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3

A New Model for Extracting the Physical Parameters from I-V Curves of Organic and Inorganic Solar Cells

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1. Introduction

As worldwide energy demand increases, conventional sources of energy, fossils fuels such as coal, petroleum and natural gas will be exhausted in the near future. Therefore, renewable resources will have to play a significant role in the world's future supply. Solar energy occupies one of the most important places among these various possible alternative energy sources. The direct photovoltaic conversion of sunlight into electricity seems to be extremely promising. Solar cells furnish the most important long-duration power supply for satellites and space vehicles. They have also been successfully employed in terrestrial application. A solar cell (also called photovoltaic cell or photoelectric cell) is a solid state device that converts the energy of sunlight directly into electricity by the photovoltaic effect. Assemblies of cells are used to make solar modules, also known as solar panels. The energy generated from these solar modules, referred to as solar power, is an example of solar energy. photovoltaic system uses various materials and technologies such as crystalline Silicon (c-Si), Cadmium telluride (CdTe), Gallium arsenide (GaAs), chalcopyrite films of Copper-Indium-Selenide (CuInSe2) and Organic materials are attractive because of their light eight, processability, and the ease of designing the materials on the molecular level.
Solar cells are usually assessed by measuring the current voltage characteristics of the device under standard condition of illumination and then extracting a set of parameters from the data. The major parameters are usually the diode saturation current, the series resistance, the ideality factor, the photocurrent and the shunt conduction. The extraction and interpretation has a variety of important application. These parameters can, for instance, be used for quality control during production or to provide insights into the operation of the devices, thereby leading to improvements in devices.

2. Equivalent circuit of solar cells

A solar cell is simply diode of large-area forward bias with a photovoltage. The photovoltage is created from the dissociation of electron-hole pairs created by incident photons within the built-in field of the junction or diode. The operating current of a solar cell is given by:

$$I = I_{ph} - I_d - I_p$$
$$= I_{ph} - I_s\left[\exp\left(\frac{\beta}{n}(V + IR_s)\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

Where, I_{ph}, I_s, n, R_s and G_{sh} (=1/R_{sh}) being the photocurrent, the diode saturation current, the diode quality factor, the series resistance and the shunt conductance, respectively. I_p is the shunt current and β=q/kT is the usual inverse thermal voltage. The shunt resistance is considered R_{sh}= (1/G_{sh})>>Rs.
The circuit model of solar cell corresponding to equation (1) is presented in figure (1).

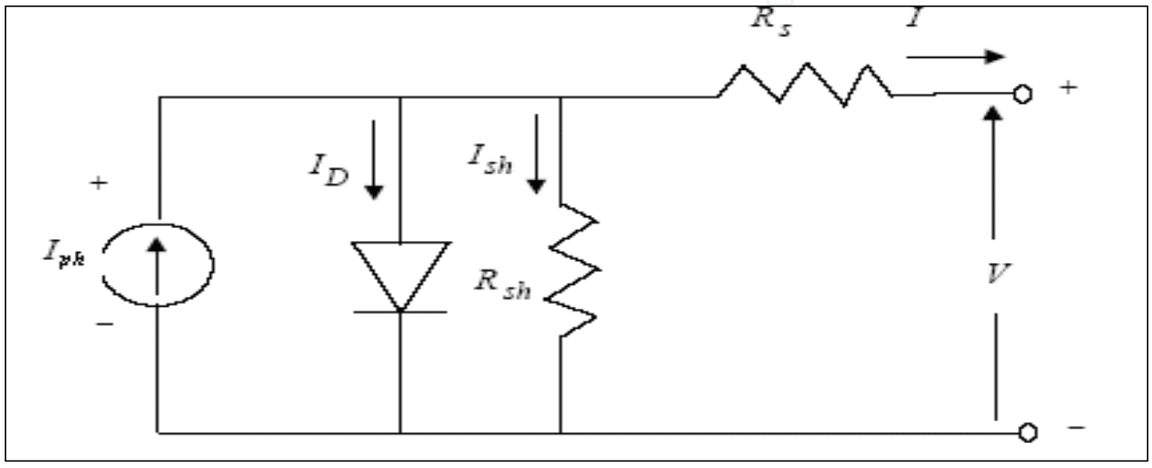


Fig. 1. Equivalent circuit model of the illuminated solar cell.

The single diode model considered here is rather simple, efficient and sufficiently accurate for process optimization and system design tasks. The single diode model can also be used to fit solar modules and arrays where the cells are series and/or parallel connected, provided that the cell to cell variations are not important.

3. Solar cell output parameters

The graph of current as a function of voltage I=f (V) for a solar cell passes through three significant points as illustrated in figure 2 below.

- The short circuit current, I_{sc}, occurs on a point of the curve where the voltage is zero. At this point, the power output of the solar cell is zero. The current in a device is almost directly proportional to light intensity and size.
- The open circuit voltage, V_{oc}, occurs on a point of the curve where the current is zero. At this point the power output of the solar cell is zero. The voltage of the cell does not depend on its size, and remains fairly constant with changing light intensity.
- The fill factor, FF, is the ration of the peak power to the product I_{sc} V_{oc}

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \quad (2)$$

The fill factor determines the shape of the solar cell I-V characteristics. Its value is higher than 0.7 for good cells. The series and shunt resistance account for a decrease in the fill factor. The fill factor is useful parameters for quality control test.

