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EVALUATION OF DIFFERENT METHODS FOR PHYSICAL PROPERTIES ESTIMATION OF PHOTOVOLTAIC DEVICES

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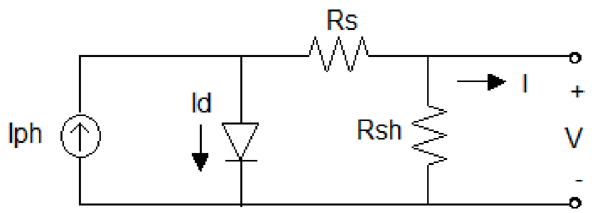
Abstract. *The present work deals with the analysis applied to the main methods used in estimating the physical properties of photovoltaic devices. These devices are related to the mono and multijunction technologies, when they are exposed to changes of temperature and solar radiation. Four parameterization methods are presented, where three of them are analytical based on the devices' electrical characteristics, however, these methods are traditionally for mono-junction photovoltaic technologies. The last one method is the Generalized Reduced Gradient (GRG2) Algorithm for optimizing nonlinear problems. In order to evaluate the accuracy of each method, four different case studies from experimental data are proposed. Consequently, it is determined that just two among the methods shown satisfactory results for this type of application.*

Keywords: *solar, photovoltaic, multijunction, parameterization.*

1. INTRODUCTION

To estimate the performance of photovoltaic devices (cell, module, or array), an equivalent electric circuit is used which is similar to the device that is to be characterized. There are a number of more or less complex models in the bibliography for simulating the behavior of a photovoltaic device (characteristic curve or intensity– voltage) for specific irradiance and temperature conditions (Blas, et al., 2002). In this work, the five parameters model shown in Fig. 1 was implemented. The current source (*Iph*) represents the photo-generated current in the cell, the PN junction responsible for the reverse saturation current (I_0) and the ideality factor (n) modelled by a diode, the series resistor (R_s) is modelling the voltage drop due to the resistance of the material in the cell, and finally the parallel resistor (R_{sh}) represents a leakage current in the photovoltaic cell (Bühler. A., 2011). For multijunction solar cell, the model is the same, but it can take two approaches. The first one analyzes all cell like a series array of subcells and the second one, consider the multijunction cell like a unique element.



$$I = I_{ph} - I_0\left[\exp\left(\frac{V + I \cdot R_s}{n \cdot Vth}\right) - 1\right] - \frac{V + I \cdot R_s}{R_{sh}}$$

Figure 1. Electrical scheme and math expression of five parameters model for a solar cell

The determination and knowledge of the influence of model parameters upon the solar cell efficiency become crucial for the optimization of fabrication processes and for the scientific research (Chegaar, Azzouzi and Mialhe, 2006). The possibility to determine the important parameters of the solar cells plays a major role in evaluating the solar cells, in controlling their quality, and also in the fabrication and power performance of reliable solar panels. (Cotfas, Cotfas and Kaplanis, 2013). In general, there are different methods for estimating these parameters, and they are mostly known as parameterization methods. These methods can be broken down into two groups: numerical methods that require a powerful mathematical tools and iterative methods to solve the implicit non-linear equation associated with the photovoltaic device and analytical methods that introduce a series of simplifications and approximations and lead to a simpler solution without introducing significant errors into the model (Blas, et al., 2002).

2. PARAMETERIZATION METHODS

Most of the methods used in determining the parameters of the solar cells use the current–voltage (I–V) characteristic (Keogh, et al., 2004), which is shown in Fig. 2. The short circuit current (I_{sc}) is the max current that the PV device can provide, similarly the open circuit voltage (V_{oc}) is the max voltage that a PV device can supply. Moreover the maximum power current (I_m) and the maximum power voltage (V_m), are the current and the voltage at maximum power point (P_m) of the I-V curve for specific conditions of temperature and solar radiation.

