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Computational tool for simulating the performance of photovoltaic panels

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Abstract

An accurate model based on Shockley equation is used to simulate photovoltaic modules. This article proposes the use of double exponential model to simulate the electrical characteristics of any photovoltaic panel on market. The modeling tool allows the analysis of the behaviour of electrical characteristics in accordance with environmental changes such as temperature and irradiance. It is verify that these extrinsic factors influence the photovoltaic efficiency.

Keywords: Photovoltaic Cells; Modeling; Simulation; MATLAB; *I-V* and *P-V* Curves.

1. Introduction

The basic unit for converting solar energy into useful electrical energy is the solar cell. Grouped cells form photovoltaic (PV) modules with the aim of increasing energy production and make the process more practical. The electrical characteristics electrical current-voltage (*I-V*) and electrical power-voltage (*P-V*) of PV systems are not linear and depend on solar radiation and temperature.

The double exponential model is composed of a series resistance, parallel resistance (shunt), two saturation currents, a photovoltaic current and ideality factor. This model offers greater accuracy than a single exponential model, which only makes use of a series resistance, a diode and a shunt resistance. The later resistance is usually neglected as indicated by Ishaque *et al.* [1-3]. Thereby it is necessary a tool to extract all the parameters that characterize the PV modules for subsequent layout of *I-V and P-V* curves, independently of the module to simulate [4].

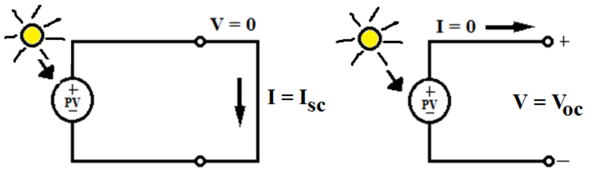
2. Modeling Photovoltaic Systems

The use of an electrical equivalent circuit makes possible modelling the electrical characteristics of a photovoltaic solar cell. To accomplish this task it is necessary to know the best way for modeling and further implementation in MATLAB. This same technique is applicable in modeling of PV modules as described by Oi [5].

2.1. Simple Model of Solar Cell

The simplest equivalent circuit representative of a solar cell is given by a current source in parallel with a diode. The source output is directly proportional to the incident light and temperature in the cell [6-7]. The current source represents the current generated by photons (too often called I_{ph} or I_l). During the night or in the dark, the solar cell is not an active device, works like a *p-n* diode junction, which generates little current. However, if connected to an external source (high voltage) generates a current I_d, called diode current [4]. The diode determines the *I-V* characteristics of the cell [7].

There are two key parameters often used to characterize PV cells, are they short-circuit current (I_{sc}) and open circuit voltage (V_{oc}).



(a) (b)

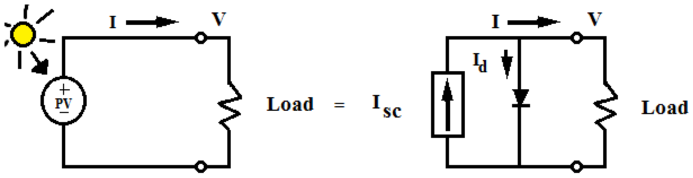
Figure 1 – Diagrams of the conditions in (a) short-circuit and (b) open circuit [5].

Closing the terminals of a photovoltaic cell (Fig. 1a), the current generated by photons that will flow out, is called short-circuit current *(I_{sc})*. Thus, $I_{ph} = I_{sc}$. When the connection of the terminals circuit is not established (open circuit), the current generated by photons is closed internally by the intrinsic *p-n* junction of the diode (Fig. 1b). This condition provides an open circuit voltage (V_{oc}) [5-6].

The output current (I) of the solar cell (Eq. 1) can be determined by applying Kirchhoff's laws in the equivalent circuit (Fig. 2) [5]. The diode current I_d (Eq. 2) is given by Shockley's equation [5, 8].

$$I = I_{sc} - I_d \tag{1}$$

$$\mathrm{I_d} = \mathrm{I_0}(\mathrm{e}^{\frac{\mathrm{qV_d}}{\mathrm{kT}}}\text{-}1) \tag{2}$$



(a) (b)

Figure 2 – Photovoltaic cell (a) loading and (b) the simple equivalent circuit [5].

2.2. High Accuracy Model

There are some effects that should be considered in the simplest model to obtain more accurately the *I-V* characteristics of the solar cell [5].

