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MATHEMATICAL MODEL FOR THE DETERMINATION OF VOLT-AMPERE CHARACTERISTICS IN SOLAR PHOTOCELLS

MODELO MATEMÁTICO PARA LA DETERMINACIÓN DE LAS CARACTERÍSTICAS VOLTIOAMPERIO EN FOTOCÉLULAS SOLARES

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Abstract: To use photovoltaic systems, it is necessary to measure precisely the light output that affects each unit of surface in the locations to be installed, which is essential to assess your energy efficiency. For this, these cells must be calibrated and their volt-ampere characteristics (I-V) known. The error made in determining these characteristics was evaluated using a simplified mathematical model and comparing the result of both models with the experimental result of 95 Si photocells from the Combined Electronic Components of the Pinar del Río province; facilitating the necessary calculation in the use of said cells as solar radiation sensors. The experimental points were extracted using the OriginPro 2017 program and processed with the Mathcad 15.0 program and the mathematical theory of numerical methods. The quality of the adjustment is determined by comparing the statistical coefficients R^2 corresponding to the complete and simplified equation, for which it has been found so far that said coefficient R^2 of the simplified equation is better than that given by the equipment with which experimental values and results are determined as good as with the complete equation.

Keywords: Si photocell, I-V characteristic, mathematical model, numerical methods.

Resumen: Para utilizar sistemas fotovoltaicos es necesario medir con precisión el flujo luminoso que incide en cada unidad de superficie en los lugares a instalar, lo cual es fundamental para evaluar su eficiencia energética. Para ello, estas celdas deben estar calibradas y conocer sus características voltamperio (I-V). El error cometido en la determinación de estas características se evaluó utilizando un modelo matemático simplificado y comparando el resultado de ambos modelos con el resultado experimental de fotocélulas de 95 Si de Componentes Electrónicos Combinados de la provincia de Pinar del Río; facilitando el cálculo necesario en el uso de dichas celdas como sensores de radiación solar. Los puntos experimentales se extrajeron con el programa OriginPro 2017 y se procesaron con el programa Mathcad 15.0 y la teoría matemática de métodos numéricos. La calidad del ajuste se determina comparando los coeficientes estadísticos R2 correspondientes a la ecuación completa y simplificada, para lo cual se ha encontrado hasta ahora que dicho coeficiente R2 de la ecuación simplificada es mejor que el dado por el equipo con el que se obtienen valores experimentales y los resultados se determinan tan buenos como con la ecuación completa.

Palabras clave: fotocélula de Si, característica I-V, modelo matemático, métodos numéricos.

1. INTRODUCTION

Fossil fuels are finite resources that will inexorably run out (Díaz, 2018). The current energy system is based on these sources that lead to a series of environmental and sustainability problems, among which we can mention the greenhouse effect (García, 2018). Fortunately, there are also renewable energies; within this group we find wind energy, photovoltaic solar energy, thermal solar energy, hydraulic energy, energy from biomass and organic waste (Beltran, 2015).
Solar energy, the emblem of renewable energies, has seen a progression in recent years due to improvements in technology, associated with cost reduction and mainly thanks to the interest shown by a large number of countries (Berri, 2014; Opalkova, 2018). In photovoltaic systems it is essential to measure the efficiency of the solar cells, since this allows knowing how much power of solar radiation (W/m^2) each one absorbs, for which it is also necessary to know precisely how much solar energy reaches each location per area unit in one second. Then, the amount of solar energy and its conversion efficiency into electrical energy are the two fundamental parameters to be measured and controlled in any photovoltaic system that uses solar energy (Alan et al., 1998). This efficiency is the ratio between the number of electrons released for electrical conduction and the number of light photons reaching the cell, called the internal quantum efficiency (Janes, 2012; Wolfgang, 2002).
To determine how much solar radiation affects 1 m^2 of surface, equipment with very expensive and slow technologies is used, since it cannot be put into practice in real time (online), which represents a great difficulty for its use in the country; it is for this reason that calibrated solar cells are used instead. For these cells to function correctly it is necessary to determine their I-V characteristics; and the mathematical model of a photovoltaic solar cell has a complex transcendent equation, this makes it very difficult to evaluate the cells as solar radiation sensors. However, when making certain approximations to such an equation, a simpler one is reached that facilitates the calculation of the I-V characteristics, but as a problem, it is unknown how precise it is. Therefore, the objective of the present work is to simplify a mathematical model for the determination of the volt-ampere characteristics of solar photocells, which facilitates the calculation of efficiency, which is necessary in the use of said cells as solar radiation sensors.