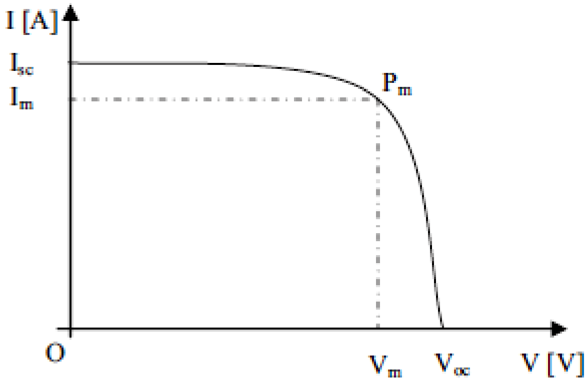


Figure 2. The I–V characteristic for solar cell

The measurement of the I–V characteristic of the solar cells can be done in the laboratory or in natural sunlight conditions. In the former case, the measurements can be performed under dark or illuminated conditions, in the latter case, solar simulators being used (Stutenbaeumer e Mesfin, 1999). Also, the manufacturer usually provides this data.

2.1 Analytical methods

Recently Blas, et al. (2002) calculates the value of the intrinsic parameters of solar cell by defining the initial values of the series and parallel resistances from the IV characteristic curve as shows Eq. (1).

$$R_{so} = -\frac{dV}{dI(V_{oc})}$$
$$R_{sho} = -\frac{dV}{dI(I_{sc})} \qquad (1)$$

The other parameters R_s, R_{sh} and n are obtained using the following equations:

$$R_s = \frac{R_{so}\cdot\left(\frac{V_{oc}}{n\cdot Vth}-1\right)+R_{sho}\left(1-\frac{I_{sc}\cdot R_{so}}{n\cdot Vth}\right)}{\frac{V_{oc}-I_{sc}\cdot R_{sho}}{n\cdot Vth}} \qquad (2)$$

$$R_{sh} = R_{sho} - R_s \qquad (3)$$

$$n = \frac{V_{mp}+I_{mp}\cdot R_s - V_{oc}}{Vth*\ln\left[\frac{I_{sc}-I_{mp}\cdot\left(1+R_s/R_{sh}\right)-V_{mp}/R_{sh}}{I_{sc}*\left(1+R_s/R_{sh}\right)-V_{oc}/R_{sh}}\right]} \qquad (4)$$

As seen, the solution of the equation system must be performed iteratively, once one parameter depends on the other.

Xiao, et al. (2004) developed a simple method to extract the parameters of the solar cell. Firstly, they considered the value of the parallel resistance very high ($R_{sh} \rightarrow \infty$) and the series resistance is calculated as follow:

$$R_s = \frac{n \cdot Vth \cdot \ln\left[\left(1 - \frac{I_{mp}}{I_{sc}}\right) \cdot \exp\left(\frac{V_{oc}}{n \cdot Vth}\right) + \frac{I_{mp}}{I_{sc}}\right] - V_{mp}}{I_{mp}} \quad (5)$$

An iterative process is used to calculate the diode ideality factor, where the convergence criterion is given by the derivative of the current with respect to voltage evaluated at maximum power point, according to Eq. 3.

$$\left.\frac{dI}{dV}\right|_{P_{mp}} = \frac{\frac{-I_0}{n \cdot Vth} \cdot \exp\left(\frac{V_{mp} + I_{mp} \cdot R_s}{n \cdot Vth}\right)}{1 + \frac{I_0 \cdot R_s}{n \cdot Vth} * \exp\left(\frac{V_{mp} + I_{mp} \cdot R_s}{n \cdot Vth}\right)} \quad (6)$$

The algorithm implemented in this parameterization method is shown in Fig. 3.

