Simple accurate non Iterrative Method determination of Serie Resistances of Solar Cells

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Abstract— **The principal aim of this paper is to provide a simple but accurate non iterative method which can be used instead of iterative methods. The protocol of extracting physical parameters affecting the Fill Factor of a solar cell should be valid for any kind of solar cells and any fabrication flow chart process. The protocol has been subdivided into two main steps. The first step was to find a method which can extract approximated parameters values. The proposed method in this paper is focusing on the first and second derivative of the Current – Voltage curves obtained by a Solar Simulator. It was necessary for this principal step to have a reference method. This reference method is the Numerical Lambert Function. It was also necessary for this step to test the method on samples for which the physical known parameters have been extracted before using the reference extracting method. The new proposed method showed clearly the extreme difference between the reference samples, which represented for us a kind of validity guarantee. The Second step which is of non-less importance was to derive factors permitting to calculate exact parameters values which should be as closer as possible to the values extracted previously by iterative methods.**

Keywords- Derivative Functions; Current Factor; Resistance Factor; Reference Method.

I. INTRODUCTION

Photovoltaic Energy is one of the strategic choices that Scientific communities, Industrial and Political spheres are focusing - on to oppose the effect of climate changes. For the Scientific communities, the need of characterization of processes is a primordial priority to correct processes and improve the ratio of production cost to efficiency. One of the characterization steps during fabrication of solar cells is to know exactly the predominant physical parameter that can affect the efficiency of a solar cell. The Aim of this paper is to find a simple, accurate and non-iterative method to free scientific community from the hard iterative methods.

In the first section we exposed briefly some analytical and also experimental methods and pointed out succinctly the weakness of each one.

The second section is subdivided into two steps, the first one exposing the main core of the innovation and the secured steps chosen to ensure having a reference method with reference results, and reference working samples. The second part of this section is consecrated to the derived factors that permit easy extraction of the physical parameters. The Third section is consecrated to comparison between the present proposed method and an experimental method.

II. ANALYTICAL METHODS

Historically, in 1982, M. A Green was one of the first authors who threated the effect of the parasitic resistances and ideality factor on the Fill – Factor [1, 2]. The author derived a new reference Resistance R_{CH} which is the Ratio of Voc to Isc.

$$R_{CH} = \frac{V_{OC}}{Isc} \tag{1}$$

Where Voc is the open circuit voltage and Isc is the short circuit current. The author derived an abacus of the Fill - Factor from the proposed formulas which depending on three ratios:

$$FF = FF\left(r_S, r_p, v_{OC}\right) \tag{2}$$

Where rs, r_p, v_{oc} are the reduced parameters, equal respectively to:

$$r_S = \frac{R_S}{R_{CH}} \tag{3}$$

$$r_p = \frac{R_p}{R_{CH}} \tag{4}$$

$$v_{OC} = \frac{V_{OC}}{n * V_{th}} \tag{5}$$

Later, T. Markvart, L. Castaner and al derived a quite similar formula of the Fill Factor [3]. Early from 1982, some authors tried to extract by numerical methods, the complete set of physical parameters of a solar cell in accordance to the one diode model. One of the still successful methods is the converging iterative method used by J. P. Charles and al [4].

Several analytical methods have been proposed but all of them showed the limited application for just a specified type of solar cells or specified type of fabrication processes. In worse encountered cases, tested analytical methods can be applied just for a given cell.

One of the older analytical methods was proposed by J.C.H. Phang and al [5]. This one is based on simple approximations, and showed in some cases good accuracy even when compared to Fitting techniques based on the reduction of standard deviation. The method proposed by Kishore and al is slightly less accurate [6], and the one proposed by Ikegami and al is the worst method [7]. Due to the weakness of most iterative methods and the problem of initial guesses when iterating, nothing was indicating that results given by iteration can serve as reference, as Ikegami taught.

Another more recent analytical method is proposed by H. Saleem and Shreepad Karmalkar in their two papers, and is based on the introducing of two factors extracted from points situated at 0.6 times Isc and 0.6 times Voc [8, 9]. It was sufficient for us to show after testing the method on just one sample for just one parameter, that the method exhibits some errors in the approximation assumptions. On our cells the test of voltage corresponding to maximum power, gave a relative error of 8.5% when compared to the value provided automatically by the I-V simulator.

