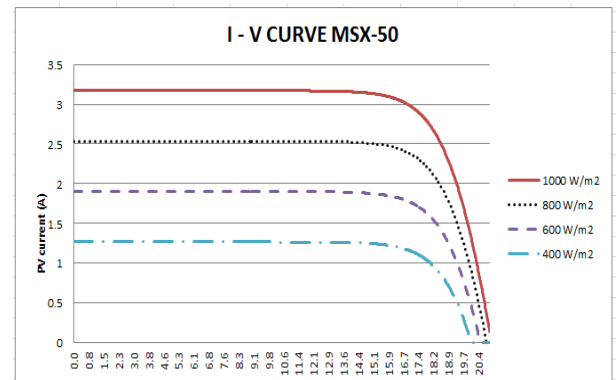


Figure 8. I-V characteristics at $T=25^\circ\text{C}$, by PSIM with different values of irradiance

5.2. PV Module simulation with Simulink simulator

Figure 9 shows the modeling circuit of the PV module by Matlab/simulink. The modeling of the PV is done applying the equations seen before, (1),(2),(3),(4),(5) and (6), the current, voltage, power instruments. Irradiance and temperature are the inputs of the system. Figure 10 shows the effect of irradiance variation (1000, 800, 600, 400) W/m² at constant temperature ($T=25^\circ\text{C}$) on V-I characteristic which is very closed to the real data.. In figure 11 the three remarkable points $V_{oc}=21.1\text{V}$, $I_{sc}=3.17\text{A}$ and maximum power point ($P_{max}=50\text{W}$, $V_{MP}=17.1\text{V}$, $I_{MP}=2.92\text{A}$) are shown and are identical to the values given by the datasheet.[5],[6],[7].

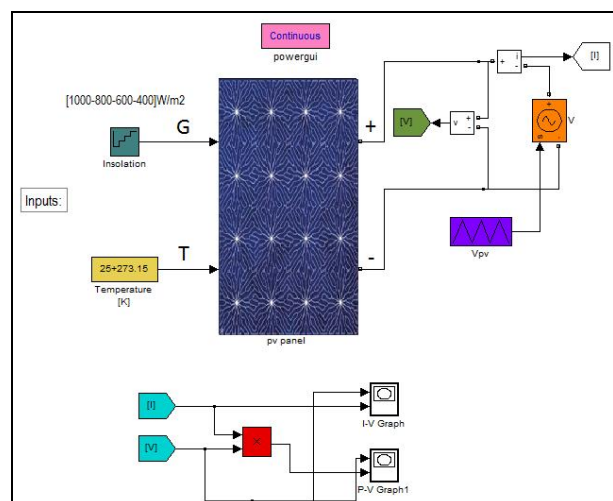


Figure 9. PV module model in Simulink.

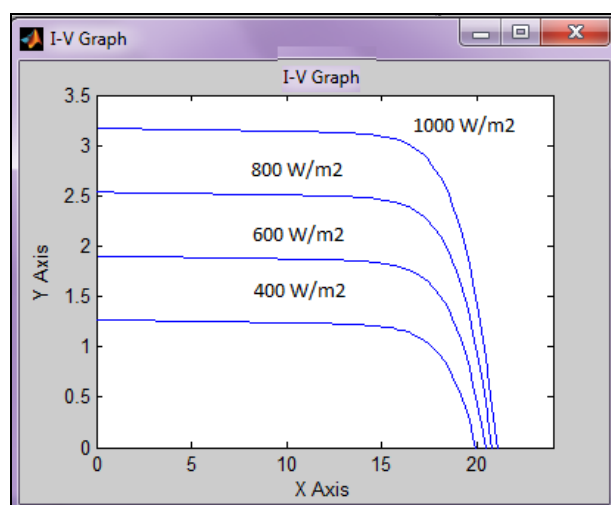


Figure 10. I-V characteristics at T=25° C ,by Simulink with different irradiances.

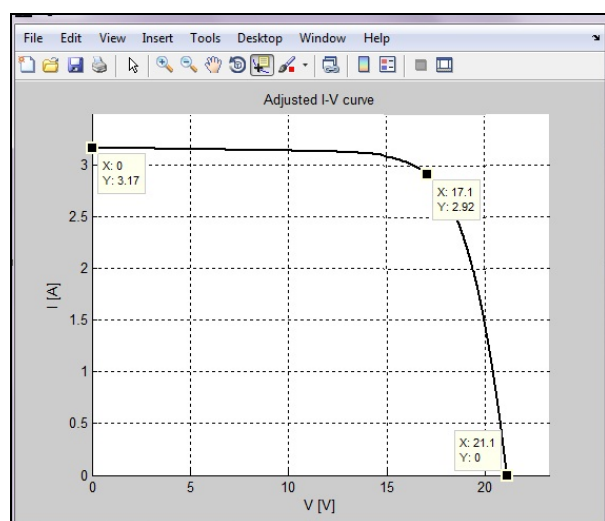


Figure 11. I-V characteristics at $T=25^{\circ}$, irradiance= 1000W/m^2 , after calculation of R_s and R_p .