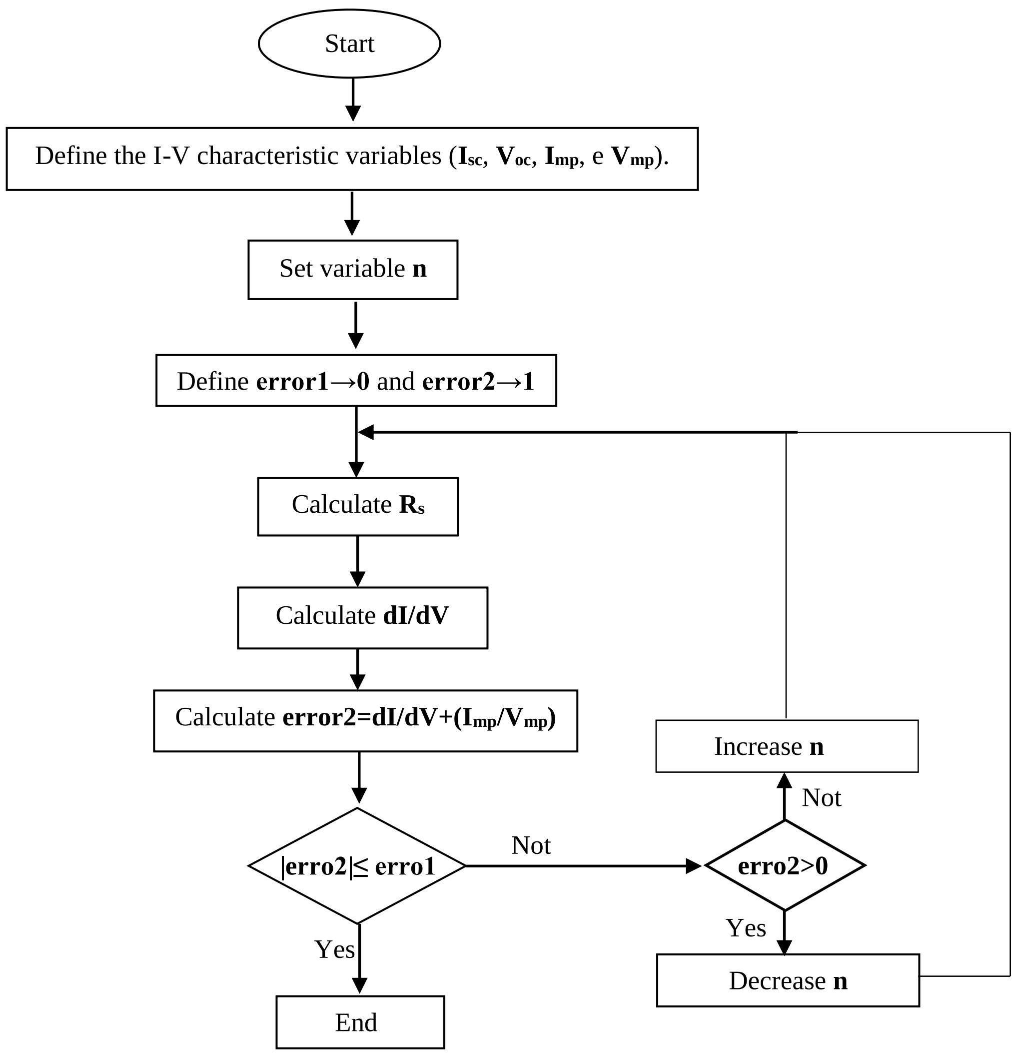


Figure 3. Flow chart for estimating solar cell parameters

Vera (2004) used a different method for the derivation of all solar cell parameters. The diode ideality factor is calculated using an empirical expression, as follows:

$$n = 2.8 - 2.3\left(\frac{I_{mp} \cdot V_{mp}}{I_{sc} \cdot V_{oc}}\right) \tag{7}$$

According to Eq. (8) the series resistance is defined as a function of current and voltage at maximum power point. This expression can be solved by Newton-Raphson method. Finally, the value of parallel resistance is given by Eq. (9) and depends on the series resistance and others parameters.

$$R_s = \left[\frac{\left(\frac{V_{mp}}{I_{mp}}\right) - R_s}{I_{mp} + \frac{I_0 \cdot I_{mp} \cdot R_s}{Vth} \cdot \exp\left(\frac{V_{mp} + I_{mp} \cdot R_s}{Vth}\right)}\right] \cdot \left\{I_{sc} - I_{mp} - I_0\left[\exp\left(\frac{V_{mp} + I_{mp} \cdot R_s}{Vth}\right) - 1\right]\right\} - \frac{V_{mp}}{I_{mp}} \tag{8}$$

$$R_{sh} = \frac{V_{mp} - I_{mp} \cdot R_s}{\frac{I_0}{Vth}\left[\left(I_{mp} \cdot R_s - V_{mp}\right) \cdot \exp\left(\frac{V_{mp} + I_{mp} \cdot R_s}{Vth}\right)\right] + I_{mp}} \tag{9}$$

2.2 Generalized Reduced Gradient (GRG) algorithm

The idea of generalized reduced gradient is to convert the constrained problem into an unconstrained one by using direct substitution. If direct substitution were possible it would reduce the number of independent variables to (*n-m*) and eliminate the constraint equations. However, with nonlinear constraint equations, it is not feasible to solve the m constraint equations *m* of the independent variables in terms of the remaining (*n-m*) variables and then to substitute to these equations into the economic model. Therefore, the procedures of constrained variation and Lagrange multipliers in the classical theory of maxima and minima are required. There, the economic model and constraint equations were expanded in a Taylor series, and only the first order terms were retained. Then with these linear equations, the constraint equations could be used to reduce the number of independent variables. This led to the Jacobian determinants of the method of constrained variation and the definition of the Lagrange multiplier being a ratio of partial derivatives.

