

Model of Photovoltaic Module in Matlab™

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Abstract— This paper define a circuit-based simulation model for a PV cell in order to allow estimate the electrical behavior of the cell with respect changes on environmental parameter of temperature and irradiance. An accurate PV module electrical model is presented based on the Shockley diode equation. The general model was implemented on Matlab scrip file, and accepts irradiance and temperature as variable parameters and outputs the I-V characteristic. A particular typical 60W solar panel was used for model evaluation, and results was compare with points taken directly from the manufacturer's published curves and show excellent correspondence to the model.

Index terms— Modeling and behavior, photocurrent, photovoltaic module.

I. INTRODUCTION

Renewable energy resources will be an increasingly important part of power generation in the new millennium. Besides assisting in the reduction of the emission of greenhouse gases, they add the much-needed flexibility to the energy resource mix by decreasing the dependence on fossil fuels [1]. In other hand, deregulation of the electric utility industry is providing an opportunity for higher penetration and use of distributed resources (DR). Distributed resources are generation sources that can be located at or near loads. Distributed resources can provide benefits that bulk power generation can not. PV systems are ideally suited for distributed resource applications. Photovoltaic (PV) systems produce DC electricity when sunlight shines on the PV array, without any emissions. The DC power is converted to AC power with an inverter and can be used to power local loads or fed back to the utility [2]. The PV application can be grouped depending the scheme of interaction with utility grid: grid connected, stand alone, and hybrid.

PV systems consist of a PV generator (cell, module, array), energy storage devices (such as batteries), AC and DC consumers and elements for power conditioning. This article refers about a model for modeling and simulation of PV module based on Shockley diode equation.

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II. PV GENERATOR

A photovoltaic PV generator is the whole assembly of solar cells, connections, protective parts, supports etc. In the present modeling, the focus is only on cell/module/array [3]. Solar cells consist of a p-n junction fabricated in a thin wafer or layer of semiconductor (usually silicon). In the dark, the I-V output characteristic of a solar cell has an exponential characteristic similar to that of a diode [4]. When solar energy (photons) hits the solar cell, with energy greater than band gap energy of the semiconductor, electrons are knocked loose from the atoms in the material, creating electron-hole pairs [5]. These carriers are swept apart under the influence of the internal electric fields of the p-n junction and create a current proportional to the incident radiation. When the cell is short circuited, this current flows in the external circuit; when open circuited, this current is shunted internally by the intrinsic p-n junction diode. The characteristics of this diode therefore set the open circuit voltage characteristics of the cell [4].

A. Modeling the Solar Cell

Thus the simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell (photocurrent I_{ph}). During darkness, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it generates a current I_D , called diode (D) current or dark current. The diode determines the I-V characteristics of the cell.

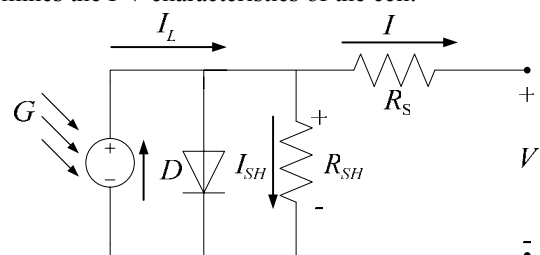


Fig. 1. Circuit diagram of the PV model

Increasing sophistication, accuracy and complexity can be introduced to the model by adding in turn [4]:

- Temperature dependence of the diode saturation current I_0 .
- Temperature dependence of the photo current I_L .
- Series resistance R_s , which gives a more accurate shape between the maximum power point and the

open circuit voltage. This represents the internal losses due to the current flow.

- Shunt resistance R_{sh} , in parallel with the diode, this corresponds to the leakage current to the ground and it is commonly neglected
- Either allowing the diode quality factor n to become a variable parameter (instead of being fixed at either 1 or 2) or introducing two parallel diodes with independently set saturation currents.