They are: the series resistance (R_s), which induces a current through the semiconductor material, the metal mesh, the shunt resistance (R_{sh}), among others [5, 9]. These losses are associated with a small leakage current associated with a resistive path in parallel with the intrinsic device [5, 9]; recombinations in photovoltaic cells area promote the reduction of non-ohmic currents routes in parallel with the intrinsic solar cell. This condition is relevant for low bias voltages and can be represented in a equivalent circuit through a second term in a diode density current (I_{s2}), which is different from the current density of an ideal diode, which usually gives an ideality factor (*a*) with a different value of 1 and a maximum value of 2 [5, 9]. Summarizing these effects, the *I-V* relationship can be described by:

$$I = I_{ph} - I_{s1}\left[e^{\left(\frac{V+I.R_S}{n_S.V_t}\right)} - 1\right] - I_{s2}\left[e^{\left(\frac{V+I.R_S}{a.n_S.V_t}\right)} - 1\right] - \left(\frac{V+I.R_S}{R_{sh}}\right) \tag{3}$$

$$\mathrm{V_t} = \frac{\mathrm{Ns.k.T}}{\mathrm{q}} \tag{4}$$

Equation 3 is called a double exponential equation, where V_t (Eq. 4) is the thermal voltage of the *p-n* junction. This equation provides the *I-V* characteristic curve (Fig. 3), where the three most important points are represented: short-circuit point (I_{sc}, 0); maximum power point, MPP (I_{mp}, V_{mp}), and open circuit voltage point (0, V_{oc}) [10-11]. These authors also suggest that Equation 5 should be used to obtain the better *I-V* characterization for cells made of amorphous silicon. This equation comes from the double exponential equation by setting the saturation current $I_{s1} = 0$. Both equations are not linear, making it difficult to determine an analytical solution [12].

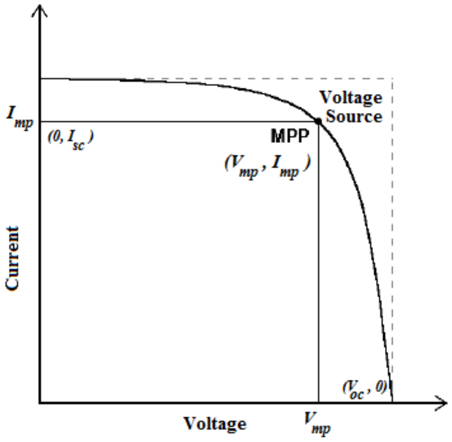


Figure 3 – *I-V* characteristic curve of a photovoltaic device and the three remarkable points: short-circuit current (0,I_{sc}), MPP (V_{mp},I_{mp}), and open circuit voltage (V_{oc},0) [10-11].

$$I = I_{ph} - I_S \left[e^{\left(\frac{V+I.R_S}{a.V_t}\right)} - 1 \right] - \frac{V+I.R_S}{R_{sh}} \tag{5}$$

Equations 3 and 5 describe the equivalent circuits that represent these relationships. The circuit of the double exponential model, corresponding to Equation 3, is shown in Fig.4a and the circuit of the simple exponential model, corresponding to Equation 5 is illustrated in Fig. 4b.

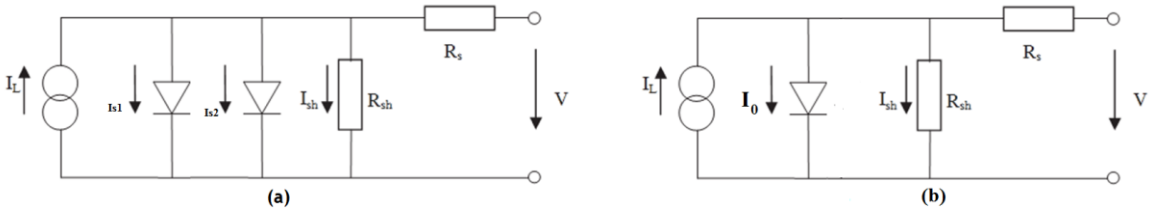


Figure 4 – (a) Double exponential model and (b) simple exponential model of a PV cell [1-3, 13].