5.3. PV Array simulation with Simulink simulator

Modules connected in parallel increase the current and modules connected in series provide greater output voltages. If the array is composed of N_{par} parallel connections of pv modules, the photovoltaic and saturation currents may be expressed as: $I_{\text{pv}} = I_{\text{pv, module}} * N_{\text{par}}$, $I_0 = I_{0, \text{module}} * N_{\text{par}}$. If the

array is N_{ser} , module, the output voltage $V = V_{module} * N_{ser}$
 $R_s, array = R_s, module * (N_{ser} / N_{par})$, $R_p, array = R_p, module$
 $* (N_{ser} / N_{par})$, and the model of the array will be as shown in
figure 12. If we take as an example $N_{ser}=2$ and $N_{par}=15$,
just to verify the validation of the array model we will have
the results of simulation shown in figure 13 for I-V
characteristic at $T=25^{\circ}C$,the $I_{sc}=6.34A$ ($3.17A * 2$) as
expected for $N_{par}=2$, $V_{oc}=316.5V$ ($21.1V * 15$) as expected
for $N_{ser}=15$. Figure 14 shows P-V characteristic for the
same conditions where the value of the peak power is as
expected to be $1500W=(15*2*50W)$

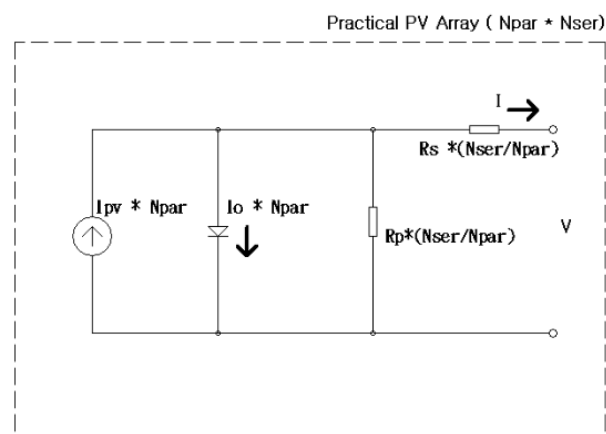


Figure 12. PV array model , Nser is No. of series of pv modules, Npar is No. of parallel pv modules

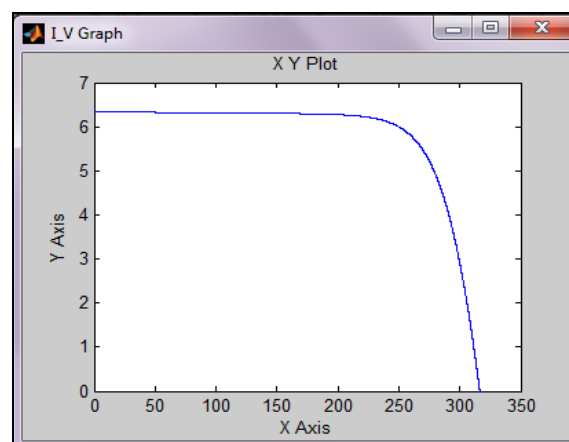


Figure 13. I-V characteristics at $T=25^{\circ}\text{C}$, $G=1000\text{w/m}^2$, by Simulink for $N_{\text{ser}}=15$, $N_{\text{par}}=2$.

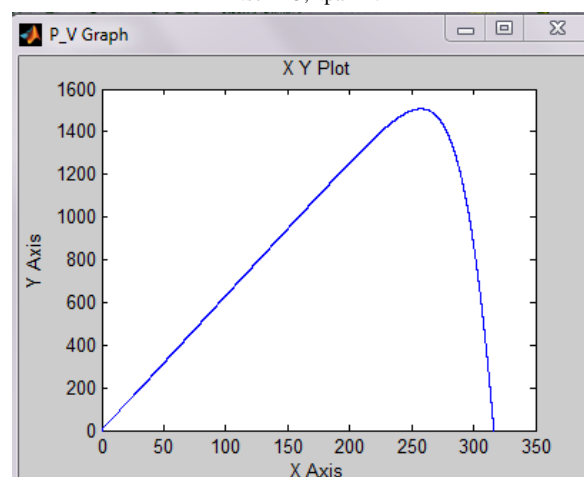


Figure 14. P-V characteristics at $T=25^{\circ}\text{C}$, 1000w/m^2 , by Simulink for $N_{\text{ser}}=15$, $N_{\text{par}}=2$

6. Conclusions

In this paper, a MATLAB Simulink / PSIM PV system simulator based on an improved single-diode model is proposed. To reduce the computational time, the input parameters are reduced to four and the values of R_p and R_s are estimated by an efficient iteration method. Furthermore the inputs to the simulator are information available on standard PV module datasheets. Simulation results show excellent correspondence to manufacturers published curves.

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