- The conversion efficiency, is the ration of the optimal electric power, P_m, delivered by the PV module to the solar insolation, P_0, received at a given cell temperature, T.

$$\eta = \frac{FF\, I_{sc} V_{oc}}{P_0} = \frac{P_m}{P_0} \tag{3}$$

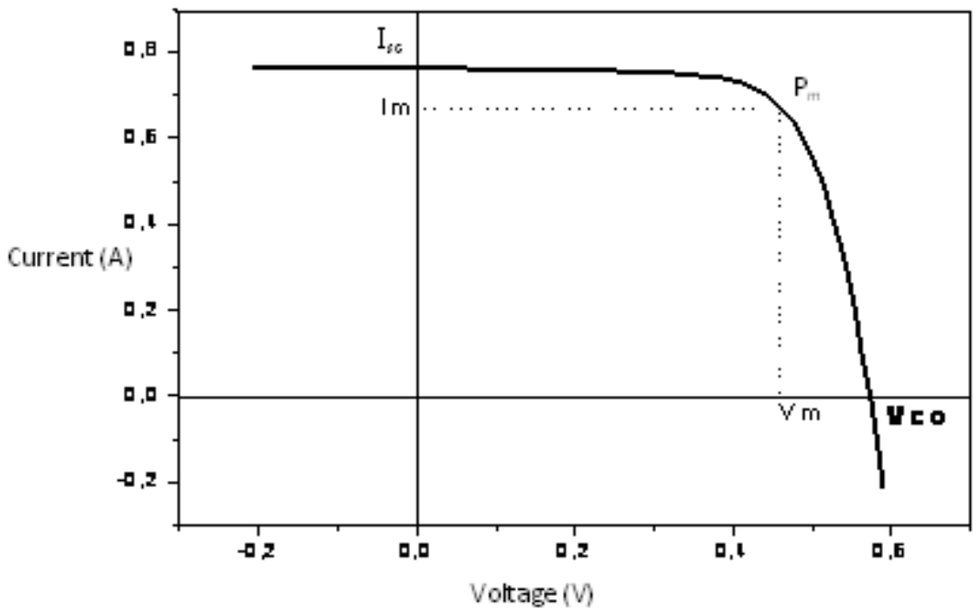


Fig. 2. Solar cell I-V Characteristics.

4. Solar cell parameters extraction

4.1 Previous works

An accurate knowledge of solar cell parameters from experimental data is of vital importance for the design of solar cells and for the estimates of their performance. The major parameters are usually the diode saturation current, the series resistance, the ideality factor, the photocurrent and the shunt conductance.

The evaluation of these parameters has been the subject of investigation of several authors. Some of the methods use selected parts of the current-voltage (I-V) characteristic (Charles et al, 1981; 1985) and those that exploit the whole characteristic (Easwarakhanthan et al, 1986; phang et al, 1986). (Santakrus et al, 2009) presents the use of properties of special trans function theory (STFT) for determining the ideality factor of real solar cell. (Priyank et al, 2007) method gives the value of series R_s and shunt resistance R_{sh} using illuminated I-V characteristics in third and fourth quadrants and the V_{oc}-I_{sc} characteristics of the cell. In the work of (Bashahu et al, 2007), up to 22 methods for the determination of solar cell ideality factor (n), have been presented, most of them use the single I-V data set. (Ortiz-Conde et al,

2006) have proposed an elegant method to extract the five parameters based on the calculation of the co-content function (CC) from the exact explicit analytical solution of the illuminated current–voltage characteristics, but this method has only been tested on a plastic solar cell. An accurate method using the Lambert W-function has been presented by (Jain and Kapoor, 2004, 2005) to study different parameters of organic solar cells, but it has been validated only on simulated I–V characteristics. A combination of lateral and vertical optimization was used (Haouari-Merbah et al, 2005; Ferhat-Hamida et al, 2002) to extract the parameters of an illuminated solar cell. (Zagrouba et al, 2010; Sellami et al, 2007) propose to perform a numerical technique based on genetic algorithms (GAs) to identify the five electrical parameters (I_{ph}, I_s, R_s, R_{sh} and n) of multicrystalline silicon photovoltaic (PV) solar cells and modules, but this technique is influenced by the choice of the initial values of population. A novel parameter extraction method for the one-diode solar cell model is proposed by (Wook et al, 2010) the method deduces the characteristic curve of an ideal solar cell without resistance using the I-V characteristic curve measured.

4.2 Proposed method of parameters extraction

The I-V characteristics of the solar cell can be presented by either a two diode model (Kaminsky et al, 1997) or by a single diode model (Sze et al, 1981). Under illumination and normal operating conditions, the single diode model is however the most popular model for solar cells (Datta et al, 1967). In this case, the current voltage (I-V) relation of an illuminated solar cell is given by Equation 1.

Equation 1 is implicit and cannot be solved analytically. The proper approach is to apply least squares techniques by taking into account the measured data over the entire experimental I-V curve and a suitable nonlinear algorithm in order to minimize the sum of the squared errors. In this section we propose a new technique that uses the measured current-voltage curve and its derivative (Chegaar et al, 2004; Nehaoua et al 2010). A non linear least squares optimization algorithm based on the Newton model is hence used to evaluate the solar cell parameters. The problem, we have, is to minimize the objective function S with respect to the set of parameters θ:

$$S(\theta) = \sum_{i=1}^{N} \left[\frac{G - G_i(V_i, I_i, \theta)}{G_i(V_i, I_i, \theta)} \right]^2 \tag{4}$$

Where Θ is the set of unknown parameters Θ= (I_s, n, R_s, G_{sh}) and I_i, V_i are the measured current, voltage and the computed conductance $G_i = dI_i / dV_i$ respectively at the i^{th} point among N measured data points. Note that the differential conductance is determined numerically for the whole I-V curve using a method based on the least squares principle and a convolution. The conductance G can be written as:

$$G = -\frac{\psi}{1 + R_s \psi} \tag{5}$$

Where ψ is given by:

$$\Psi = \frac{\beta}{n} \left\{ I_{ph} + I_p - I - G_{sh} \left(V + R_s I \right) \right\} + G_{sh} \tag{6}$$