Therefore, modelling PV modules primarily involves the estimation of nonlinear *I-V* curves. Researchers have used circuit topologies to model the electrical characteristics of PV modules when subject to variations such as irradiance and temperature. By far the simplest approach is the simple exponential model, i.e. a current source in parallel with a diode. An improvement of this version is the consideration of a series resistance (R_s) [1-3]. However, the model remains very simple, exhibiting serious shortcomings when subjected to high temperature variations, due to the non introduction of the open voltage coefficient (k_v) [7]. An extension of the simple exponential model further includes a shunt resistance (R_{sh}).

Including this resistance, the number of parameters increases to five, increasing its complexity but also increasing the accuracy of the results [1-3, 14-15].

The models behave like a “black box” (Fig. 5), so systems designers use environmental parameters such as irradiance, *G*, and temperature, *T*, in order to study the system conversion to any fixed point or variable with respect to these parameters. It is necessary to relate the five variable parameters of the equation with the two environmental parameters (*G*, *T*) [12].

The simple exponential model is based on a formulation where the recombination losses are disregarded. In a real solar cell, recombination represents substantial losses, but is not adequately modeled by simple exponential model. This loss can be considered in the double exponential model. However, the inclusion of a diode increases the calculation parameters from five to seven, where the latter is the I_{s2} and a_2 [1-3].

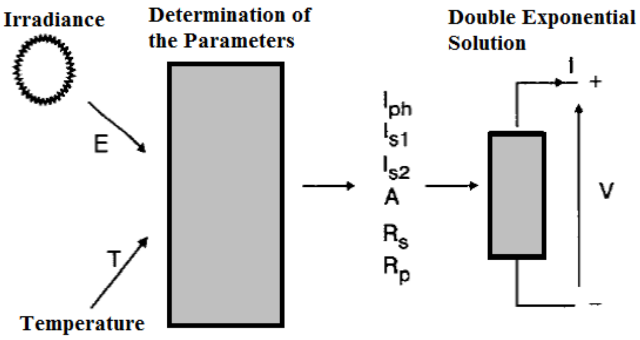


Figure 5 – Basic process of modeling PV panels [12].

2.3. Modeling of a Photovoltaic Module

The modeling strategy for a photovoltaic module is not very different from the modeling of a photovoltaic cell. The model is similar, consider the same parameters, however the parameter open circuit voltage (V_{oc}) is different and must be divided by the number of existing cells in the module [5]. In this particular study, we use the double exponential model for modeling of a PV panel in order to reduce the computational error propagation [1-3]. Therefore, using this model offers a more accurate calculation compared to others. In particular, the double exponential model is a preferred choice, but it is necessary to take into account the most demanding computational calculations [1-3, 16].

The manufactures of PV modules provide access to few experimental data about the thermal and electrical characteristics. Unfortunately, some of the parameters required for modeling PV modules cannot be found in the manufacturer’s datasheets, such as the current generated by light, series and shunt resistances, diode ideality constant, reverse saturation current and energy of the band gap of the semiconductor. All datasheets of photovoltaic modules have information concerning the: nominal open circuit voltage ($V_{oc,n}$); nominal short circuit current ($I_{sc,n}$); voltage in the MPP, (V_{mp}); current in the MPP (I_{mp}); temperature coefficient of the open circuit voltage (k_v); temperature coefficient of the short-circuit current (k_i), and maximum experimental peak power ($P_{max,e}$). This information is provided with reference to the standard test conditions (*STC*) for temperature and irradiance [10-11].

Therefore, upon making use of the double exponential model, should obey to Equation 3 and the circuit of Figure 4 to perform the modeling and the *I-V* characterization. For this, other equations are required to find the parameters needed for modeling: I_{ph}, I_{s1}, I_{s2}, R_{sh}, R_s, a_1 and a_2. For simplicity, it is assumed that $a_1 = 1$ and $a_2 = 1{,}12$. This latter value is an approximation of recombinations that occur in the Schokley’s diode [1-3].

