

Modelling of Photovoltaic Module.

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Abstract. This paper proposes a review of the main characteristics and parameters that have to be considered in modelling a photovoltaic module. For the study it will be left from the photovoltaic cell, fundamental element of the conversion of light to electrical current.

Also, a photovoltaic model using Matlab, which can be representative of PV cell and module, is presented. The created model has been based on previous studies. With the information of those previous models, curves IV and PV have been calculated comparing the results to each other. Also, the MPP of all the models has been calculated.

Finally, the model has been validated with experimental data of a commercial PV module, Mitsubishi PV-TD1185MF5.

Key words

Photovoltaic (PV), PV Cells, Matlab, PV Module, Modelling.

1. Introduction

The increasing interest for renewable energies is due to the world conscience of revising the energy policies, in order to fight against the emissions of CO₂. Some proposals to achieve this goal are: substitute the fossil fuels for cleaner energies, limit the damages in the environment and in the ecosystem, as well as incentives to develop alternative resources.

The photovoltaic energy is a clean energy, with a long lifespan and a high reliability. So, it can be considered as one of the most sustainable of the renewable energies. These systems can be located in or near where the necessity takes place, avoiding losses of transmission and contributing reductions to the CO₂ emission in urban centers

The photovoltaic module is the result of associating a group of photovoltaic cells in series and parallel (figure 1), with their protection devices, and it represents the conversion unit in this generation system. Besides, the obtained energy depends on the solar radiation, the temperature of the cell and the voltage produced in the photovoltaic module.

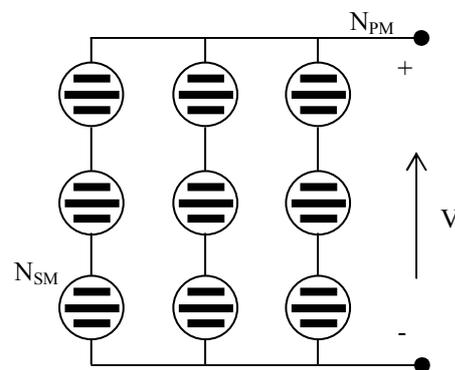


Fig. 1. PV module cell.

Although the mathematical and simulation photovoltaic modules development began time ago, improvements of these models are analysed and presented continually. One of the objectives of this paper is a review of those existing methods and models. Also, a model has been realised in MATLAB that is based on other existing ones. For their design, the parts of the programs have been chosen that better adapt to our model.

2. Photovoltaic cell

The solar cell is the basic unit of a photovoltaic module and it is the element in charge of transforming the sun rays or photons directly into electric power.

The solar cell used is the PN union, whose electrical characteristics differ very little from a diode, represented

by the equation of Shockley (1). So, the process of modeling this solar cell can be developed based on equations (1), (2) and (3).

$$I_D = I_0 \cdot \left(e^{\frac{V_C q}{ak T_{ck}}} - 1 \right) \quad (1)$$

Where:

- “ I_D ” is a dark current (A),
- “ I_0 ” is a saturation current of the diode (A),
- “ V_C ” is a cell voltage (V),
- “ q ” is the charge of an electron, equal to $1.6 \cdot 10^{-19}$ (Coul),
- “ a ” is the diode ideality constant,
- “ k ” is the Boltzman’s constant, $1.38 \cdot 10^{-23}$ (j/K),
- “ T_{ck} ” is the cell temperature.

Being the net current of the cell, the difference of the photocurrent I_L , (the current generated by the incident light, directly proportional to the sun irradiation) and I_D (the normal diode current), as shown in equation (2).

$$I = I_L - I_D \quad (2)$$

Additionally equation (3) presents the simplified model of the work presented by Gow y Manning [1]).

$$I = I_L - I_0 \cdot \left(e^{\frac{(V+IR_s)q}{ak T_{ck}}} - 1 \right) \quad (3)$$

Therefore, the ideal solar cell can, theoretically, be modeled as a current source in anti-parallel with a diode (figure 2). Improving the PV cell model includes the effects of series and shunt resistance, as it presented in section 3.