The term between brackets is equal to $I_s \exp\left(\frac{\beta}{n}(V + IR_s)\right)$ and when replaced in equation 6, the conductance G will be independent of the photo-current I_{ph}. This equation can be written as:

$$\Psi = \frac{\beta}{n} I_s \exp\left(\frac{\beta}{n}(V + IR_s)\right) + G_{sh} \tag{7}$$

Consequently, by minimizing the sum of the squares of the conductance residuals instead of minimizing the sum of the squares of current residuals as in (Easwarakhanthan et al, 1986). Using this method, the number of parameters to be extracted is reduced from five Θ = (I_s, n, R_s, G_{sh}, I_{ph}) to only four parameters Θ= (I_s, n, R_s, G_{sh}). The fifth parameter, the photocurrent, can be easily deduced using Eq. (1) at V=0, which yield to the following equation (Chegaar et al, 2001, 2004; Nehaoua et al 2010):

$$I_{ph} = I_{sc}\left(1 + R_s G_{sh}\right) + I_p\left(\exp\frac{\beta I_{sc} R_s}{n} - 1\right) \tag{8}$$

Where I_{sc} is the short circuit current.
Newton's method can be used to obtain an approximation to the exact solution. Newton's method is given by:

$$\theta_i = \theta_{i-1} - \left[J(\theta)\right]^{-1} F(\theta) \tag{9}$$

Where J(Θ) is the Jacobian matrix which elements are defined by:

$$J = \frac{\partial F}{\partial \theta} \tag{10}$$

For minimizing the sum of the squares, it is necessary to solve the equations F(Θ)=0, where F(θ) is described by the equation:

$$F(\theta) = \frac{\partial S}{\partial \theta} \tag{11}$$

Although Newton's method converges only locally and may diverge under an improper choice of reasonably good starting values for the parameters, it remains attractive with the number of variables being limited (four in this case) and their partial derivatives easily. To illustrate the approach, we have first applied the method to a computer calculated curve reproducing the same solar cell characteristic used by Eswarakhantan et al. To test the effects of different initial values on the method, the known exact solutions were multiplied by the factors [0.5-1.7] respectively and after carrying out the calculations; the extracted solar cell parameters were almost identical to the theoretical ones. Also noticed is the obvious and expected fact that the CPU calculation time decreases quickly when the initial values used are closer to the exact solution. In order to test the quality of the fit to the experimental data, the percentage error is calculated as follows:

$$e_i = \left(I_i - I_{i,cal}\right)\left(100 / I_i\right) \tag{12}$$

Where $I_{i,cal}$ is the current calculated for each V_i, by solving the implicit Eq.(1) with the determined set of parameters (I_{ph}, n, R_s, G_{sh}, I_s). (I_i, V_i) are respectively the measured current and voltage at the ith point among N considered measured data points avoiding the measurements close to the open-circuit condition where the current is not well-defined (Chegaar M et al, 2006). Statistical analysis of the results has also been performed. The root mean square error (RMSE), the mean bias error (MBE) and the mean absolute error (MAE) are the fundamental measures of accuracy. Thus, RMSE, MBE and MAE are given by:

$$\begin{aligned} RMSE &= \left(\sum |e|_i^2 / N \right)^{1/2} \\ MBE &= \sum e_i / N \\ MAE &= \sum |e|_i / N \end{aligned} \tag{13}$$

N is the number of measurements data taken into account.

As test examples, the method has been successfully applied on solar cells under illumination and used to extract the parameters of interest using experimental I–V characteristics of different solar cells and under different temperatures. It has been successfully applied to the measured I–V data of inorganic solar cells. These devices are a 57 mm diameter commercial silicon solar cell at a temperature of 33°C and a solar module in which 36 polycrystalline silicon solar cells are connected in series at 45°C. It has also been successful when applied to an illuminated organic solar cell, where the currents are generally 1000 times smaller and have high series resistances compared to inorganic (silicon) solar cells. The results obtained are compared with previously published data related to the same devices and good agreement is reported. Comparisons are also made with experimental data for the different devices.

4.3 Results and discussion

The experimental current–voltage (I–V) data were taken from (Easwarakhantan et al, 1986) for the commercial silicon solar cell and module and from (Ortiz-Conde et al, 2006) for the organic solar cell. The extracted parameters obtained using the method proposed here for the silicon solar cell and modules are given in Table 1. Satisfactory agreement is obtained for most of the extracted parameters. Those of the organic solar cell are shown in Table 2. A comparison with different methods is also given, and good agreement is reported. Statistical indicators of accuracy for the method of this work are shown in Table 3.

The best fits are obtained for the silicon solar cell and module with a root mean square error less than 1% and 2% for the organic solar cell. In figures 3, 4 and 5, the solid squares are the experimental data for the different solar cell and the solid line is the fitted curve derived from Equation (1) with the parameters shown in Table 1 for the silicon solar cell and module and Table 2 for the organic solar cell.

Good agreement is observed, especially for the inorganic solar cells. It is therefore necessary to emphasize that the proposed method is not based on the I-V characteristics alone but also on the derivative of this curve, i.e. the conductance G. Indeed, it has been demonstrated that it is not sufficient to obtain a numerical agreement between measured and fitted I-V data to verify the validity of a theory, but also the conductance data have to be predicted to show the physical applicability of the used theory. The interesting points with the procedure described herein is the fact that it has been successfully applied to experimental I–V

characteristics of different types of solar cells from inorganic to organic solar cells with completely different physical characteristics and under different temperatures. In contrast to other methods that have already been developed for this purpose, the proposed method has no limitation condition on the voltage. Furthermore, the presented method, tested for the selected cases, is more reliable to obtain physically meaningful parameters and is straightforward and easy to use.