2. MATERIALS AND METHODS

2.1 Theoretical Foundation

The PV solar cell can be modeled by means of the equivalent circuit shown in figure 1, using the laws of circuit theory, the following mathematical model for the solar cell is obtained (Morales, 2014).

$$I = I_L - I_D\left[e^{\frac{q(V+R_S I)}{mKT}} - 1\right] - \frac{V+R_S I}{R_{sh}} \quad (1)$$

Then, for a photovoltaic module or panel, the characteristic equation is:

$$I = I_L - I_D\left[e^{\frac{(V+R_S I)}{a}} - 1\right] - \frac{V+R_S I}{R_{sh}}$$

(2)

Where [$a=mKTN_s/q$], where *m* is the dimensionless recombination coefficient of the cell (between 1 and 3); *K* is Boltzmann's constant ($1.38 \cdot 10^{-23}$ J/K); *q* is the charge of the electron ($1.6 \cdot 10^{-19}$ C); *T* is the temperature in Kelvin and N_s is the number of cells in the module.

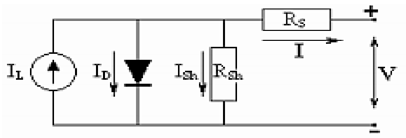

Fig. 1 Equivalent Circuit of a Photovoltaic Solar Cell, by Díaz, 2018

[$I_L \approx I_{sc}$], where I_L is the maximum intensity and I_{sc} is the short circuit intensity. [$I_D = I_L \cdot e^{-V_{oc}/a}$], where V_{oc} is the open circuit voltage:

$$V_{oc} = \frac{mKT}{q} ln\left(\frac{I_L}{I_D}\right) = mV_T \, ln \, ln \, \left(\frac{I_L}{I_D}\right)$$

(3)

$$\left[V_T = \frac{KT}{q}\right] \quad (4)$$

The series resistance is:

$$R_S = \frac{a \cdot ln\left(1 - \frac{I_{mp}}{I_L}\right) - V_{mp} + V_{oc}}{I_{mp}} \quad (5)$$

Where I_{mp} and V_{mp} are the Intensity and Voltage at the point of maximum power given by the expressions:

$$I_{mp} = I_L(1 - c^{-d}) \quad (6) \qquad V_{mp} \cong V_{oc}\left(1 - \frac{\ln c}{c}\right) \quad (7)$$

Where $\left[c = 1 + \ln\left(\frac{I_L}{I_D}\right)\right]$ y $\left[d = \frac{c}{c+1}\right]$ (8)

Equation (2) is a transcendent equation, which makes the process cumbersome to determine the intensity *I* for the different voltage values *V* necessary for the evaluation of photovoltaic cells as sensors of solar radiation. To facilitate these calculations, a simpler equation can be arrived at by making an approximation, since the value of R_{sh}, the parallel resistance, which is found in the denominator of the term corresponding to the intensity of the current I_{sh}, is much greater than its numerator and can be considered negligible. The characteristic equation for a PV module or panel is:

$$I = I_L - I_D\left[e^{\frac{(V+R_S I)}{a}} - 1\right] \quad (9)$$

This equation defines *I* as an implicit function of *V*, but also defines *V* as an explicit function of *I*, obtaining the following expression.

$$V(I) = a\ln\left(\frac{I_D - I + I_L}{I_D}\right) - IR_s \quad (10)$$

2.2 Materials, Equipment and Methods to Follow

95 images of 95 graphs of the I-V characteristics corresponding to 95 photocells are taken as a sample. These data were supplied by the UEB for PV energy, CCE Combined for Electronic Components, located on Álvaro Barba Airport Highway Km 2 ½, Colon Avenue, Passage A, No.16 between Álvaro Barba and Passage B, Pinar del Río province, Cuba. In the conformation of the solar panels, technology from the firm EPSON or Seiko Epson Corporation is used, which is a Japanese company and one of the world's largest manufacturers of electronic components such as SCARA robots for industrial use. While the Solar Simulator HSM2 is used to test the main electro-optical characteristics of solar cells and map the I-V curve. The 95 images are digitized with the OriginPro 2017 program to extract the experimental points corresponding to the characteristic curves of intensity I versus voltage V. The program is data analysis and graph generation software. It is a leader in the scientific-technical sector; belongs to OrginLab Corporation and is used to import, graph, explore, analyze and interpret data as needed.