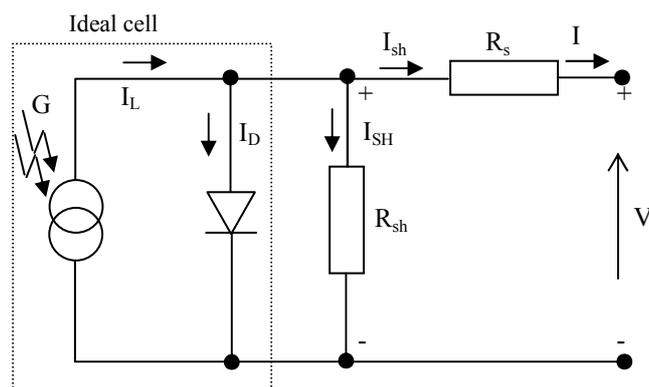


Fig. 2. Equivalent circuit for PV modules.

3. Photovoltaic Module

Because in the real operation of the solar cell some losses exist, they have been added to the model as a resistance in series (R_s) and another in parallel (R_{sh}) to get a more real behaviour and to pick up these losses. The final model is as shown in figure 2.

Moreover, the basic equation (3) does not represent the I-V characteristics of a practical PV module. In order words, this module is composed of several connected cells and resistances. Therefore the observation of the characteristics at the terminal of the PV module requires the inclusion of additional parameters, as shown in equation (4).

$$I = I_L - I_0 \cdot \left(e^{\frac{(V+IR_s)q}{ak T_{ck}}} - 1 \right) - \frac{(V+IR_s)}{R_{sh}} \quad (4)$$

Thus, this equation (4) represents that the output current generated depends on the PV module voltage, solar irradiance on PV module, wind speed, and ambient temperature.

In order to apply these concepts to developments of a solar cell model, the Mitsubishi PV-TD1185MF5 PV module has been chosen for modelling. This module has 50 series connected polycrystalline cells. The key specifications are shown in table I.

Table I. – Key specifications of the Mitsubishi PV panel.

Maximum Power [W]	185
Voltage, max power V_{mpp} [V]	24'40
Current, max power I_{mpp} [A]	758
Open Circuit Voltage V_{oc} [V]	30'60
Short circuit Current I_{sc} [A]	8'13
STC (1000 W/m ² , 25(±2)°C, AM 1'5 at EN 6090-4)	

4. Model programming

The created model has been based on previous studies like for example developed by G. Walker [2], Akihiro Oi [7] and F.M. González-Longatt [8].

The function developed by all authors is very similar. This function is based on Matlab Software, which needs three values to calculate the net current of the cell (Module operating current):

- V_a = Module operating voltage
- G [Suns] = Irradiance, 1 Suns = 1000 W/m².
- TaC = Module temperature, in °C

The body of the program is divided in three main parts:

- Definition of constants (Boltzman’s constant, electron charge, diode ideality-quality factor...)
- Definition of variables – Calculation of I_L , I_0 and R_s (equations 5-9),are used.
- Calculation of I_A

A. Characteristic equations of the solar cell

The sun cell structure is similar to a diode. Consequently, its characteristic would be similar to the exponential characteristic of a semiconductor. Knowing that a panel is a composed by set of cells, the current contributed by

the unit can be obtained based on the fotocurrent and inverse saturation current of the diode.

In this section, the most outstanding equations are presented in order to develop the sun cell model. Besides, photoelectric current depends on the variations of the temperature and the existing irradiation around the cell. (ec. 5)

$$I_L = I_L(T_1) + K_0(T-T_1) \quad (5)$$

Knowing that, $I_L(T_1)$ and K_0 are:

$$I_L(T_1) = I_{SC}(T_{1,nom}) \frac{G}{G_{(nom)}} \quad (6)$$

$$K_0 = \frac{I_{SC}(T_2) - I_{SC}(T_1)}{(T_2 - T_1)} \quad (7)$$

Moreover, the inverse saturation current of the diode can be defined as shown in equations (8) and (9):

$$I_0 = I_0(T_1) \left(\frac{T}{T_1}\right)^{\frac{3}{n}} e^{\frac{qV_q(T_1)}{nk\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \quad (8)$$

$$I_0(T_1) = \frac{I_{SC}(T_1)}{\left(e^{\frac{qV_{OC}(T_1)}{nkT_1}} - 1\right)} \quad (9)$$