2.4. Determination of All Parameters in Double Exponential Model

In order to proceed with the calculation of all parameters, the photovoltaic current (I_{ph}) for a given cell temperature (T) must be firstly calculated:

$$\mathrm{I_{ph}} = \left(\mathrm{I_{ph\,STC}} + \mathrm{k_i}.\Delta\mathrm{T}\right)\frac{\mathrm{G}}{\mathrm{G_{STC}}} \tag{6}$$

Where $I_{ph\ \mathrm{STC}}$ (in Ampere) is the current generated by light in standard test conditions (STC), equal to $I_{sc\ \mathrm{STC}}$. The thermal variation, ΔT, is equal to the difference between the cell temperature, T, and the STC temperature (T_{STC} = 25 ºC). The saturation currents of diodes I_{s1} and I_{s2} are determined according to the formulation suggested by [1-3], i.e., $I_{s1} = I_{s2}$.

$$\mathrm{I_{s1}} = \mathrm{I_{s2}} = \mathrm{I_{s,STC}}\left(\frac{\mathrm{T_{STC}}}{\mathrm{T}}\right)^3 \mathrm{e}^{\left[\frac{\mathrm{q.E_g}}{\mathrm{a.k}}\left(\frac{1}{\mathrm{T_{STC}}}-\frac{1}{\mathrm{T}}\right)\right]} \tag{7}$$

The nominal saturation current is obtained through the expression proposed by [12]:

$$I_{s,STC} = \frac{I_{sc,STC}}{e^{\left(\frac{V_{oc,STC}}{V_t}\right)}-1} \tag{8}$$

The short circuit current, $I_{sc\ \mathrm{STC}}$, and the open-circuit voltage, $V_{oc\ \mathrm{STC}}$, both nominal (STC), can be obtained from the datasheets of PV modules manufacturers. E_g is the semiconductor band gap (E_g = 1,14 eV) and $I_{s,\mathrm{STC}}$ is the nominal saturation current. Two parameters remain to be found, they are R_s and R_{sh}. The calculation of these parameters is based by the fact that there is only one pair of R_s and R_{sh} that ensures the maximum power calculated by the model, $P_{\mathrm{max,m}}$, to be equal to the experimental maximum power, $P_{\mathrm{max,e}}$, shown in the datasheet of the PV module in the maximum power point (V_{mp}, I_{mp}) of the I-V curve, i.e., $P_{\mathrm{max,m}} = P_{\mathrm{max,e}} = V_{\mathrm{mp}} \times I_{\mathrm{mp}}$ [10-11]. The underlying idea is maximizing the maximum power point, i.e., to match the value of peak power, $P_{\mathrm{max,m}}$, with the experimental value, $P_{\mathrm{max,e}}$, by increasing the value of R_s while simultaneously calculates the value of R_{sh} [1-3].

$$\mathrm{P_{max,m}} = \mathrm{V_{mp}}\left\{\mathrm{I_{ph}}\text{-}\mathrm{I_{s1}}\left[\mathrm{e}^{\left(\frac{\mathrm{q}}{\mathrm{kT}}\frac{\mathrm{V_{mp}+R_S I_{mp}}}{\mathrm{N_S}}\right)}\text{-}1\right]\text{-}\mathrm{I_{s2}}\left[\mathrm{e}^{\left(\frac{\mathrm{q}}{\mathrm{kT}}\frac{\mathrm{V_{mp}+R_S I_{mp}}}{\mathrm{aN_S}}\right)}\text{-}1\right]\text{-}\frac{\mathrm{V_{mp}+R_S I_{mp}}}{\mathrm{R_{sh}}}\right\} = \mathrm{P_{max,e}} \tag{9}$$

$$\mathrm{R_{sh}} = \frac{\mathrm{V_{mp}(V_{mp}+I_{mp}R_S)}}{\left\{\mathrm{V_{mp}I_{ph}}\text{-}\mathrm{V_{mp}I_{s1}}\mathrm{e}^{\left[\frac{(\mathrm{V_{mp}+I_{mp}R_S})}{\mathrm{N_S}}\frac{\mathrm{q}}{\mathrm{kT}}\right]}\text{-}\mathrm{V_{mp}I_{s2}}\mathrm{e}^{\left[\frac{(\mathrm{V_{mp}+I_{mp}R_S})}{\mathrm{aN_S}}\frac{\mathrm{q}}{\mathrm{kT}}\right]}+\mathrm{V_{mp}I_{s1}}+\mathrm{V_{mp}I_{s2}}\text{-}\mathrm{P_{max,e}}\right\}} \tag{10}$$