	Method (Easwarakhantan et al, 1986)	Method (Chegaar M et al ,2006)	Method of this work
Cell (33°C)			
G_{sh} (Ω^{-1})	0.0186	0.0094	0.0114
R_s (Ω)	0.0364	0.0376	0.0392
n	1.4837	1.4841	1.4425
I_s(μA)	0.3223	0.3374	0.2296
I_{ph}(A)	0.7608	0.7603	0.7606
Module (45°C)			
G_{sh} (Ω^{-1})	0.00182	0.00145	0.001445
R_s (Ω)	1.2057	1.1619	1.2373
n	48.450	50.99	47.35
I_s(μA)	3.2876	6.3986	2.4920
I_{ph}(A)	1.0318	1.030	1.0333

Table 1. Extracted parameters for commercial silicon solar cell and module.

	Co-content function (Ortiz, 2006)	Method (Chegaar et al,2006)	Method of this work
G_{sh} (mΩ^{-1})	5.07	5.07	4.88
R_s (Ω)	8.59	8.58	3.16
n	2.31	2.31	2.29
I_s(nAcm^{-2})	13.6	13.6	12.08
I_{ph}(mAcm^{-2})	7.94	7.94	7.66

Table 2. Extracted parameters for an organic solar cell.

	RMSE (%)	MBE (%)	MAE (%)
Solar cell (33°C)	0.442	-0.016	0.310
Module (45°C)	0.252	-0.008	0.204
Organic solar cell (27°C)	1.806	0.638	1.201

Table 3. Statistical indicators of accuracy for the method of this work.

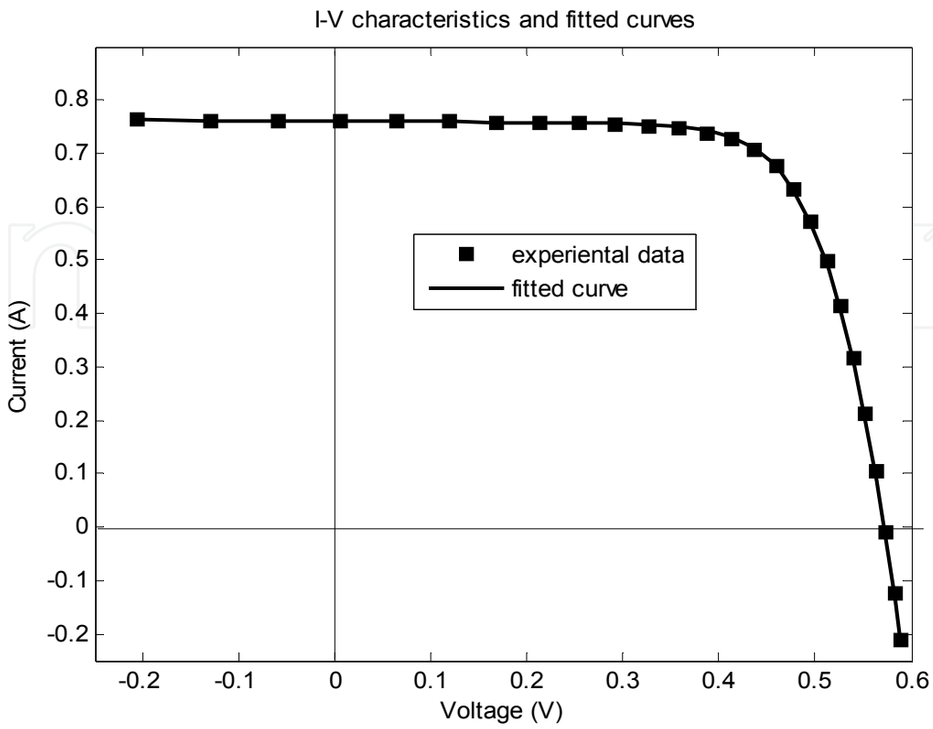


Fig. 3. Experimental data (■) and the fitted curve (-) for the commercial silicon solar cell.

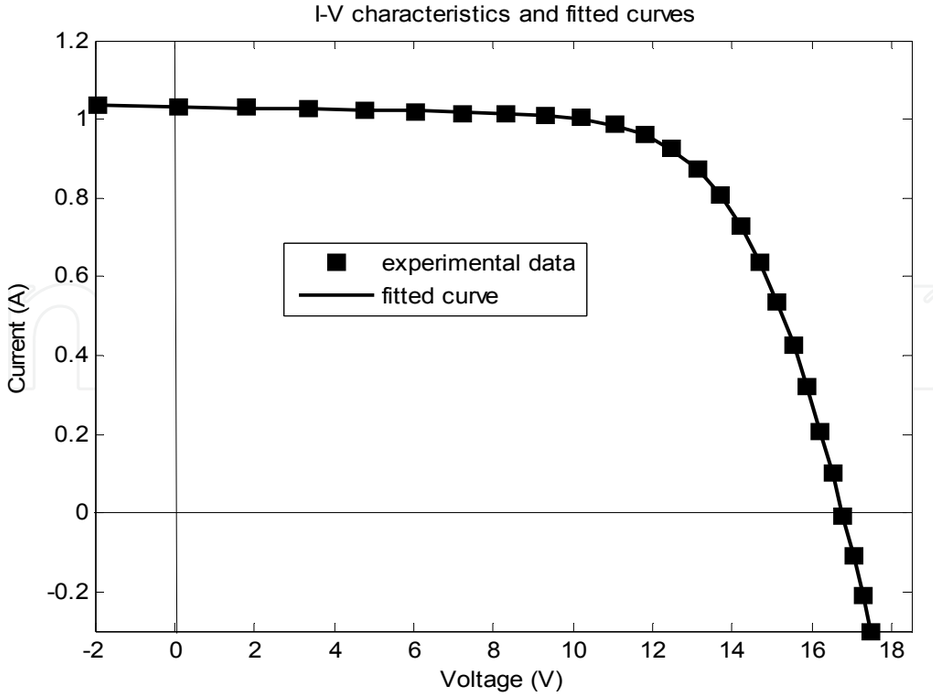


Fig. 4. Experimental data (■) and the fitted curve (-) for the commercial silicon solar module.