Another more elegant analytical method proposed by A. Ortiz-Conde, F. J. G. Sanchez and J. Muci [10]. The method is based on the introduction of an Integration function called Co Content Function CC, and its elegance comes from that it's not based on any assumption.

$$CC\left(I,V\right)=\int_{0}^{V}(I-I_{SC})dV \quad (6)$$

After integration of the relation above from I – V curve, the obtained function is equalized to a quadratic polynomial, in the form:

$$CC\left(x,y\right)=(b*x)+(c*y)+\left[d*(x^2)\right]+\left[e*(y^2)\right]+\left[f*(x*y)\right] \quad (7)$$

where the variable x is the voltage and the second variable is the difference I minus Isc.

In some tested cases, the physical parameters can be extracted with polynomial functions; however some coefficients of the polynomial function should be positive, especially the third and fourth coefficients since they are respectively equal to:

$$d=\frac{1}{2*R_p} \quad (8)$$

$$e=\frac{R_S}{2}*\left[1+\left(\frac{R_S}{R_p}\right)\right] \quad (9)$$

Another problem related to the used Fitting tool is the presence of a residual coefficient ″ a ″. The ratio of this coefficient on the others in absolute value should be as small as possible. When the accuracy of Co Content Function tested on one reference sample, it gives greater Shunt Resistance value and lower Serie resistance than values obtained by Lambert Function in ratios of:

$$\frac{R_p(CCF)}{Rp(W_0)}\approx n^{3,476} \quad (10)$$

$$\frac{R_s(W_0)}{R_s(CCF)}\approx n^{7,352} \quad (11)$$

These results demonstrate the need of a new analytical method which can give at least a good evaluation.

III. NEW PROPOSED ANALYTICAL METHOD

The initial motivation that led us to work on this paper was the lack of accuracy when trying to extract series resistance values from an I-V curve. The first step was to find a reliable method that gives us reliable values with given reference I-V curves. We focused our choice on the Lambert – Function method which appears to give accurate extracted values [11, 12, 13, 14]. F. Ghani and M. Duck treated in their paper the same reference samples treated by J. P. Charles, J.C.H. Phang and Kishore, and obtained quit similar results to those obtained by Charles. It was necessary for us to rebuild the I-V curves for the blue and grey cells to be used as reference samples on which our proposed method is based. For that it was necessary to reduce the errors on Voc, Isc, Vmp, Imp, Rsh_0 and Rs_0. We use the notation $\mathbf{R_{p0}}$ and $\mathbf{R_{s0}}$ for Shunt and Series Resistances instead of $\mathbf{R_{sh0}}$ and $\mathbf{R_{s0}}$ symbols used by Charles. The obtained results from data reconstitution are summarized in the tables 1 and 2 below with relative errors:

TABLE I. DATA RECONSTITUTION FOR BLUE CELL

Parameters	Charles Data	Uncertainties given by Charles (%)	Fitted Data	Relative Error (%)
V_{oc} (V)	0.5360		0.533588	0.45
I_{sc} (A)	0.1023		0.101297	1
V_{mp}(V)	0.4370		0.434750	0.52
I_{mp} (A)	0.0925		0.093468	1.05
R_{p0} (Ω)	1000	3	970.273441	2.98
R_{s0} (Ω)	0.45	2.23	0.439127	2.42

TABLE II. DATA RECONSTITUTION FOR GREY CELL

Parameters	Charles Data	Uncertainties given by Charles (%)	Fitted Data	Relative Error (%)
V_{oc} (V)	0.524		0.524157	0.03
I_{sc} (A)	0.561		0.561966	0.2
V_{mp}(V)	0.39		0.387100	0.8
I_{mp} (A)	0.481		0.484734	0.8
R_{p0} (Ω)	25.9	3.1	25.802993	0.4
R_{s0} (Ω)	0.162	0.62	0.158775	2

It was possible for use to reduce the uncertainties on most of the parameters; however, since our method is based on the values of R_{p0} and R_{s0}, this was a constraint to reduce first the uncertainties on these two parameters. It should be pointed out that relative errors tend to decrease when compared to the values given by Duke. The main innovation of the proposed method is to use the first and second derivative of the I-V curves, since that the first derivative is giving the inverse of resistance versus voltage, and the second derivative is giving the inverse of the square of resistance. When dividing the first derivative on the second, this gives a resistance:

$$\frac{\left[\frac{\partial I(V)}{\partial V}\right]}{\left[\frac{\partial^2 I(V)}{\partial V^2}\right]} \equiv R(V) \qquad (12)$$

When deriving the I-V curves and making the ratio of the first on second derivative, we observed the presence of an absolute minima, a relative maxima and a relative minima as shown in the figures 1 and 2 below.