Fig. 2 Photo Taken at OriginPro 2017 Program

Once these are obtained, they are introduced in the MathCad 15.0 program, which is a software designed mainly for the verification, validation, documentation and use of engineering calculations that allows exploring problems, formulating ideas, analyzing data, modeling and checking scenarios, determine the best solution; as figure 3 shows.

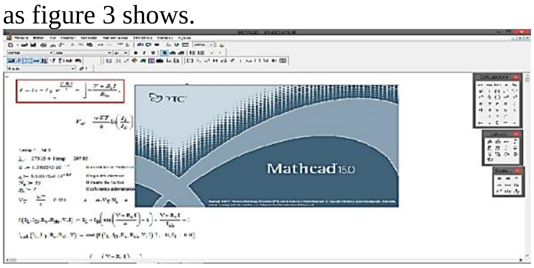

Fig. 3 Photo Taken from the MathCad 15.0 Program

3. PRESENTATION AND DISCUSSION OF THE RESULTS

The 95 images were digitized where the corresponding data to be processed in the MathCad program were obtained, which consist of its main electro-optical parameters. Taking into account their efficiency values, they are classified by colors according to the order of quality, very good (High quality), fair (Medium quality) and poor (Low quality), as shown in the table in figure 4.

No.	T, ºC	V_{oc}, V	I_{sc}, A	$P_{máx}$, W	V_m, V	I_m, A	FF^a, %	R_s, Ω	R_{sh}, Ω	Eff^b, % (celda)	Eff, % (módulo)
1	24.2	38.067	8.506	219.681	28.392	7.737	67.85	0.776	113.551	15.045	13.531
2	24.2	38.437	8.600	224.438	28.562	7.858	67.90	0.778	115.569	15.371	13.823
3	24.2	38.431	8.737	228.325	28.566	7.993	68.00	0.758	116.057	15.637	14.063
4	24.6	38.248	8.731	218.454	27.753	7.871	65.42	0.831	39.634	14.961	13.455
5	24.5	38.279	8.728	200.190	25.401	7.881	59.92	1.255	98.319	13.710	12.330
6	24.3	38.449	8.699	228.061	28.341	8.047	68.19	0.820	73.430	15.619	14.047
7	24.1	38.349	8.798	217.725	27.150	8.019	64.53	0.944	98.087	14.911	13.410
8	24.1	38.736	8.867	260.007	31.394	8.282	75.70	0.513	112.601	17.807	16.014
9	24.2	37.980	8.706	197.484	26.353	7.494	59.73	0.378	61.191	13.525	12.163
10	24.4	37.988	8.859	209.801	27.440	7.646	62.34	0.369	61.371	14.368	12.922
11	24.2	38.42	8.689	181.917	24.384	7.461	54.48	1.619	61.855	12.459	11.205
12	23.9	29.945	8.813	197.656	24.056	8.216	74.90	0.321	78.493	13.537	12.174
13	24.1	38.390	8.643	166.749	22.921	7.275	50.26	1.920	91.558	11.420	10.270
14	23.9	38.42	8.607	166.397	24.250	6.862	50.31	1.691	44.922	11.396	10.249
15	23.9	38.502	8.699	176.28	23.709	7.435	52.63	1.790	43.611	12.073	10.858
$(X=\bar{X}\pm \Delta X)^c$	24.3± 0.69	38.15± 2.56	8.69± 0.18	236.83± 48.73	29.78± 4.57	7.95± 0.91	71.4± 13.27	0.63± 0.63	108.82± 62.25	108.8± 62.25	14.59± 3.00

Good: Cell efficiency greater than or equal to 15 %.

Fair: Cell efficiency between 12 and 14 %.

Bad: Cell efficiency between 10 and 11 %.

Fig. 4 Sample of 15 of the 95 Photocells with their Main Electro-Optic Parameters classified by Colors into Good, Regular and Bad according to their Efficiency

Note. [a] Fill Factor, area of the cell that is "filled" with solar radiation and converts it into electricity. [b] Efficiency. [c] Electro-optical parameters with their mean values and absolute errors of measurements from the root mean square deviation.

Below are scatter diagrams for the main electro-optical parameters of the 95 photovoltaic solar cells studied with their mean values and their respective maximum and minimum errors.