In an ideal cell $R_s = R_{sh} = 0$, which is a relatively common assumption [6]. For this paper, a model of moderate complexity was used. The net current of the cell is the difference of the photocurrent, I_L and the normal diode current I_0 :

$$I = I_L - I_0 \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) \quad (1)$$

The model included temperature dependence of the photocurrent I_L and the saturation current of the diode I_0 .

$$I_L = I_L(T_1) + K_0(T - T_1) \quad (2)$$

$$I_L(T_1) = I_{SC}(T_{1,nom}) \frac{G}{G(nom)} \quad (3)$$

$$K_0 = \frac{I_{SC}(T_2) - I_{SC}(T_1)}{(T_2 - T_1)} \quad (4)$$

$$I_0 = I_0(T_1) \times \left(\frac{T}{T_1} \right)^{\frac{3}{n}} e^{\frac{qV_g(T_1)}{nk} \left(\frac{1}{T} - \frac{1}{T_1} \right)} \quad (5)$$

$$I_0(T_1) = \frac{I_{SC}(T_1)}{\left(e^{\frac{qV_{OC}(T_1)}{nkT_1}} - 1 \right)} \quad (6)$$

A series resistance R_s was included; which represents the resistance inside each cell in the connection between cells.

$$R_s = -\frac{dV}{dI_{V_{OC}}} - \frac{1}{X_V} \quad (7)$$

$$X_V = I_0(T_1) \frac{q}{nkT_1} e^{\frac{qV_{OC}(T_1)}{nkT_1}} - \frac{1}{X_V} \quad (8)$$

The shunt resistance R_{sh} is neglected. A single shunt diode was used with the diode quality factor set to achieve the best curve match. This model is a simplified version of the two diode model presented by Gow and Manning [7]. The circuit diagram for the solar cell is shown in Figure 1.

B. Current-Voltage I-V Curve for a solar Cell

A typical I-V characteristic of the solar cell for a certain ambient irradiation G and a certain fixed cell temperature T , is shown in Fig 2. For a resistive load, the load characteristic is a straight line with slope $I/V=1/R$. It should be pointed out that the power delivered to the load depends on the value of the resistance only.

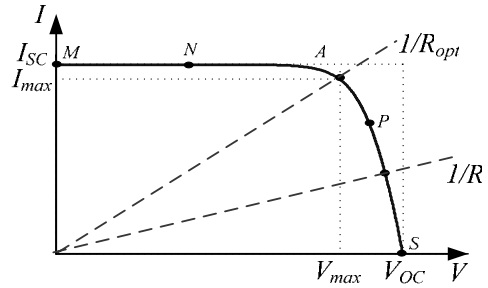


Fig 2. A typical current-voltage I-V curve for a solar cell. However, if the load R is small, the cell operates in the region $M-N$ of the curve (Fig 2), where the cell behaves as a constant current source, almost equal to the short circuit current. On the other hand, if the load R is large, the cell operates on the regions $P-S$ of the curve, the cell behaves more as a constant voltage source, almost equal to the open-circuit voltage [3].

A real solar cell can be characterized by the following fundamental parameters, which are also sketched in Fig. 2.

- **Short circuit current:** $I_{sh} = I_{ph}$. It is the greatest value of the current generated by a cell. It is produced by the short circuit conditions: $V = 0$.
- **Open circuit voltage** corresponds to the voltage drop across the diode (p-n junction), when it is transverse by the photocurrent I_{ph} (namely $I_L = I_{ph}$), namely when the generated currents is $I = 0$. It reflects the voltage of the cell in the night and it can be mathematically expressed as:

$$V_{OC} = \frac{nkT}{q} \ln \left(\frac{I_L}{I_0} \right) = V_t \ln \left(\frac{I_L}{I_0} \right) \quad (9)$$

Where $V_t = \frac{mkT_c}{e}$ is known as thermal voltage and

T is the absolute cell temperature.

- **Maximum power point** is the operating point $A(V_{max}, I_{max})$ in Fig 2, at which the power dissipated in the resistive load is maximum: $P_{max} = V_{max}I_{max}$.
- **Maximum efficiency** is the ratio between the maximum power and the incident light power.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max}V_{max}}{AG_a} \quad (10)$$

Where G_a is the ambient irradiation and A is the cell area.

- **Fill factor** is the ratio of the maximum power that can be delivered to the load and the product of I_{sc} and V_{OC} :

$$FF = \frac{P_{max}}{V_{OC}I_{SC}} = \frac{I_{max}V_{max}}{V_{OC}I_{SC}} \quad (11)$$

The fill factor is a measure of the real I-V characteristic. Its value is higher than 0.7 for good cells. The fill factor diminishes as the cell temperature is increased.