B. Differences in the programming

The models analyzed, Walker [2], Akihiro [7] and González [8], developed by the three authors are very similar and the differences are small. Following, these aspects are pointed out:

- Diode ideality or quality factor Value (A, n) is around 1'2 or 1'62. Band gap voltage is the same for the three authors (1'12, for silicon), although it could vary depending on the material type (1'42 for GaAs, 1'5 for CdTe and 1'75 for amorphous silicon).
- In the case of Ahikiro, it only requests a pair of values of I_{SC} y V_{OC} , whereas Walker and González request two pairs.
- Considering Temperature coefficient of I_{SC} (a ó k_0), Ahikiro takes it from data sheet of the model, whereas Walker (ec. 10) and González (ec 11) calculates it:

$$a = \frac{I_{SC2} - I_{SC1}}{I_{SC} \left(\frac{1}{T_2} - \frac{1}{T_1}\right)} \quad (10)$$

$$k_0 = \frac{I_{SC}(T_2) - I_{SC1}(T_1)}{T_2 - T_1} \quad (11)$$

- Photoelectric current (I_L o I_{ph}) is equal for Ahikiro (12) and Walker (14) and something different for González (13):

$$I_{ph} = G (I_{SC_TrK} (1 + a(TaK - TrK))) \quad (12)$$

$$I_L = I_{SC}(T_1) \cdot \text{Suns} + k_0 (TaK - TrK) \quad (13)$$

$$I_{ph} = I_{SC_T1} \text{Suns} (1 + a(TaK - TrK)) \quad (14)$$

- Finally, in the definition of the I_a current González and Walker use the same equation (15) while Ahikiro uses equation (16).

$$I_a = I_a - \frac{I_a - I_{ph} + I_r \left(e^{\frac{V_C + I_a R_s}{Vt_Ta}} - 1 \right)}{I_r R_s \left(e^{\frac{V_C + I_a R_s}{Vt_Ta}} - 1 \right) + 1} \quad (15)$$

$$I_a = I_a - \frac{I_a - I_{ph} + I_r \left(e^{\frac{V_C + I_a R_s}{Vt_Ta}} - 1 \right)}{\frac{I_r R_s e^{\frac{V_C + I_a R_s}{Vt_Ta}}}{Vt_Ta} + 1} \quad (16)$$

5. Calculation of the characteristic curves

The parameters that determine the operation of a sun cell reflected in their characteristic curves, I-V and P-V.

For the calculation of two families of curves, first the temperature stayed constant at 25 °C varying the irradiance (700, 800, 900 and 1000 W/m²) generating a type of curves. Later, the irradiance is maintained constant at 1000 W/m² calculating the curve for 0, 25, 50 and 75 °C

A. Curve I-V

Fotocurrent depends on the irradiation of the moment. The higher the irradiation, the greater the current. On the otherhand, voltage is going to maintain almost constant and it is not going to vary much, although increases or diminishes the irradiation. (Fig. 3)

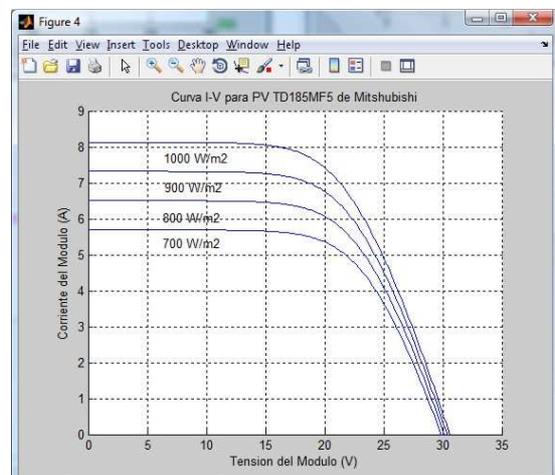


Fig. 3. Curve I-V for constant T^a.