3. PROPOSED CASE STUDIES

To evaluate the different methods for estimating solar cell parameters earlier presented four case studies were proposed. The first one uses the datasheet of a commercial monocrystalline PV module. The next two case studies took experimental data from bibliography related with multijunction solar cells for different temperature and solar radiation conditions. The last case study analyzes the data of a commercial multijunction solar cell (MPRI 2014).

3.1 Monojunction Devices

Table 1 shows the data (under STC[1]) of the PV module Kyocera KC85T used in this work. The parameterization methods were implemented also for the other temperature and solar radiation conditions specified in datasheet.

Table 1. Electrical Characteristics of Kyocera KC85T module

Parameter	Value
Maximum Power (W)	87
Maximum power voltage (V)	17,4
Maximum power current (A)	5,02
Open circuit voltage (V)	21,7
Short circuit current (A)	5,34
Temperature Coefficient of Isc (A/°C)	$2{,}12\text{x}10^{-3}$
Temperature Coefficient of Voc (V/°C)	$-8{,}21\text{x}10^{-2}$

[1] Standard Test Condition (1000W/m^2 and 25 °C)

3.2 Multijunction Devices

In recent work (Ota, et al, 2010) (Segev, et al., 2012), the performance of multijunction solar cell (In0.49Ga0.51P/In0.01Ga0.99As/Ge) was studied, taking consideration an individual approach for each sub-cell. The most important results of that study are tabulate in Tab. 2.

Table 2. Electrical properties of multijunction solar cell (In0.49Ga0.51P/In0.01Ga0.99As/Ge) at 25°C.

Solar concentration factor	1X			350X		
Parameter	InGaP	InGaAs	Ge	InGaP	InGaAs	Ge
I_{ph} (A)	6,7522x10^{-3}	7,7126x10^{-3}	10,094x10^{-3}	4,292	4,792	6,101
I_0 (A)	3,30x10^{-15}	6,00x10^{-11}	3,00x10^{-5}	1,101x10^{-13}	2,813x10^{-13}	8,543x10^{-7}
n	1,97	1,75	1,96	1,993	1,278	1,421
R_s (Ω)	0,0236	0,0012	0,0008	7,195x10^{-3}	3,352x10^{-3}	2,492x10^{-4}
R_{sh} (Ω)	16,0x10^{6}	4,5x10^{6}	540	587	389	100

Font: Segev, et al. (2012) and Ota, et al. (2010)

Table 3 (Ben Or and Appelbaum 2014) shows the data used in third case study. The multijunction cell is considered at sixteen different operating conditions, with four temperature conditions (10 °C, 25 °C, 80 °C and 90 °C) and four concentrations condition (350X, 555X, and 900X 750X).

Table 3. Electrical properties of multijunction solar cell under different conditions of temperature and concentration

Parameter	X\T(°C)	10	25	80	95
I_{ph} (A)	350	4,2984	4,3357	4,4848	4,5035
	555	6,8159	6,8531	7,0956	7,1702
	700	8,4942	8,5501	8,8671	8,9604
	900	10,956	10,993	11,422	11,534
I_0 (A)	350	4,593810^{-20}	4,3281x10^{-19}	6,2299x10^{-16}	2,5774x10^{-15}
	555	1,2252x10^{-19}	7,3238x10^{-19}	9,6539x10^{-16}	4,9272x10^{-15}
	700	2,5577X10^{-19}	1,3766X10^{-18}	1,4445X10^{-15}	7,3726X10^{-15}
	900	4,8072X10^{-19}	2,7747X10^{-18}	2,6692X10^{-15}	1,4862X10^{-14}
n	350	2,8863	2,7947	2,6157	2,5705
	555	2,9408	2,8516	2,6515	2,611
	700	3,0025	2,9009	2,7114	2,6527
	900	3,0412	2,9508	2,7507	2,7214
R_s (Ω)	350	0,01350	0,01597	0,02301	0,02702
	555	0,01131	0,01330	0,01701	0,01823
	700	0,00961	0,01078	0,01442	0,01511
	900	0,00810	0,00869	0,01093	0,01211
R_{sh} (Ω)	350	549,45	449,51	41456	343,02
	555	404,73	361,04	316,26	261,100
	700	327,18	262,2	202,67	169,36
	900	185,74	168,26	149,756	122,94