The open circuit voltage increases logarithmically with the

ambient irradiation, while the short circuit current is a linear function of the ambient irradiation. The dominant effect with increasing cell's temperature is the linear decrease of the open circuit voltage, the cell being thus less efficient. The short circuit current slightly increases with the cell temperature,

C. Considerations in the model about environment variables

The influence of the ambient irradiation G and the cell temperature T on the cell characteristics, can be obtained from the model equations. The PV cell photocurrent I_L (A) is directly proportional to solar irradiance G (W/m²). When the solar cell is short circuited, negligible current flows in the diode. Hence the proportionally constant in (3) is set to the rated short circuit current I_{SC} at is delivered under rated irradiation. Solar intensities are commonly normalized with respect to full solar radiation at sea level with average humidity and aerosol particulate concentration (1 Sun = 1000Watt/m²). Though somewhat contrary to intuition, PV cell performance does not degrade significantly between full sun and cloudy conditions. The power output decreases nearly linearly with incident solar energy, but efficiency is nearly flat over the region of concern.

The relationship between the photo-current and temperature is linear (eqn. 2) and is deduced by noting the change of photo-current with the change of temperature (eqn. 4). When the cell is not illuminated, the relationship between the cell's terminal voltage and current is given by the Shockley equation. When the cell is open circuited and illuminated, the photo-current flows entirely in the diode. The I-V curve is offset from the origin by the photo generated current (eqn 1). The value of the saturation current I_0 at 25°C is calculated using the open circuit voltage and short circuit current at this temperature (eqn 6). An estimate must be made of the unknown "ideality factor". Green [3] states that it takes a value between 1 and 2, being near one at high currents, rising towards two at low currents. A value of 1.3 is suggested as typical in normal operation, and may be used initially, until a more accurate value is estimated later through curve fitting. The relationship of I_0 to temperature is complex, but fortunately contains no variables requiring evaluation (eqn 5) [7]. The series resistance of the panel has a large impact on the slope of the I-V curve at $V = V_{OC}$. Equations 7 and 8 are found by differentiating equation 1, evaluating at $V = V_{OC}$, and rearranging in terms of R_s [7].

III. MATLAB MODEL OF THE PV MODULE

The Solarex MSX60 PV module was chosen for modeling, due is well-suited to traditional applications of photovoltaics. The MSX 60 module provides 60 watt of nominal maximum power, and has 36 series connected polycrystalline silicon cells. The key specifications are shown in Table 1.

The model of the PV module was implemented using a Matlab program. The model parameters are evaluated during

execution using the equations listed on the previous section. The program, calculate the current I , using typical electrical parameter of the module (I_{SC} , V_{OC}), and the variables Voltage, Irradiation (G), and Temperature (T).

TABLE 1
TYPICAL ELECTRICAL CHARACTERISTIC¹ OF MSX-60 PV MODULE.

Parameter	Variable	Value
Maximum Power	P_m	60W
Voltage@ P_m	V_m	17.1V
Current @ P_m	I_m	3.5A
Short circuit current	I_{SC}	3.8A
Open-circuit voltage	V_{OC}	21.1.V
Temperature coefficient of open-circuit voltage	β	-(80±10)mV/°C
Temperature coefficient of short-circuit current	α	(0.0065±0.015)%/°C
Temperature coefficient of power NOCT ²		-(0.5±0.05)%/°C

NOTES:

- (1) The data are based on measurements made in a solar simulator at Standard Test Conditions (STC), which are:
 - Illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5;
 - Cell temperature of 25°C or as otherwise specified (on curves).
- (2) Under most climatic conditions, the cells in a module operate hotter than the ambient temperature. NOCT (Nominal Operating Cell Temperature) is an indicator of this temperature differential, and is the cell temperature under Standard Operating Conditions: ambient temperature of 20°C, solar irradiation of 0.8 kW/m², and wind speed of 1 m/s.

The program considers the series resistance in the model. This resistance make the solution for the current I , (eqn. 1) a non-linear problem, that be solved using numerical methods. In this program the Newton-Raphson method was used, because literature indicate much more rapidly convergence, and for both positive and negative currents. A Matlab™ Script file was implemented consider the parameters of MSX-60 module, a listing of this is shown in Fig. 2.

IV. RESULTS OF MATLAB™ PV MODULE MODEL

The output of the Matlab™ function is shown first for various irradiation levels (Fig. 3) and then for various temperatures (Fig. 4).