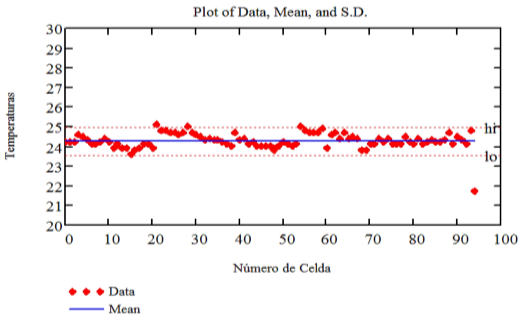

Fig. 5 Graphic Representation of the Temperature Measurements, with their Respective Average Value and Errors

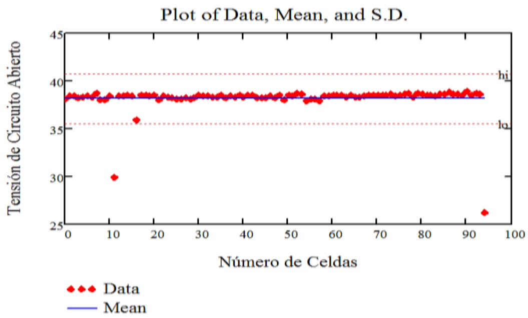

Fig. 6 Graphic Representation of the Open Circuit Voltage Measurements with their Respective Average Value and Errors

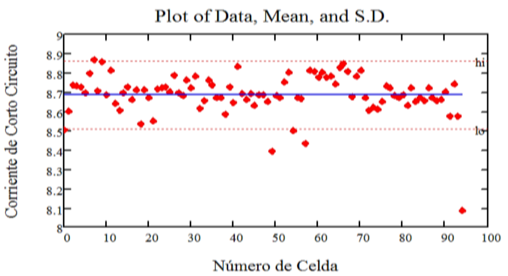

Fig. 7 Graphic Representation of the Short Circuit Current Measurements with their Respective Average Value and Errors

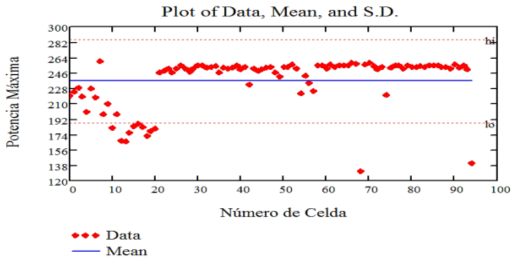

Fig. 8 Graphic Representation of the Maximum Power Measurements with their Respective Average Value and Errors

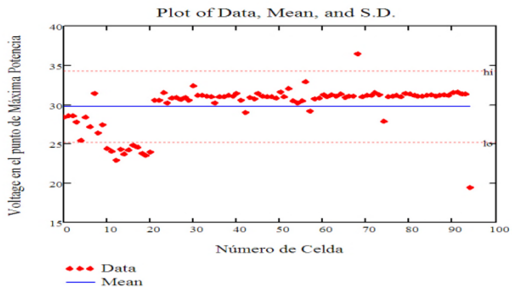

Fig. 9 Graphic Representation of the Measurements of the Voltage at the Point of Maximum Power with its Respective Mean Value and Errors

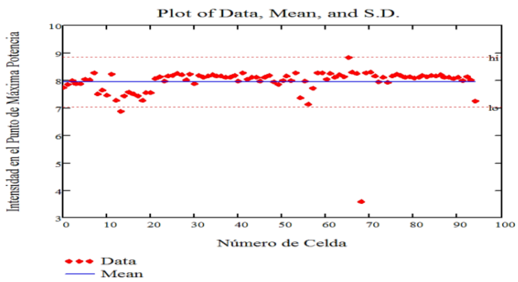

Fig. 10 Graphic Representation of the Measurements of the Intensity at the Point of Maximum Power with its Respective Average Value and Errors

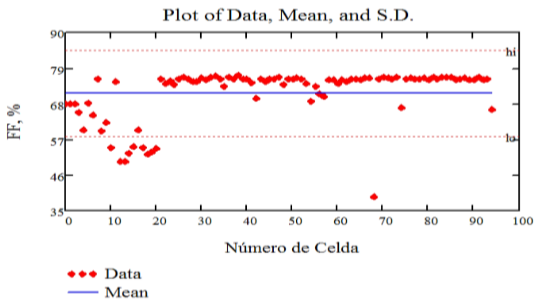

Fig. 11 Graphic Representation of the Filling Factor Measurements with their Respective Mean Value and Errors