Equation 10 considers that for each value of R_s there is a value of R_{sh} that makes the I-V curves match with the experimental point (V_{mp}, I_{mp}). The goal is to find a value of R_s and R_{sh} which superposes the peak of the mathematical curve with the PV peak power point ($P_{\mathrm{max,m}}$, V_{mp}). This formulation requires an iterative process whose convergence criterion is given by the equality $P_{\mathrm{max,m}} = P_{\mathrm{max,e}}$ [1-3]. Thus, for solving the I-V equation is necessary to apply an iterative method with fast convergence to estimate the roots of the function, such as the Newton-Raphson method [5-6]:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{11}$$

Where *f'*(*x*) is the derivative of the function, *f*(*x*) = 0, x_n is the value of the present iteration, and x_n+1 is the value in the next iteration. Rewriting Equation 3, it comes:

$$f(I) = I_{ph} - I - \left[I_{s1}.\, e^{\left(\frac{V+I.R_S}{a_1.V_{t1}}\right)} - 1 \right] - \left[I_{s2}.\, e^{\left(\frac{V+I.R_S}{a_2.V_{t2}}\right)} - 1 \right] - \frac{V+I.R_S}{R_{sh}} = 0 \tag{12}$$

Substituting in Eq. 11, we obtain the following equation to calculate the current, *I*, iteratively.

$$I_{n+1} = I_n - \frac{I_{ph} - I_n - \left[I_{s1}.e^{\left(\frac{V+I.R_S}{a_1.V_{t1}}\right)} - 1 \right] - \left[I_{s2}.e^{\left(\frac{V+I.R_S}{a_2.V_{t2}}\right)} - 1 \right] - \frac{V+I.R_S}{R_{sh}}}{-1 - \left[I_{s1}.\frac{R_S}{a_1.V_{t1}}.e^{\left(\frac{V+I.R_S}{a_1.V_{t1}}\right)} \right] - \left[I_{s2}.\frac{R_S}{a_2.V_{t2}}.e^{\left(\frac{V+I.R_S}{a_2.V_{t2}}\right)} \right]} - \frac{R_S}{R_{sh}} \tag{13}$$

Where: $V_{t1} = \frac{a_1.N_S.k.T}{q}$ and $V_{t2} = \frac{a_2.N_S.k.T}{q}$, are the respective thermal voltages.

3. Results Analysis and Discussion

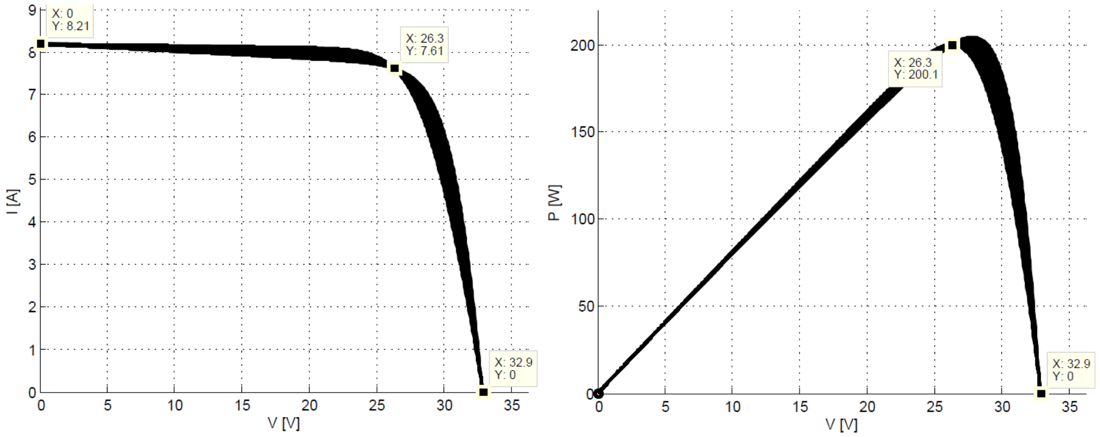
This section makes the analysis of the graphics obtained in the numerical model developed in MATLAB. To this end, experimental values of PV modules are needed to compare and validate the numerical predictions. The PV modules selected are the *KC200GT* and the *MSX60* [10-11]. Thus, we intend to make an analysis of data obtained in numerical modeling and it is therefore necessary to access the technical specifications provided in the datasheets of each PV modules manufacturer for each model aforesaid. Thus, for further expeditious evaluation of the specifications of each model of PV module are presented in Table 1. These values that characterize each PV modules, when inserted in the numerical model allow the prediction of *I-V* e *P-V* characteristics curves.