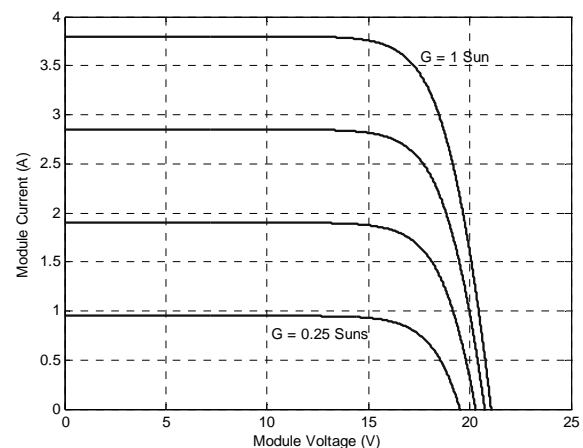


Fig 3. Matlab model I-V curves for various irradiation levels (MSX-60, $G = 0.25, 0.5, 0.75, 1 \text{ Sun}$, $T = 25^\circ\text{C}$)

```

function Ia=solar(Va,Suns,TaC)
% Datos del arreglo solar MSX-60
% Calcula la corriente dado el voltaje, iluminacion y la temperatura
% Ia = solar (Va,G,T) = vector de voltaje
% Ia,Va = vector de corriente y voltaje
% G = numero de Suns (1 Sun = 1000 W/m^2)
% T = Temp en grados Celcius
k = 1.38e-23; % Constante de Boltzman's
q = 1.60e-19; % Carga de un electron
% Entre las siguientes constantes aqui, y el modelo sera
% calculado en base a ellas. Para 1000Watt/m^2
n=1.2; % Factor de calidad del diodo, factor
% n =2 para cristalino, <2 para amorfo
Vg = 1.12; % Voltaje de la banda, 1.12eV para xtal Si,
% 1.75 para Si amorfo.
Ns = 36; % Numero de celdas en serie (diodos)

T1 = 273 + 25;
Voc_T1 = 21.06 /Ns;
% Voltaje de circuito abierto por celda a temperatura T1
Isc_T1 = 3.80;
% Corriente de cortocircuito de la celda a temperatura T1
T2 = 273 + 75;
Voc_T2 = 17.05 /Ns;
% Voltaje de circuito abierto por celda a temperatura T2
Isc_T2 = 3.92;
% Corriente de cortocircuito de la celda a temperatura T2
TaK = 273 + TaC; % Temperatura de trabajo del arreglo
K0 = (Isc_T2 - Isc_T1)/(T2 - T1); % Ecuacion (4)
IL_T1 = Isc_T1 * Suns; % Ecuacion (3)
IL = IL_T1 + K0*(TaK - T1); % Ecuacion (2)
IO_T1=Isc_T1/(exp(q*Voc_T1/(n*k*T1))-1);
IO= IO_T1*(TaK/T1).^(3/n).*exp(-q*Vg/(n*k).*(1./TaK)-(1./T1));
Xv = IO_T1*q/(n*k*T1) * exp(q*Voc_T1/(n*k*T1)); % Ecuacion (8)
dVdI_Voc = - 1.15/Ns / 2;
% dV/dI a Voc por celda desde la garficas del fabricante
% Rs resistencia serie por celda
Rs = - dVdI_Voc - 1/Xv; % Ecuacion (7)
Vt_Ia = A * k * TaK / q; % = A * kT/q
Vc = Va/Ns;
Ia = zeros(size(Vc));
% Método de Newton
for j=1:5;
Ia = Ia - (IL - Ia - IO.*( exp((Vc+Ia.*Rs)./Vt_Ia) - 1))./...
...(-1 - (IO.*( exp((Vc+Ia.*Rs)./Vt_Ia) - 1)).*Rs./Vt_Ia);
end
    
```

Fig. 2. Matlab scrip file for the PV module model

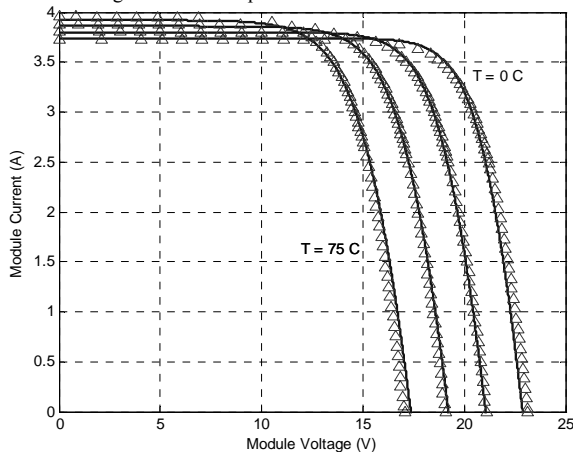


Fig. 4. Matlab model I-V curves for various temperatures. (MSX-60, G = 1 Sun, T = 0, 25, 50 y 75°C)

A number of discrete data points are shown on the curves in Fig. 4. These are points taken directly from the manufacturer's published curves, and show excellent correspondence to the model. For the MSX60 the curves show, I_L changes from 3.80 to 3.92A (3%) as T changes from 25 to 75°C. The Fig. 4, show power voltage curves for several temperatures, again the discrete data points taken directly from the manufacturer's published curves, and show excellent correspondence to the

model.