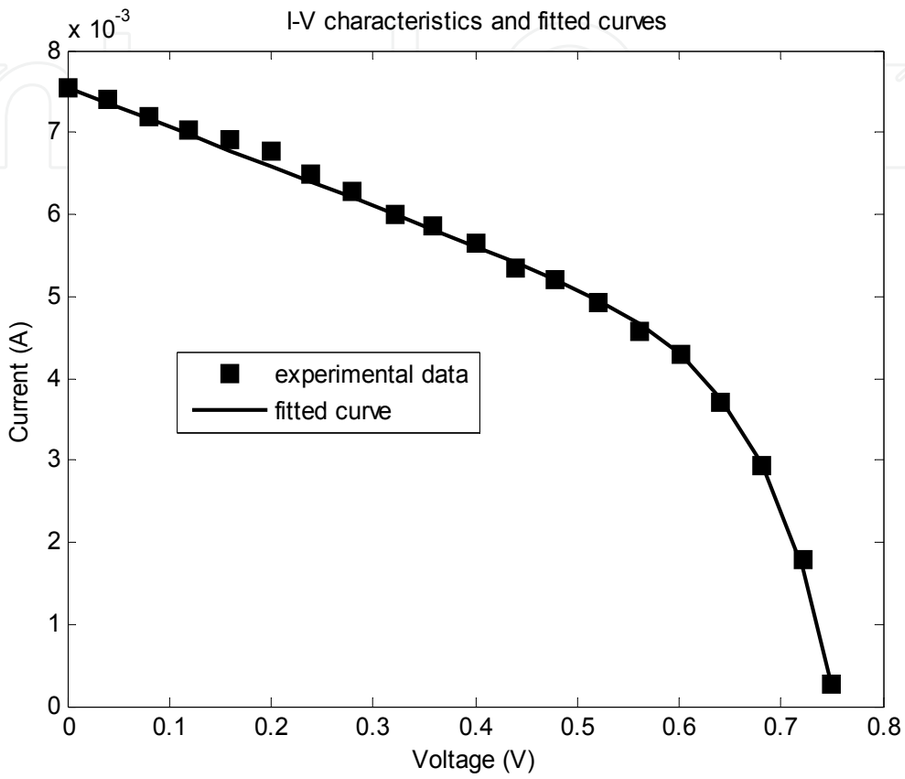


Fig. 5. Experimental data (■) and the fitted curve (-) for the organic solar cell.

4.4 Effects of parameters on the shape of the I-V curve

Figures 6-13 show the effect of the series resistance and shunt resistance on the current-voltage (I-V), power-voltage (P-V) characteristics and their effect on the fill factor (FF) and conversion efficiency (η). Change in the shape of the I-V curve due to changes in parameters values. First, as seen in fig.6, the shape of the I-V curve in the voltage source region is depressed horizontally with a gradual increase in the value of series resistance from zero, too, the power conversion decrease with a gradual increase in the value of series resistance. When shunt resistance decreases from infinity, the shape of the I-V curve in the current source region is depressed leftward as shown in fig.10, and the power conversion decrease too. Second, figure 8, 9, 12 and 13 show the effect of the series resistance and shunt resistance on the fill factor (FF) and conversion efficiency (η). Where the fill factor (FF) and conversion efficiency (η) values decrease when the values of series and shunt conductance ($G_{sh}=1/R_{sh}$) increase.

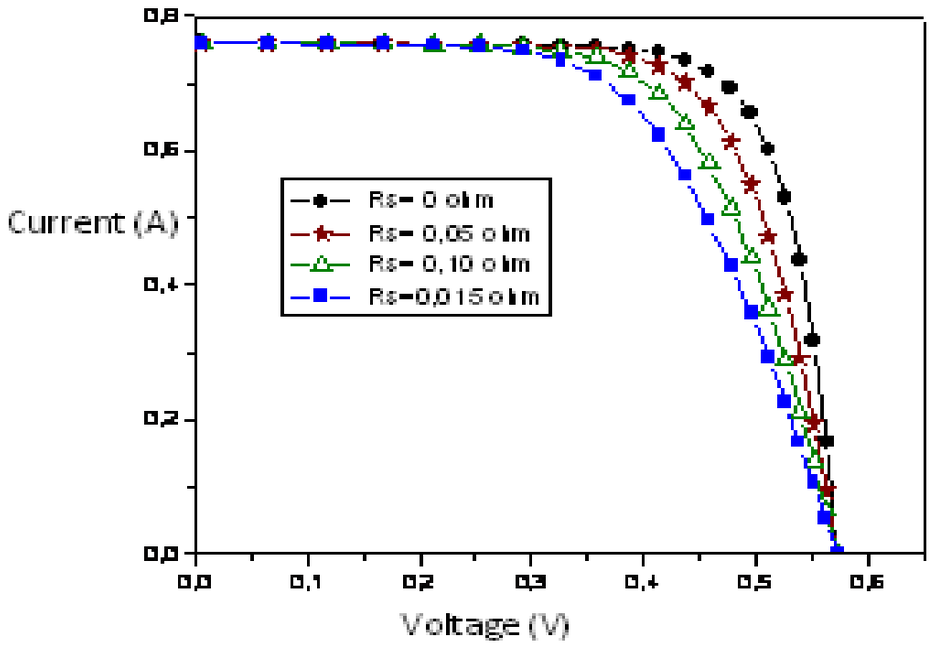


Fig. 6. Effect of series resistance on the I-V characteristics of an illumination solar cell.