The subsequent application of mathematical model through programming in MATLAB, allows to iteratively finding the value of R_s and thus the value of R_{sh}, with which it does match the peak of the *P-V* curve with the mathematical maximum peak power experimental point (V_{mp}, I_{mp}). This process requires a lot of iterations until $P_{max,m} = P_{max,e}$.

In the iterative process, R_s should be increased slowly starting, for example, the value R_s =0,02 Ω. Adjusting the *P-V* curve to match the experimental data requires sufficient calculations of the values of both resistances R_s and R_{sh}, in order to achieve the goal of minimizing the error estimation. The best resistance values are calculated in the STC conditions at the last iteration, i.e., when the convergence criterion is satisfied. These results allow further analysis of the behavior of photovoltaic modules for the various values of temperature and irradiance. Figure 6 shows the iterative process of calculating the series and shunt resistance graphically in the *P-V* and *I-V* characteristics curves for the PV module *KC200GT*. The process of calculating the resistance for the module *MSX60* follows the same procedure.

Table 1- PV Module specifications *KC200GT* and *MSX60* under the standard test conditions (STC: 25 °C, A.M 1,5; 1000 W/m^2).

Technical specifications	Units	*KC200GT*	*MSX60*
Maximum Power, $P_{max,e}$	W	200	60
Voltage at maximum power point, V_{mpp}	V	26,3	17,1
Current at maximum power point, I_{mpp}	A	7,61	3,5
Open-circuit voltage, V_{oc}	V	32,9	21,1
Short circuit current, I_{sc}	A	8,21	3,8
Temperature coefficient for V_{oc}	V/°C	$-123\text{x}10^{-2}$	$-80\text{x}10^{-2}$
Temperature coefficient for I_{sc}	A/°C	$3{,}18\text{x}10^{-2}$	$3\text{x}10^{-2}$
Cells number, N_s		54	36

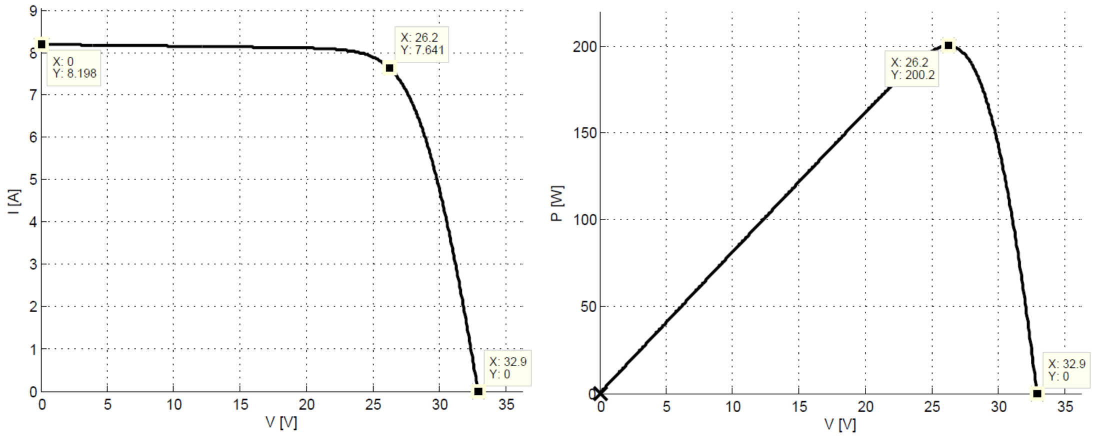


(a) (b)

Figure 6 – (a) *P-V* and (b) *I-V* curves for different values of R_s and R_{sh} (PV module *KC200GT*).