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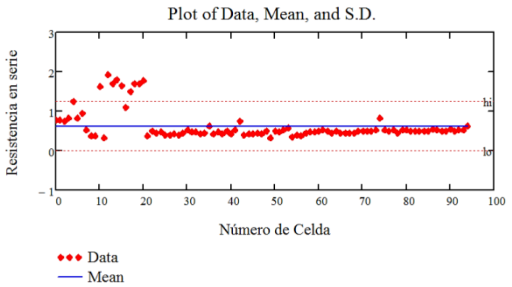

Fig. 12 Graphic Representation of the Resistance Measurements in Series with their Respective Average Value and Errors

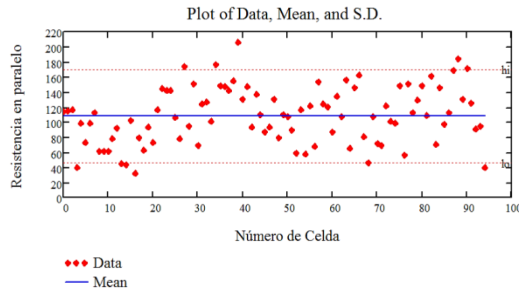

Fig. 13 Graphic Representation of Resistance Measurements in Parallel with their Respective Mean Value and Errors

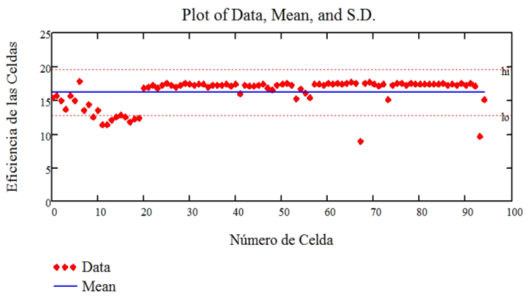

Fig. 14 Graphic Representation of the Efficiency of the Cells, in %, with their Respective Average Value and Errors

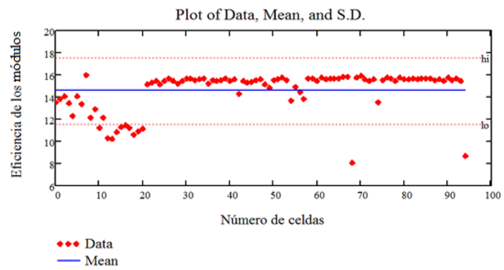

Fig. 15 Graphic Representation of the Efficiency of the Modules, in %, with their Respective Average Value and Errors

3.1 Adjustments of the Experimental Results to the Exact and Approximate Models

The table in figure 16 shows 15 examples of the adjustments with the main electro-optical parameters of the 95 cells studied for the exact model, for the approximate model and for reported experimental values. The table in figure 16 shows 15 examples of the adjustments with the main electro-optical parameters of the 95 cells studied for the exact model, for the approximate model and for reported experimental values. The quality of the fits is determined by comparing the corresponding statistical coefficients of determination R^2 (error), where the perfect fit corresponds to $R^2=1$.