Font: Ben Or and Appelbaum (2014)

Finally, the data sheet of a commercial multijunction cell 3C44C of AzurSpace Company was used whose basic characteristics were illustrated in Tab. 4.

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Table 4. Electrical characteristics of AzurSpace multijunction solar cell (3C44C) at 25 °C

Parameter \ X	250	500	1000
V_{oc} (V)	3,06	3,10	3,13
I_{sc} (A)	1,15	2,3	4,60
V_{mp} (V)	2,81	2,83	2,8
I_{mp} (A)	1,13	2,25	4,48
P_{mp} (W)	3,17	6,37	12,55
FF	0,901	0,893	0,872
η (%)	41,5	41,7	41,1

4. RESULTS

Figure 4 shows the I-V characteristic obtained from the implementation of the different parameterization methods on monocrystalline PV module.

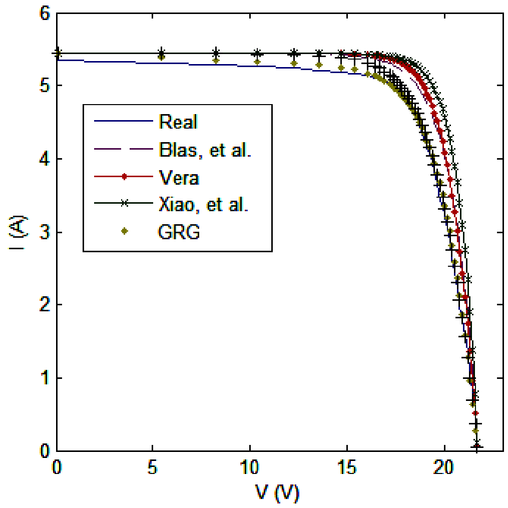


Figure 4. I-V Characteristic curve of monocrystalline PV module at 25 °C and 1000W/m^2.

It is clearly visible in Fig. 1 that all the parameterization methods exhibit some errors along the I-V curve. The error at the inflection point of the I-V curve (maximum power point) has been quantified in Fig. 5 for different temperature and solar radiation conditions.

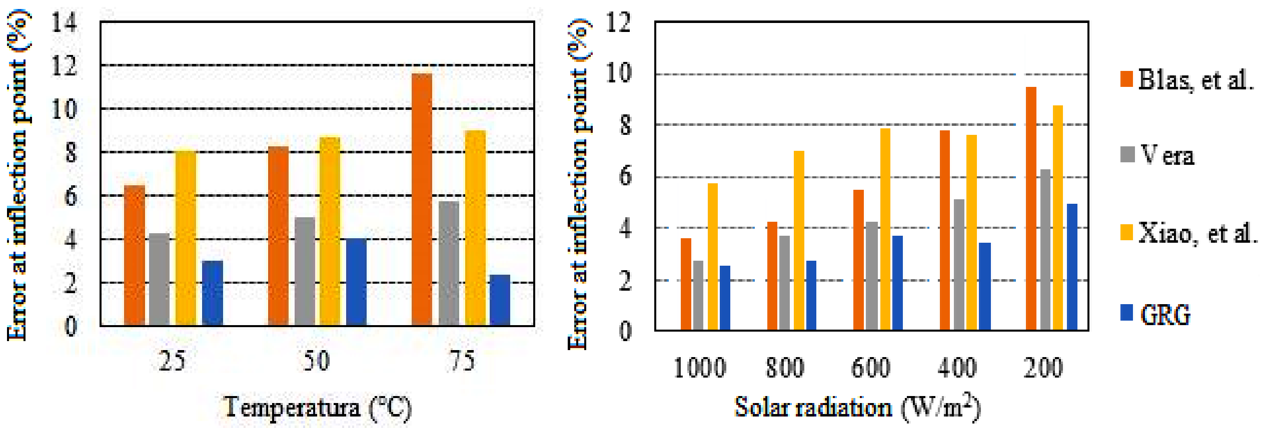


Figure.5 Parameterization methods error for monocrystalline PV module.