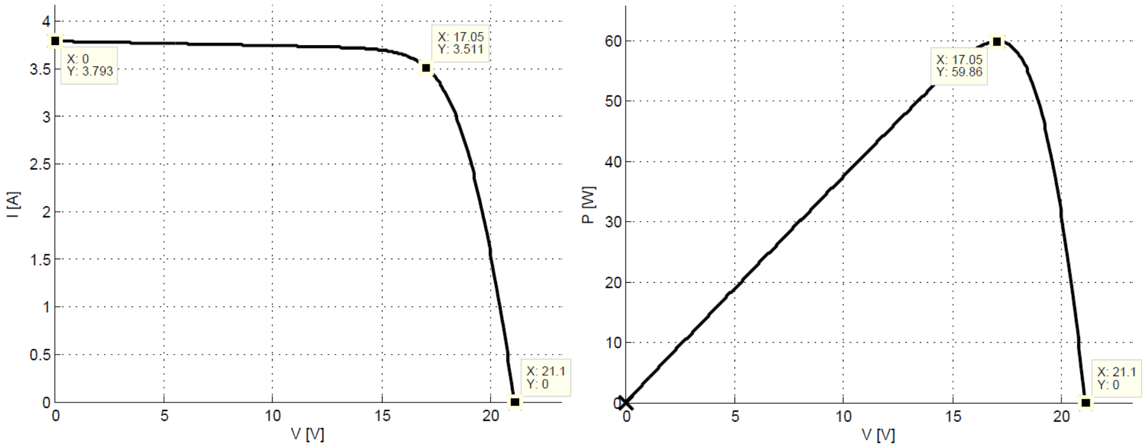
The iterative method provides the solution R_s = 0,32 Ω and R_{sh} = 179,6 Ω for the PV module *KC200GT*. There is only a single point corresponding to unique values of R_s and R_{sh} that satisfies the condition $P_{max,m} = V_{mp} \cdot I_{mp}$ in point (V_{mp}, I_{mp}). Similarly, for the PV module *MSX60*, the solutions obtained are R_s = 0,36 Ω and R_{sh} = 184,6 Ω.

Figures 7 and 8 show the final curves *I-V* and *P-V* adjusted by the iterative method of their PV modules, which are those that most closely match to the experimental curves shown in their datasheets. The curves superpose exactly with the three most important experimental points provided by the manufacturers: I_{sc}, $P_{max,m}$ and V_{oc}. The main parameters obtained numerically are shown in Table 2.



(a) (b)

Figure 7 –(a) *I-V* and (b) *P-V* final curves of the PV module FV *KC200GT* and the three remarkable points (I_{sc}, $P_{max,m}$, V_{oc}).



a) (b)

Figure 8 – (a) *I-V* and (b) *P-V* final curves of the PV module *MSX60* and the three remarkable points (I_{sc}, $P_{max,m}$, V_{oc}).

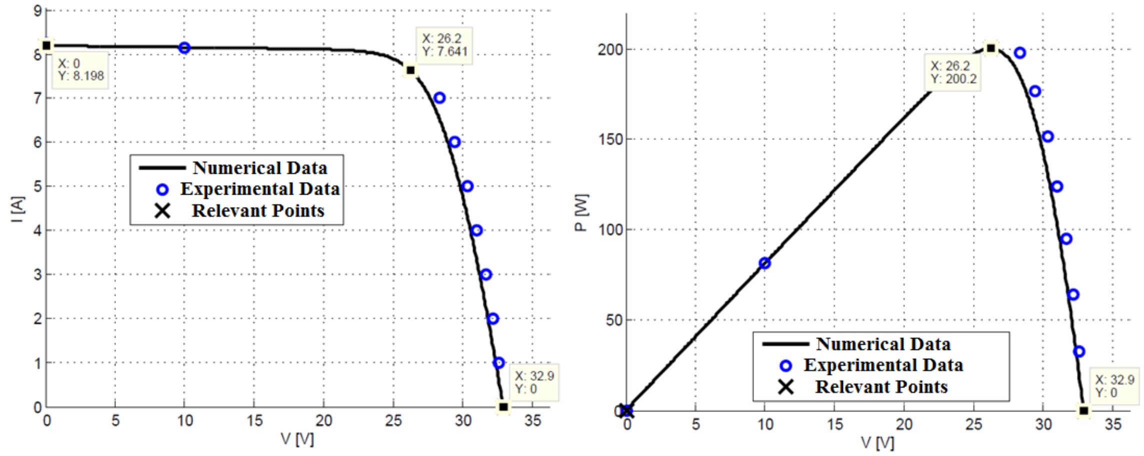
Table 2: Parameters obtained numerically for the modules FV *KC200GT* and *MSX60* at the STC conditions.