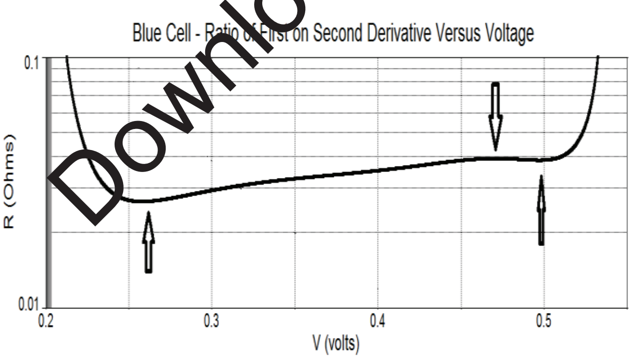

Figure 1. Region of local maxima and minima for Blue Cell.

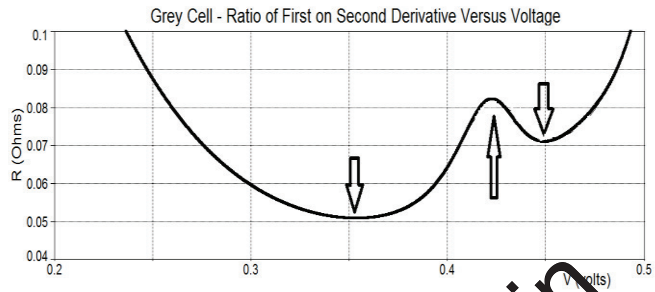

Figure 2. Region of local maxima and minima for Blue Cell.

A summarizing of the values of these resistances with corresponding voltages and currents is given in tables III and IV.

From these resistances, and their corresponding voltages and currents, we derived three main factors, resistance factor, current and voltage factor, equal respectively to:

$$F(R) = \frac{R_{\max} - R_{\min}}{R_{\max} - R_{med}} \qquad (13)$$

$$F(I) = \frac{I_{\max} - I_{\min}}{I_{\max} - I_{med}} \qquad (14)$$

$$F(V) = \frac{V_{\max} - V_{\min}}{V_{\max} - V_{med}} \qquad (15)$$

TABLE III. DERIVED RESISTANCES FOR BLUE CELL

Voltage (V)	Resistance (Ω)	Current (A)
0.25780	0.026867	0.101141
0.47090	0.039875	0.080662
0.49695	0.039265	0.060769

TABLE IV. DERIVED RESISTANCES FOR GREY CELL

Voltage (V)	Resistance (Ω)	Current (A)
0.353425	0.051054	0.516082
0.422475	0.082483	0.425676
0.449150	0.071231	0.358955

TABLE V. SERIES RESISTANCES GIVEN BY REFERENCE METHODS

	Blue Cell	Grey Cell
Rs (Charles & al)	0.07 ± 0.009	0.08 ± 0.01
Rs(Ghani & Duke)	0.0671	0.0784

where R_{max}, I_{max} and V_{max} in (13), (14) and (15) are the highest values in the tables III and IV, R_{min}, I_{min} and V_{min} are the smallest values, and R_{med} I_{med} and V_{med} are the medium values.

The first thing that we should emphasis on is the fact that all the derived resistances are in the right range of the series resistances extracted by Charles and Duke as summarized in Table V.

IV. PARAMETERS EXTRACTION

It was interesting for us to extract series resistances, shunt resistances and diode ideality factors for these two reference samples, but for this first step, we content just with the series resistances extraction. From the paragraph above, resistance and Current factors for both blue and grey cells are given in table IV.

In order to extract series resistances; we have to introduce a new resistance, equal to the equivalent resistance between R_{s0} and R (Vmp, Imp) noted R_{Vmp} for convenience. R_{Vmp} is the resistance at the maximum power point corresponding to V_{mp} and I_{mp}. This resistance can be calculated directly by dividing V_{mp} by I_{mp}, or by the value of first derivative from I- V curve at V_{mp}. The relative error between these two calculation methods are below 0.0126% for the Blue sample and below 0.042% for the Grey one.

$$R_{eq}\left(R_{Vmp}, R_{s0}\right) = \frac{R_{Vmp}.R_{s0}}{\left(R_{Vmp} + R_{s0}\right)} \qquad (16)$$

Finally the proposed formula for R_s calculation is:

$$R_s = \frac{R_{eq}}{\{\ln\left[F\left(R\right)\right]\} * F\left(I\right)} \qquad (17)$$

TABLE VI. DERIVED FACTORS FOR BLUE AND GREY CELLS

	Blue Cell	Grey Cell
F (R)	21.330445	2.793228
F (I)	1.971461	1.738022

TABLE VII. EXTRACTED R_S FOR BLUE AND GREY CELLS

	Blue Cell	Grey Cell
Rs (Ω)	0.06651	0.07481
ε (%)	0.88	4.58

Since our R_{Vmp} are similar to those given by Duke which are used as reference, no corrections have been made on these values; However for R_{s0}, we chose to take the arithmetic average between our values and the values given by Charles. Table VII summarizes the results obtained with relative errors compared to those given by Ghani and Duke.