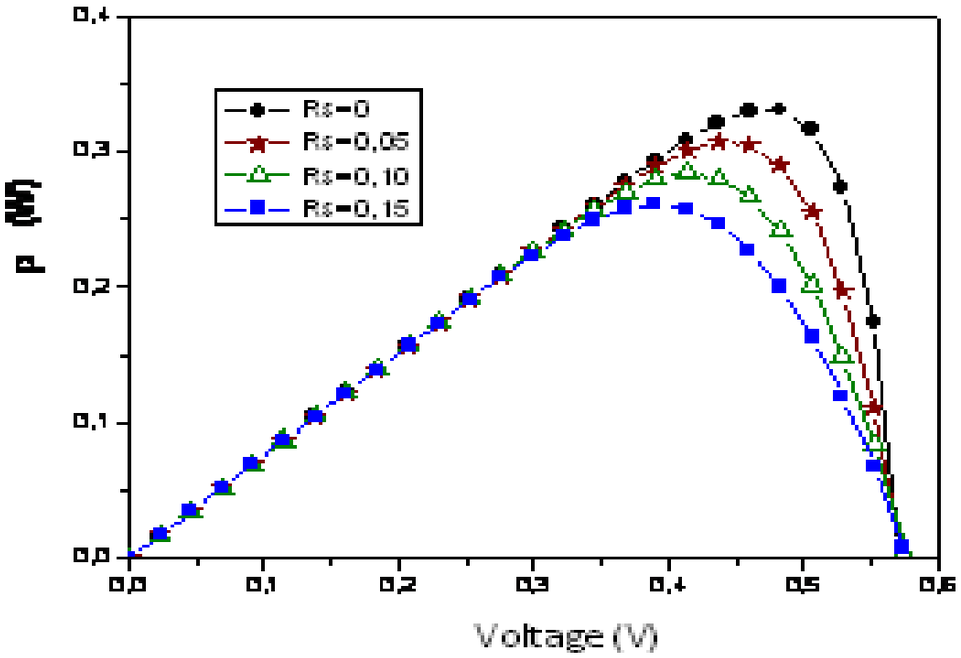


Fig. 7. Effect of series resistance on the P-V characteristics of an illumination solar cell.

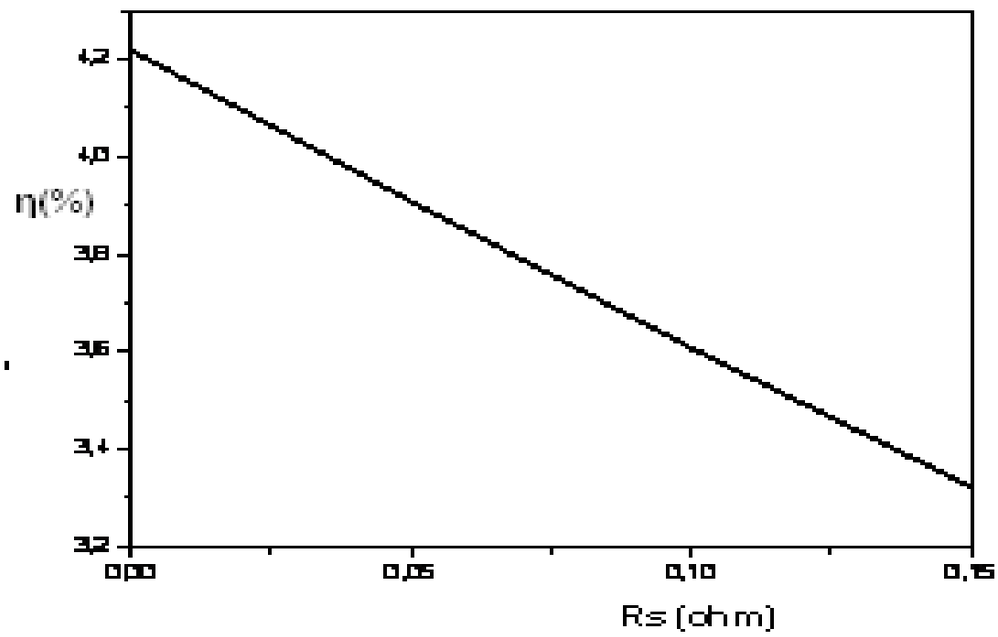


Fig. 8. Effect of series resistance on the η and FF.

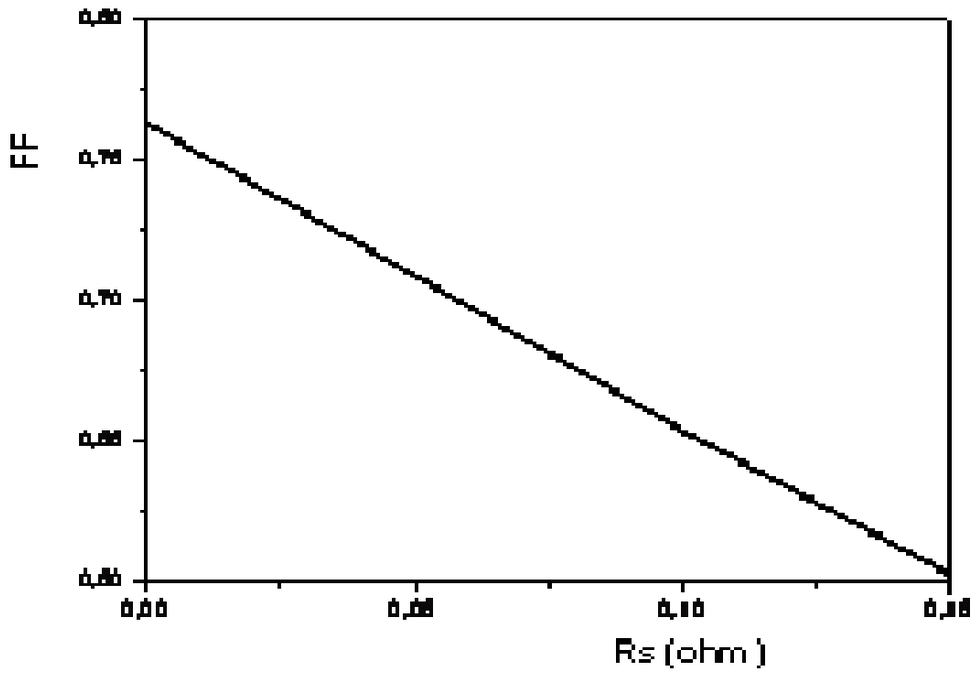


Fig. 9. Effect of series resistance on the η and FF.