Technical specifications	$I_{mp,e}$	$V_{mp,e}$	$I_{mp,m}$	$V_{mp,m}$	$P_{max,m}$	I_{sc}	V_{oc}	$I_{s1,n} = I_{s2,n}$	I_{pv}	a_2	R_{sh}	R_s
Units	A	V	A	V	W	A	V	A	A		Ω	Ω
KC200GT	7,61	26,3	7,64	26,2	200,20	8,21	32,9	4,128x10^{-10}	8,21	1,12	179,6	0,32
MSX60	3,5	17,1	3,51	17,1	59,86	3,80	21,1	4,704x10^{-10}	3,80	1,12	184,6	0,36

The resistance values calculated and the error between the experimental maximum power and the maximum power obtained numerically are shown in Table 3. Compared with the figures presented in the table, there is a good approximation of values and consequently a very small error, which shows the accuracy of the simulation program.

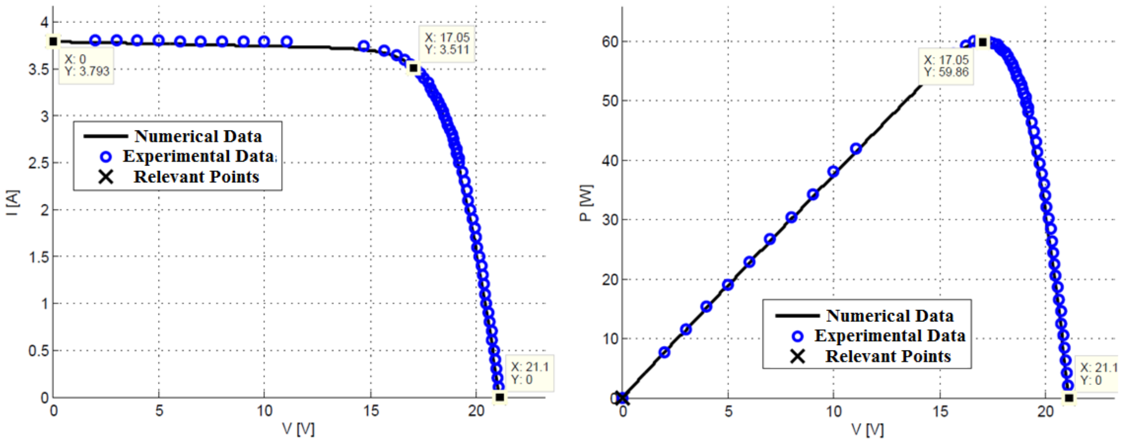
4. Analysis of Numerical and Experimental Curves

For a final analysis of the numerical program was necessary to compare their results with the experimental voltage and current data of the PV modules *KC200GT* and *MSX60*. Using the experimental data provided by [10-11], are drawn in Figures 9 and 10 the characteristics curves, *I-V* and *P-V*, of which module that supply a comparison between experimental and numerical values calculated using the double exponential model.



(a) (b)

Figure 9 -(a) *I-V* and (b) *P-V* curves of the exponential model and the experimental points for the PV module *KC200GT*



(a) (b)

Figure 10 – (a) *I-V* and (b) *P-V* curves of the double exponential model and the experimental points for the PV module *MSX60*.

Table 3 shows the error between the experimental and numerical maximum power and the calculated relative error between curves, evaluating thus the proximity of each numerical value obtained iteratively and its experimental value of each value.

Table 3: Best values of series and shunt resistances obtained numerically for both panels and the corresponding errors between powers and between curves.

PV Model	R_s [Ω]	R_{sh} [Ω]	Relative Error (P_{max}) [%]	Absolute Error (curves) [A]
KC200GT	0,32	179,6	0,021	0,5
MSX60	0,36	184,6	0,014	0,07
KC200GT [1-3]	0,32	160,5	-	-
MSX60 [1-3]	0,35	176,4	-	-

5. Conclusion

This work proposes the modeling of photovoltaic modules in MATLAB based on the double exponential model. In order for the modeling provide consistent results, it was necessary to refer to datasheets of photovoltaic modules and simulate some specific parameters. The computational modeling tool has the ability to simulate the most important features of any photovoltaic panel. The accuracy of this simulator is verified in two ways. First, when determining the best values for R_s and R_{sh}, the error between the experimental and numerical maximum power is very low for both panels tested. The second error verification was the comparison of experimental and numerical values of *I-V* and *P-V* characteristic curves, where there was also a low error too.
This article provides a formulation intended for numerical simulation with high accuracy performance of photovoltaic panels.

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