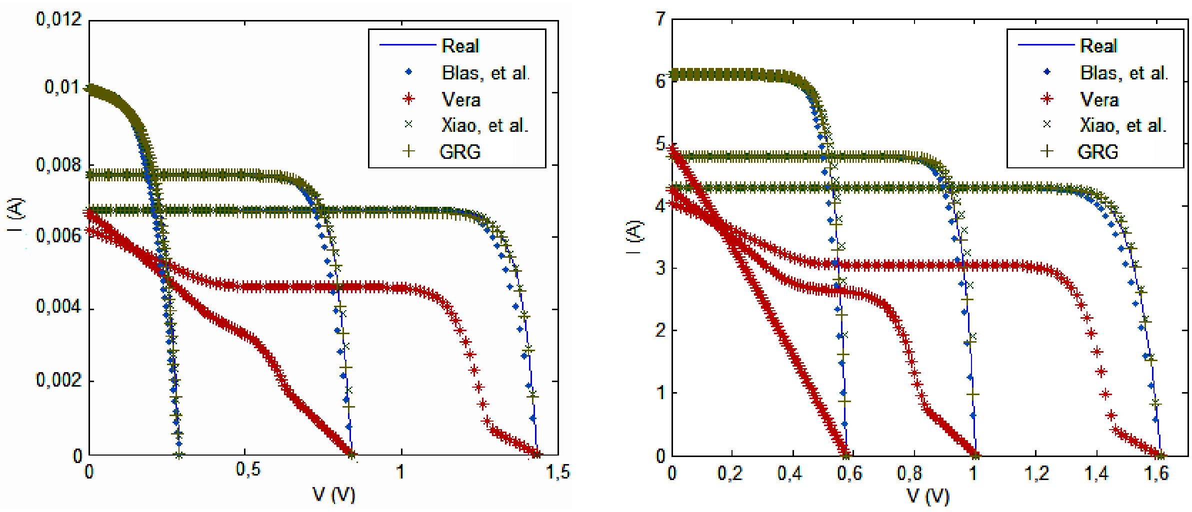
Similar to it was made with monocrystalline module, Fig. 6 shows the I-V characteristic obtained from the different parameterization methods under the defined two solar concentrations.

It is seen from Fig. 6 that only the method of (Vera) was excluded from the expected results. For this reason, Vera's parameterization method was isolated from the subsequent analysis. Table 5 shows the maximum error of the others methods at the specified solar concentration condition.

Table 5. Maximum error of parameterization methods for a multijunction solar cell at 25 °C.

Concentration	1X			350X		
Parameterization Method	GaInAs	GaInP	Ge	GaInAs	GaInP	Ge
Blass et al.	42,6%	41,4%	44,9%	38,1%	35,7%	41,7%
Xiao et al.	0,19%	0,15%	0,34%	0,12%	0,14%	0,21%
GRG	0,01%	0,01%	16,8%	0,06%	0,08%	0,03%

From Tab. 5, it can be observed that just two of the methods presented an error less than 10% (Xiao et al. and GRG) in almost all the conditions. Hence, for the next case studies, only these aforementioned methods have been considered.