The effect of varying the ideality factor can be seen in the MSX60 model, Fig. 6 – higher values soften the knee of the curve. The series resistance of the model has a large impact on the slope of the I-V curves at V_{OC} as seen in Fig. 7. Considering the values obtained from the MSX60 manufactures' curves, a value of total panel series resistance R_s , (8mΩ) was calculated.

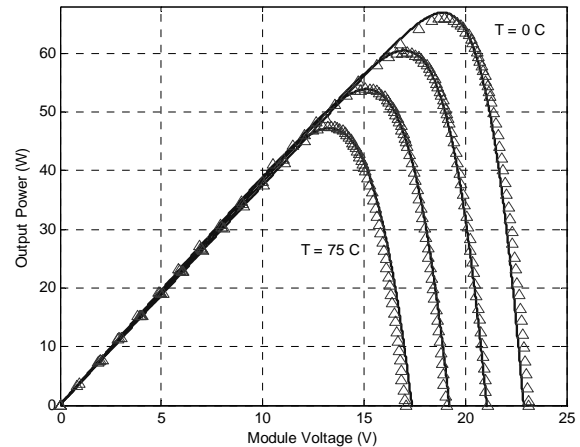


Fig. 5. Matlab model P-V curves for various temperatures. (MSX-60, G = 1 Sun, T = 0, 25, 50 y 75°C)

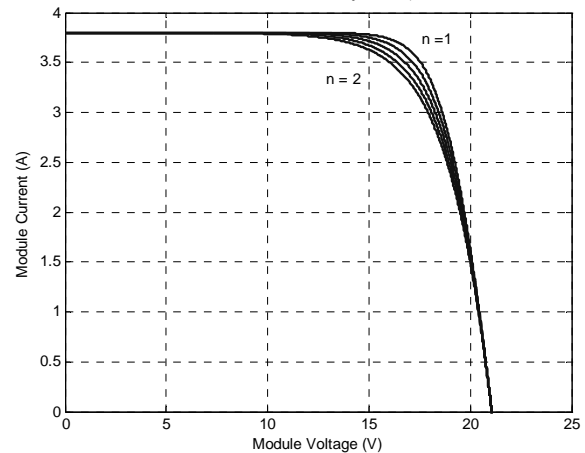


Fig. 6. Matlab model I-V curves, for various diode quality factors (MSX-60, G = 1 Sun, T = 25°C, n = 1, 1.25, 1.5, 1.75 and 2)

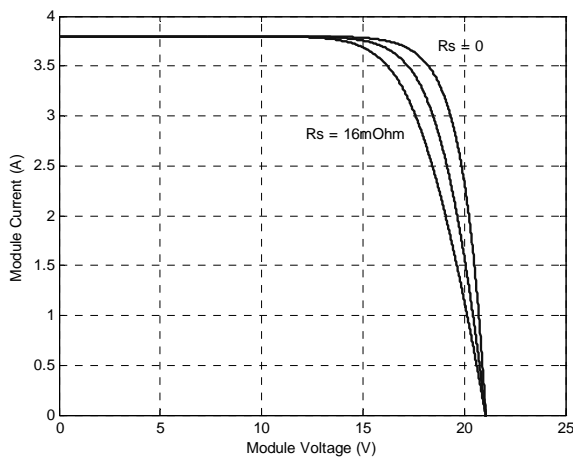


Fig. 7. Matlab model I-V curves, for various model series resistances (MSX-60, $G = 1 \text{ Sun}$, $T = 25^\circ\text{C}$, $R_s = 0, 8\text{m}, 16\text{m}\Omega$)

V. CONCLUSIONS

An accurate PV module electrical model is presented and demonstrated in Matlab for a typical 60W solar panel. Given solar insolation and temperature, the model calculates the current for a given voltage. The results from the Matlab™ model show excellent correspondence to manufacturer's published curves. Finally the model development was used to show the effect of: insolation, temperature, ideality factor and series resistances

This paper is the first step to develop a complete solar photovoltaic power electronic conversion system in simulation. The final objective is develops a general model to simulate the electrical behavior of the PV systems in a grid-connected application.

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