Additionally, the efficiency of the solar cells falls when temperature increases, mainly, due to the decrease of the open circuit voltage. (Fig. 4)

Finally, the current density is going to maintain more insensible to temperature, although it increases slightly. (Fig. 4)

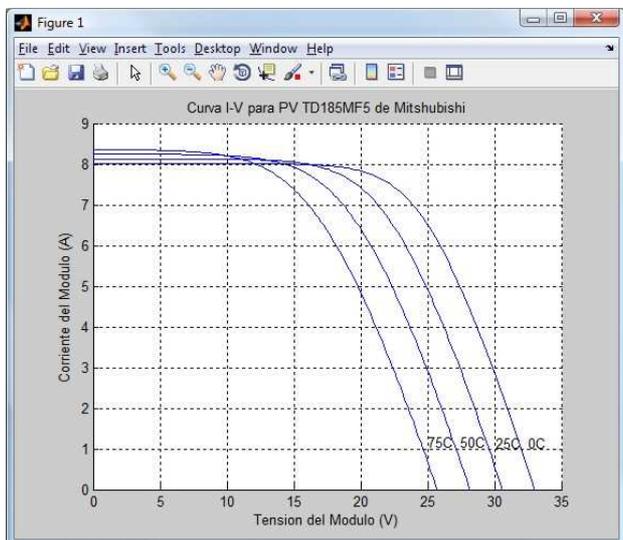


Fig. 4. Curve I-V for constant G.

B. Curve P-V

The influence of the Irradiation variation, at constant temperature, is fundamental for the calculation of the maximum power point (MPP) (Fig. 5). The higher the irradiation, the major MPP will be obtained in the photovoltaic module.

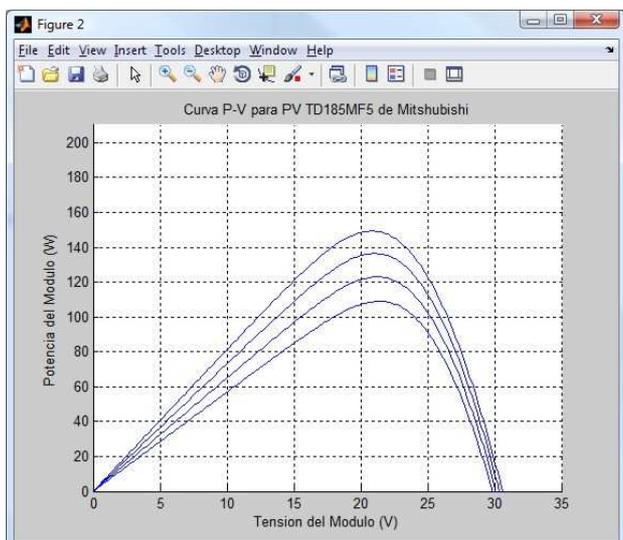


Fig. 5. Curve P-V for constant T^a.

In this case, the influence of the temperature on the voltage can be seen (fig 6). The greater the temperature, the smaller the voltage. Staying almost linear the power until a value. From that value, the power also decreases with the increase of temperature.

Thus, the temperature increase makes diminish the voltage and power output. At noon, although the greatest irradiation is being received, the power generated by the panel falls due to the rise of the temperature work.

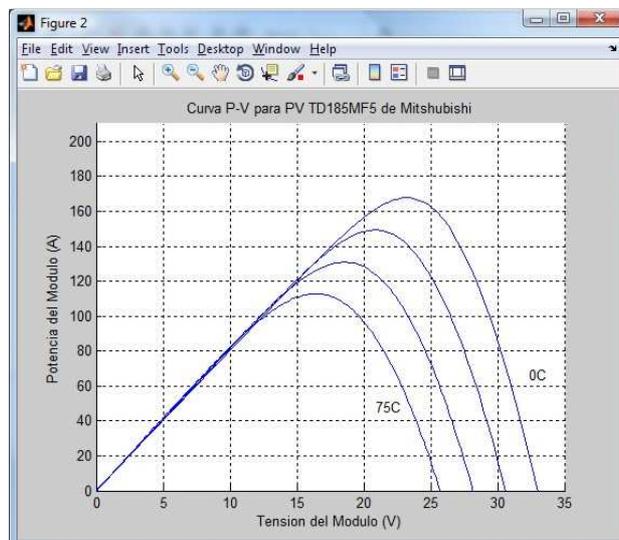


Fig. 6. Curve P-V for constant G.