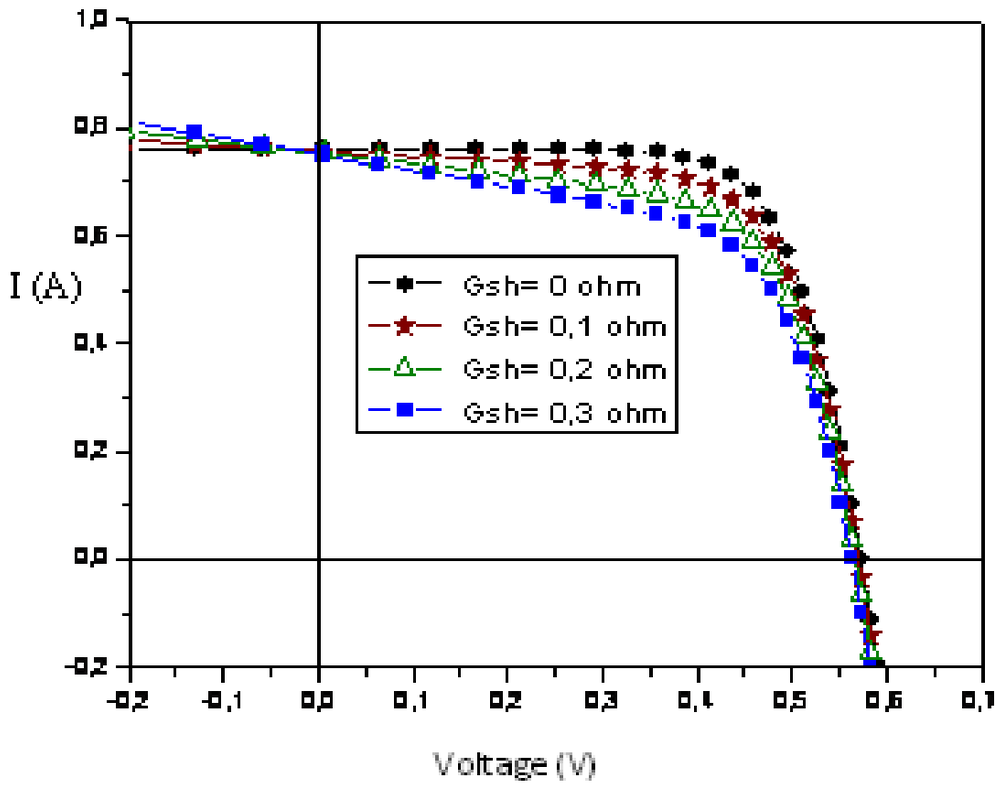


Fig. 10. Effect of shun resistance on the I-V characteristics of an illumination solar.

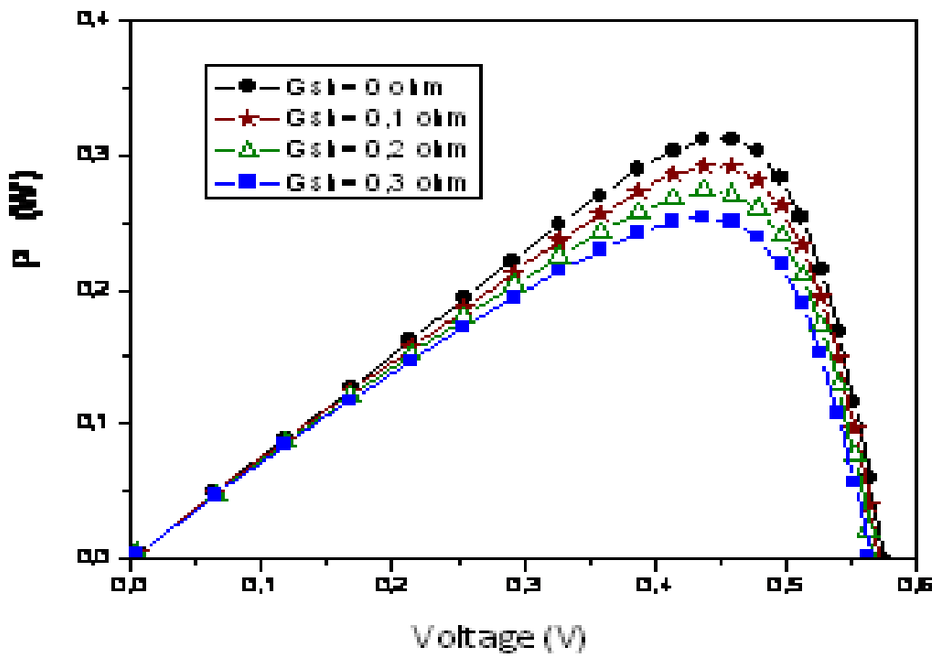


Fig. 11. Effect of shun resistance on the P-V characteristics of an illumination solar.