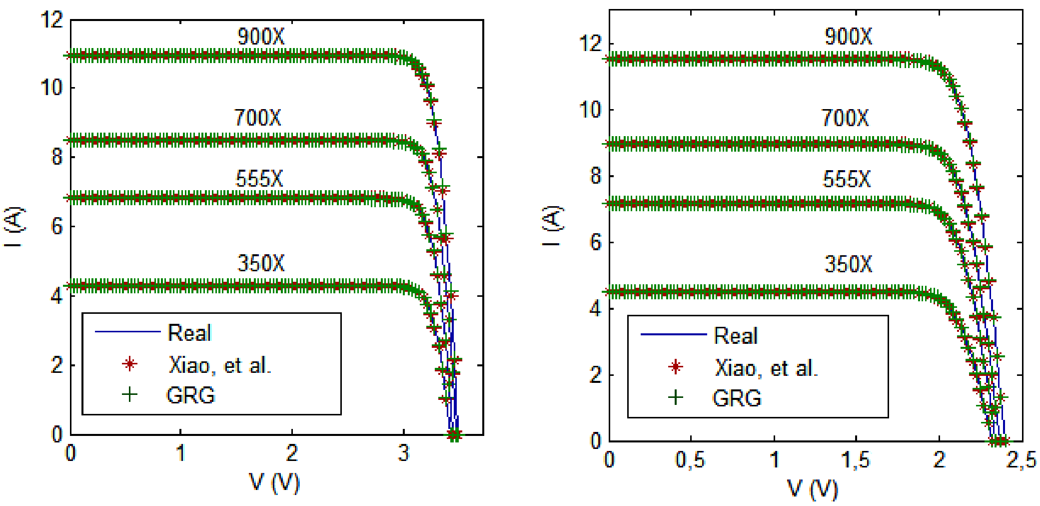


a) 1X b) 350X

Figure 6. I-V Characteristic curve of multijunction solar cell at 25 °C.

For the third case study, Fig 7 shows the I-V characteristic for the most critical temperature conditions under 350X, 555X, 700X and 900X of solar concentration, obtained from the application of Xiao et al. and GRG parameterization methods.

The maximum error found for Xiao et al. and GRG methods, was 2,81% (at 10 °C and 350X) and 1,22% (at 10 °C and 555X) respectively.



a) 10 °C b) 95°C

Figure7. I-V Characteristic curve of multijunction solar cell at 25 °C.

Finally, Fig. 8 shows the I-V characteristic obtained from the implementation of Xiao et al. and GRG parameterization methods on the commercial multijuction solar cell aunder various solar concentration conditions at 25 °C.

Since all the I-V curve points weren't available for comparison, the error of the parameterization methods was calculated just in the operational points of the curve. This data are summarized in Tab. 7.

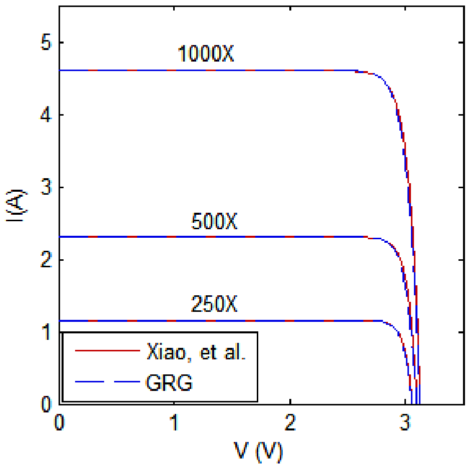


Figure 8. Characteristics of multijunction solar cell at 25 °C.

Table 6. Error of parameterization methods at operational characteristics of a multijunction solar cell.

Parameter	X	Xiao, et al. (error %)	GRG (error %)
V_m (V)	250	0,4421	0.3559
	500	0,3534	0
	1000	0,5880	0.3571
I_m (A)	250	0,3965	0.3399
	500	0,3394	0.0050
	1000	0,5372	0.3586
P_m (W)	250	0,2111	0.1820
	500	0,0265	0.0443
	1000	0,0002	0.0505
FF	250	0,1916	0.1624
	500	0,0192	0.0014
	1000	0,0404	0.0908
Mean (%)		0,2621	0,1623

5. CONCLUSIONS

The results obtained with the application of analytical methods for monocrystalline PV module, presented results below expectations, and since for some conditions of temperature or radiation the error obtained from these methods were higher than 10%. However, the analytical method that had the lowest error for most working conditions was the method implemented by VERA (2004).

Among the analytical parameterization methods that were tested in this work, the only one with satisfactory results for multijunction devices was the method proposed by Xiao, et al. (2004). Ironically, the method that had the lowest error for the monocrystalline PV module, presented an inadequate performance for multijunction cells.

Although the parameterization method proposed by Xiao was not designed for multijunction solar cells, and even this is based on a simplified model, it was obtained a satisfactory performance from this method. The maximum error was less than 3% at all the case studies for multijunction devices. This performance is satisfactory a lot, in terms of cost-benefit.

In almost all the cases studies, the better results were obtained from GRG algorithm. However, the error at one of the imposed conditions was higher than the acceptable. This fact can indicate a convergence problem in the algorithm or in the execution way.

6. ACKNOWLEDGEMENTS

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