Data	T, °C	Ajuste Ec. Completa				Ajuste Ec. Simplificada			Ajuste Valores Reportados			
		I_D, A	R_s, Ω	R_{sh}, Ω	R^2	I_D, A	R_s, Ω	R^2	I_D, A	R_s, Ω	R_{sh}, Ω	R^2
1	24.2	$8.770x10^{-9}$	0.610	179.191	0.99986	$8.763x10^{-9}$	0.644	0.99905	$9.304x10^{-9}$	0.776	113.551	0.96879
2	24.2	$6.953x10^{-9}$	0.626	243.302	0.99987	$6.925x10^{-9}$	0.651	0.99941	$7.697x10^{-9}$	0.778	115.569	0.96157
3	24.2	$7.268x10^{-9}$	0.621	264.120	0.99986	$7.240x10^{-9}$	0.645	0.99933	$7.846x10^{-9}$	0.758	116.057	0.96998
4	24.6	$8.159x10^{-9}$	0.726	78.780	0.99905	$8.004x10^{-9}$	0.820	0.99349	$8.902x10^{-9}$	0.831	39.634	0.96656
5	24.5	$8.526x10^{-9}$	1.061	155.449	0.99955	$8.380x10^{-9}$	1.114	0.99789	$8.690x10^{-9}$	1.255	98.319	0.97976
6	24.3	$7.423x10^{-9}$	0.652	277.097	0.99976	$7.419x10^{-9}$	0.675	0.99932	$7.790x10^{-9}$	0.820	73.430	0.96224
7	24.1	$7.869x10^{-9}$	0.804	187.002	0.99973	$7.853x10^{-9}$	0.838	0.99884	$8.202x10^{-9}$	0.944	98.087	0.98217
8	24.1	$6.398x10^{-9}$	0.270	211.607	0.99968	$6.469x10^{-9}$	0.288	0.99912	$6.701x10^{-9}$	0.513	112.601	0.92875
9	24.2	$7.007x10^{-9}$	0.408	28.022	0.97526	$4.433x10^{-9}$	0.922	0.95249	$9.983x10^{-9}$	0.378	61.191	0.94938
10	24.4	$7.334x10^{-9}$	0.466	39.676	0.98259	$5.956x10^{-9}$	0.732	0.96564	$1.026x10^{-8}$	0.369	61.371	0.96849
11	24.2	$7.928x10^{-9}$	1.360	166.909	0.99989	$7.777x10^{-9}$	1.410	0.99863	$7.819x10^{-9}$	1.619	61.855	0.96998
12	23.9	$7.472x10^{-9}$	0.162	1025.000	0.99918	$7.483x10^{-9}$	0.166	0.99916	$7.743x10^{-9}$	0.321	78.493	0.92418
13	24.1	$8.113x10^{-9}$	1.610	177.705	0.99978	$7.867x10^{-9}$	1.671	0.99869	$7.880x10^{-9}$	1.920	91.558	0.97396
14	23.9	$6.565x10^{-9}$	1.494	43.523	0.99622	$5.242x10^{-9}$	1.791	0.97687	$7.584x10^{-9}$	1.691	44.922	0.98289
15	23.9	$7.541x10^{-9}$	1.445	97.111	0.99924	$7.335x10^{-9}$	1.533	0.99539	$7.360x10^{-9}$	1.790	43.611	0.95437

Good: R^2 in the order of 0.999.

Regular: R^2 in the order of 0.990.

Bad: R^2 in the order of 0.900 or less.

Fig. 16 Sample of 15 of the 95 Fits for the Exact Model, the Approximate Model and for the Reported Experimental Values

Figure 17 shows examples that are considered good, regular and bad, taking into account the quality of their adjustments according to R^2 ; both for the exact model (complete equation) and for the approximate model (simplified equation) and for experimental values reported consecutively.

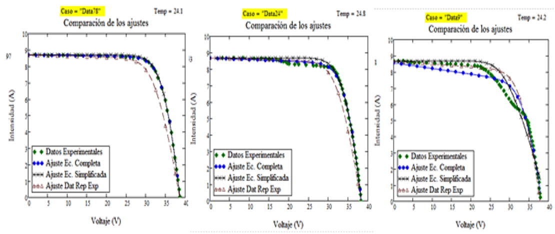

Fig. 17 Examples of Adjustments Classified as Good, Regular and Bad according to their R^2

3.2 Analysis and Comparison

The quality of solar cells for use or not in solar panels is determined from the electro-optical parameters given by the manufacturer, and also the number of cells that are classified as good, fair and poor in quality, according to the quality of the corresponding adjustments from the R^2 of each one with the main electro-optical parameters.

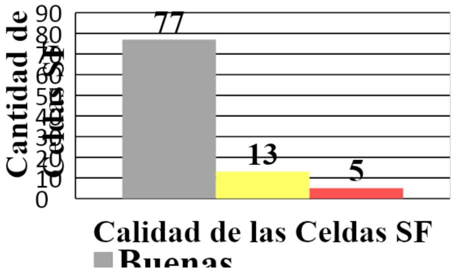

Fig. 18 Quality of the SF Cells Classified as Good, Regular and Bad According to their Efficiency

Fig. 19 Quality of the SF Cells According to the Quality of Fit R2 for the Exact, Approximate Models and for Reported Experimental Points

It can be concluded whether a batch is good, fair or bad depending on the percentage of cells classified as good, fair and bad. It can also be seen that the coefficient R^2 of the simplified equation is better than the one given by the equipment with which the experimental values are determined and in the order of the R^2 for the complex equation. That is to say, the results are as good as with the complete equation; in addition, the simplified equation is easier to work with, since it is possible to clear one variable as a function of another.

5. CONCLUSIONS

Experimental data were extracted from their corresponding I-V curve images of the 95 photocells.

The results of the mathematical models were compared, both with the transcendental equation and with the simplified equation, with the experimental values; the simplified model has turned out to be a good one.

The approximate model was used without making large errors.

The quality of the solar cells for their use or not in the solar panels was determined from the electro-optical parameters given by the manufacturer.

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