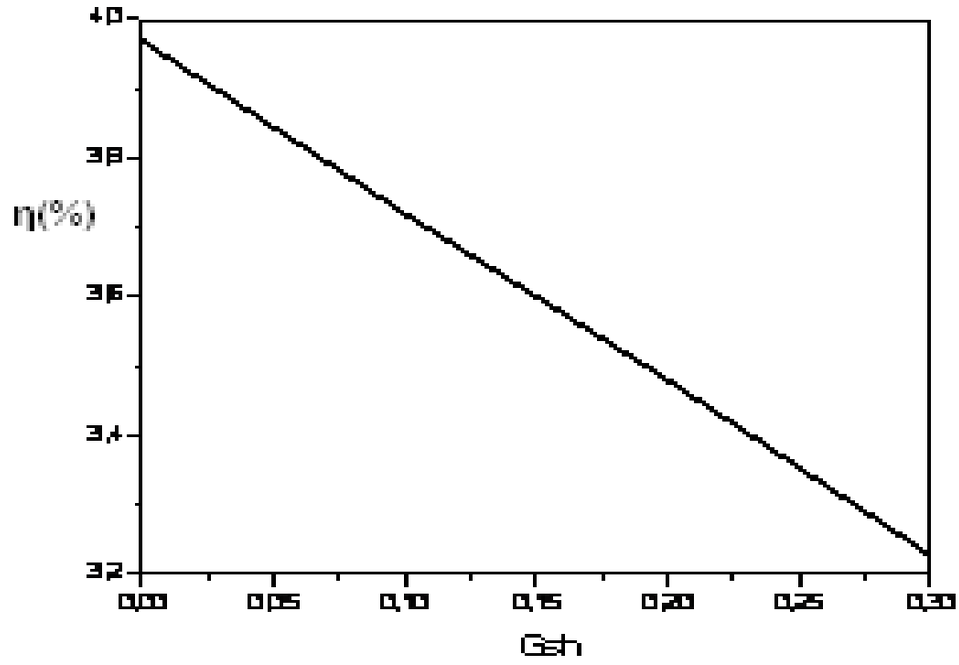


Fig. 12. Effect of shunt resistance on the η and FF.

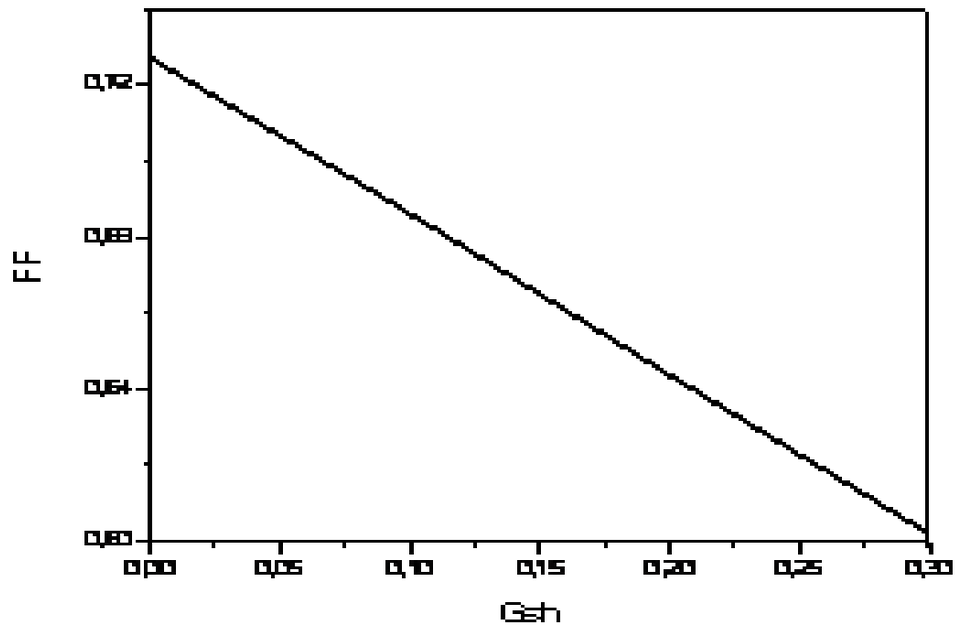


Fig. 13. Effect of shunt resistance on the η and FF.

5. Conclusion

This contribution present and analyse a simple and powerful method of extracting solar cell parameters which affect directly the conversion efficiency, the power conversion, the fill

factor and current-voltage shape of the solar cell. These parameters are: the ideality factor, the series resistance, diode saturation current and shunt conductance. This technique is not only based on the current-voltage characteristics but also on the derivative of this curve, the conductance G. by using this method, the number of parameters to be extracted is reduced from five I_s, n, R_s, G_{sh}, I_{ph} to only four parameters I_s, n, R_s, G_{sh}. The method has been successfully applied to a silicon solar cell, a module and an organic solar cell under different temperatures. The results obtained are in good agreement with those published previously. The method is very simple to use. It allows real time characterisation of different types of solar cells and modules in indoor or outdoor conditions.

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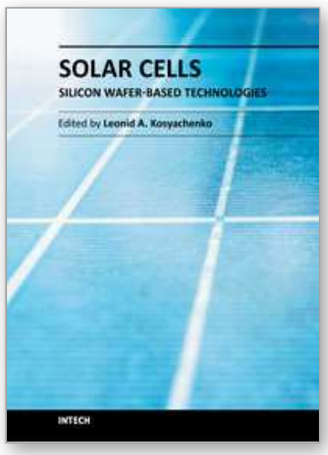
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The third book of four-volume edition of 'Solar Cells' is devoted to solar cells based on silicon wafers, i.e., the main material used in today's photovoltaics. The volume includes the chapters that present new results of research aimed to improve efficiency, to reduce consumption of materials and to lower cost of wafer-based silicon solar cells as well as new methods of research and testing of the devices. Light trapping design in c-Si and mc-Si solar cells, solar-energy conversion as a function of the geometric-concentration factor, design criteria for spacecraft solar arrays are considered in several chapters. A system for the micrometric characterization of solar cells, for identifying the electrical parameters of PV solar generators, a new model for extracting the physical parameters of solar cells, LBIC method for characterization of solar cells, non-idealities in the I-V characteristic of the PV generators are discussed in other chapters of the volume.

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