C. Curve I-V and P-V

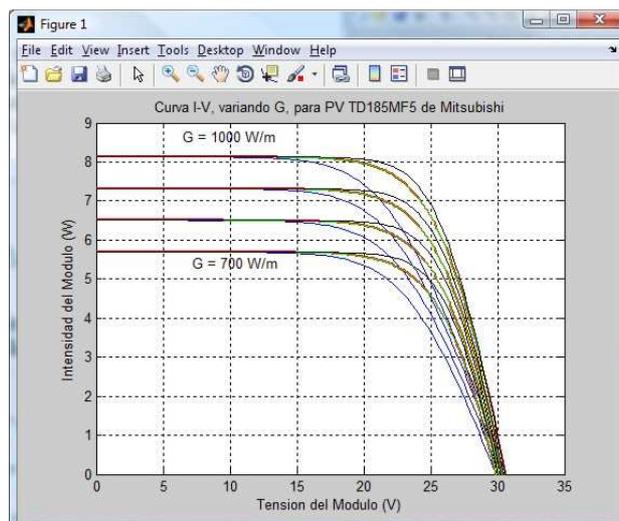


Fig. 8. Curve I-V for constant T^a.

In the case of curve IV calculation, for constant temperature of 25° and varying the irradiation, for all models, a better behavior for the generic curve (our model) is appraised and worse for the model of Ahikiro

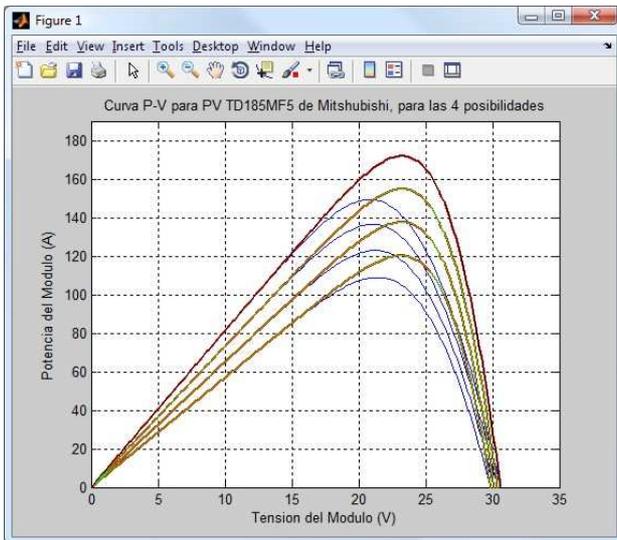


Fig. 7. Curve P-V for constant T^a .

The four possibilities of solar cell modelling in an unique graph, have been analyzed (Fig. 7). It can be observed that models of Walker, González and the generic one give similar results, whereas Ahikiro model always gives inferior values of the MPP.

6.- Calculation of the MPP

The Maximum Power Point (MPP) comes defined by the product of the maximum values obtained from current and voltage (ec. 17):

$$P_{\max} = V_{\max} \cdot I_{\max} \quad (17)$$

For the calculation of the MPP two different criteria have been used, giving very similar final results.

A. First criterion

The necessary data are the value of the irradiance (between 0.1 and 1) and the temperature of the module in °C. The best results were obtained for $G = 1$ and $T = 22$ °C:

- Maximum power output (P_{\max}) 185'4524 Watts
- Maximum voltage output (V_{\max}) 23'84 Volts
- Maximum current output (I_{\max}) 7'779 Amperes

B. Second criterion

The necessary data are three, the value of the irradiance (between 0.1 and 1), the temperature of the module in °C and the value of the module operating voltage. The best results were obtained for $G = 1$, $T = 22$ °C and $V = 24$ Volts:

- Maximum power output (P_{\max}) 185'4488 Watts
- Maximum voltage output (V_{\max}) 23'8 Volts
- Maximum current output (I_{\max}) 7'792 Amperes

7. Conclusion

In this paper, different models have been compared to analysing the performance of solar cells.

The developed model, with electric main parameters, is valid for I-V characteristics measured and can work with few parameters of input demonstrate to graph and numerically the operation of a solar model.

The objective is develops in the future a complete model to simulate the electrical behaviour of the PV systems. And to develop, starting off of these models, other models, but in this case in Simulink.

Unfortunately, the manufacturers do not provide the values of the resistance in series nor in parallel of the cell. That they would make easier the simulation.

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