For the determination of shunt resistances, we propose the simple formula:

$$R_p = R_{p0} * \left[1 - \left(\frac{R_{Vmp}}{R_{p0}}\right)\right] \qquad (18)$$

Since our procedure to reconstitute data is tainted with errors, we chose to take for the working values of R_{p0}, the average between our obtained values and values given by Charles.

In fact when reconstituting the data from the paper of Charles, we used a piece wise method, dividing the curves into two pieces, one with a good accuracy on R_{s0}, and the other with accuracy on R_{p0}, and at the last step we assembled the data with a lack in the middle of the curve. The final result of reconstitution procedure shows clearly the loss in accuracy especially for the Grey Cell due to the small value of shunt resistance, and the lower resistance factor.

Results for shunt resistances are summarized in table VIII below:

TABLE VIII. EXTRACTED R_P FOR BLUE AND GREY CELLS

	Blue Cell	Grey Cell
R_p (Ω)	980.485421	25.05356
ε (%)	0.357	3.862

V. DISCUSSION

When the Derivative method applied to an ARCO cell of 100 W/m^2, comparison to the shading technique proposed by S. Bowden and A. Rohatgi [15] gives values of Serie resistances in the range, but the relative difference was about 30%. It should be pointed out that spectra of resistance versus voltage for this tested cell showed stiffness inversion are show in figure 3.

For shading method, calculations were conducted between full I – V and 460 W/m^2. Ideal shadowing level recommended by Bowden can be estimated by the difference between I_{sc} and I_{mp} at 1000 W/m^2. In our case with a given I_{sc} of 2.979 Amperes and an I_{mp} of 2.636 Amperes, and when supposing a linear proportionality between ratios of light intensities and short circuit currents, the ideal shadowing level is estimated being around 340 W/m^2 The obtained results are summarized in tables IX and X.

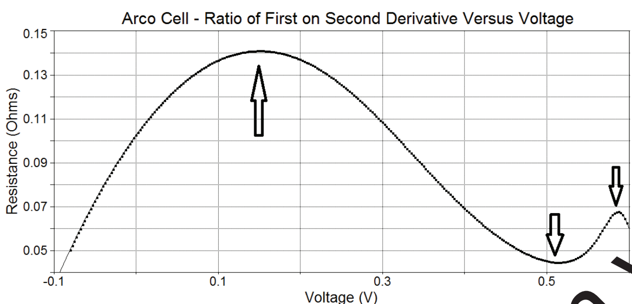

Figure 3. Region of local maxima and minima for ARCO Cell with inversed stiffness.

TABLE IX. DERIVED RESISTANCES FOR ARCO CELL

Voltage (V)	Resistance (Ω)	Current (A)
0.15	0.140910	2.966359
0.515	0.044615	2.352358
0.58625	0.067635	0.482769

TABLE X. PARAMETERS FOR FULL AND SHADED ARCO CELL

V_{oc} – Shaded (V)	0.57422
I_{sc} – Shaded (A)	1,368527
I_{sc} – Full (A)	2,978087
Va (I_{sc}(Full) - I_{sc}(Shaded)) (V)	0.555063

After deriving resistance and current factors, the resistance calculated by our proposed method is equal to 0.015476116 Ω.

As reminding, the formula used by Bowden is:

$$R_{s-Bowded-Rohatgy} = \frac{(V_{oc-shaded} - Va)}{(I_{sc-full} - I_{sc-shaded})} \qquad (19)$$

Calculated value by Bowden - Rohatgi method is equal to 0.011901943 Ω.

Due to lack of results calculated using the reference method, it's impossible to decide if the shading method is more accurate or not. Since decreasing light intensity leads values of Serie resistances to converge to the ones that can be extracted by dark I – V, we think that a standard of shading level should be established.

VI. CONCLUSION

A simple method of calculating Serie Resistances has been derived from just full I – V curves, based on ratios of first and second derivative, conducted both in same processing. When compared to the reference method with reference samples, this method was in accordance with the reference results. Simple empirical formula for extracting Shunt resistance is proposed also.

A reviewing of previous analytical methods was conducted with focusing on accuracy in comparison to the reference method.

Since the tested formulas for deriving diode ideality factor were not really satisfying, it was not possible to us to extend application of the method to non – reference samples. We wish that someone can complete this work following same philosophy.

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