International Journal of Engineering Research and Technology.
ISSN 0974-3154 Volume 7, Number 3 (2014), pp. 185-199

http://www.irphouse.com

Detecting the Parameters of Solar Cells Using Efficient Curve Fitting Techniques

Rameen S. AbdelHady

Researcher, National Water Research Center,
Ministry of Water Resources and Irrigation, Egypt
Tel.: (+20)(2)44446180- 44447353 Fax: (+20)(2)44446761
E-mail address: rameens@hotmail.com

Abstract

Direct photovoltaic conversion of sunlight into electricity has proved to be a highly promising source of renewable energy. Extraction and interpretation of the solar cell's parameters are rather important for the operation and management of a solar generation system. This paper proposes an approach that is effective, physically rational and accurate when compared to the currently available methods developed for parameters' extraction.The parameters of 36 series cells, of type SOLARX (MSX- 56),have been extracted by the proposedmethod using sets of experimental data over a range of operating conditions. When compared with the so called 'five parameter model'; the parameters from the suggestedapproach showed to be in better fit with the observed data over a range of operating conditions.Moreover; the values of the parameters were in accordance with their physical interpretation.The approach can be recommendedto be applied for all kinds of solar cells whosecurrent-voltage (I-V) characteristics follow the single-diode model.

Keywords: Solar Cell Parameters; I-V characteristics; Lambertω; Least Square; Temperature; Illumination

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 [1]. 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.

Paper Code: 14588-IJERT

Extensive research has been conducted so that renewable and nonpolluting energy sources such as solar and fuel cell systems supplement the electricity generation.Research efforts have been devoted to solar cells' performance improvement.

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 [2]. Assemblies of cells are used to make solar modules, also known as solar panels. 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).

Solar cells furnish the most important long-duration power supply for satellites and space vehicles [1]. They have also been successfully employed in terrestrial applications. Solar Pumping System can be applied to daily use agricultural irrigation, it improves the reliability of the system, at the same time, it lowers the operation and maintenance costs of the irrigation system dramatically.

In recent years, with the promotion of the utilization of new energy resources, Solar Pumping System is more and more used in fountain irrigation systems in the residential areas. A solar irrigation system consists of only one pump, a power - matched solar array and an inverter. The rotational speed of pump is regulated according to the irradiation on the solar array; when the sunlight reaches its peak, the pump runs at the rated speed, and the output approaches the peak power of the solar array; when the sunlight is less abundant, the speed of pump varies bellow the range of the rated speed; when the speed as low as the capacity becomes zero, the solar pumping system stops working. So, there are big differences between solar irrigation systems and traditional pumping systems in system design, and the system should be optimized according to the requirements of head, capacity, and local conditions of sunlight. The aim of optimization is to reduce the amount of PV (photovoltaic) modules as much as possible on the premise of filling the requirement of head and capacity. The photovoltaicpumping system always needs to work with high efficiency[3]. Hence for most applications, solar cells' performance has to be evaluated regularly.

Solar cells are usually assessed by measuring the current voltage characteristics of the device under standard conditions of illumination and then extracting a set of parameters from the data. In order to improve the solar cell efficiency and thus further to simulate, design, fabricate and quality control it, it is necessary to know its parameters accurately from experimental data. 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 their performance.

The major parameters are usually the diode saturation current, the series resistance, the ideality factor, the photocurrent and the shunt resistance. Photovoltaic cells exhibit an extremely non-linear volt-ampere characteristic that is strongly dependent on array insolation and temperature (Figure 1). Here; the parameters of 36 series cells, of type SOLARX (MSX- 56), have been extracted by a fitting method using sets of experimental data over a range of operating conditions.

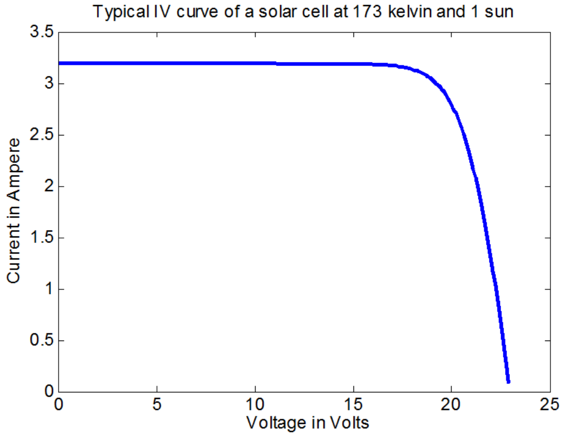

Fig. 1: Typical I-V characteristic of a solar cell at 1 sun insolation and 173^o kelvin

2. Related Work

Different modeling techniques have been proposed to extract an exact value of the solar cell parameters [3-9]. Zhang et al.[4] used an explicit analytic expression for I with the help of Lambertω function to be able to utilize the conventional curve fitting methods. The parameters are deduced by reducing their number, the expression for I depends only on the ideality factor n, the series resistance R_s and the shunt resistance R_{sh}. By applying the abridged equation at known conditions (V_{oc}, I_{sc}., $V/\partial I_{v=voc}$, $\partial V/\partial I_{I=Isc}$) and assuming that $R_{sh}>>>R_s$, which is applicable. The approach here is also numerical, i.e. the suggestedequation is not directly used to fit the experimental data. The proposed method has been used to analyze various solar devices, including Si (Silicon) solar cells, Si solar module, standalone organic solar cells, tandem organic solar cells, multi-junction organic solar cells and dye-senstized solar cells (DSSCs). In the previous work[4] the intended approach has been applied to various types of solar cells which have different properties to test its validity, yet the effect of illumination and temperature on the solar cell parameters was not investigated nor taken into account although the operating conditions of solar cells are always variable; also the mentioned above points cannot be always available and deducing them by interpolation is not very accurate.

AlsoJain [5], used Lambertω function for the same purpose. However, their study is validated only on simulated I-V characteristics instead of the parameter deduction from the experimental data.

CabestanyandCastaner[6] adopted the two diode model of the solar cell. A numerical procedure is described to calculate the parameters of the equivalent circuit; based on algorithms to optimize nonlinear functions defining the difference between the experimental characteristic and the theoretical model. The short come of their work is that only the dark characteristic is taken into consideration.

They presented an elaborate method to obtain the initial solution so the complexity of‘a must have’ good initial guess is present.Kishore’s approach [7] is one of the most popularmethod, it depends on deducing the parameters of the solar cells with the recognitionof five points (Open circuit voltage, Short circuit current, Voltage at maximum power point, Current at maximum power point, First degree derivative at open circuit voltage, First degree derivative at short circuit current), in sequence referred to as: (V_{oc}, I_{sc}., V_m, I_m, $-(\partial V/\partial I_{v=voc})$ and$-(\partial V/\partial I_{I=Isc})$)derivedexperimentally, sometimes referred to as the ‘five point method’. Although this work avoided the approximations considered by Phang et al. [8] which were:

$$\frac{R_s}{R_{sh}} \approx 0 \tag{1}$$

$$\frac{[nkTe^{\frac{-qv_{oc}}{nk(t+273)}}]}{q(I_0R_s)} \approx 0 \tag{2}$$

$$\frac{[qe^{\frac{-qI_{sc}R_s}{nk(t+273)}}]}{nKT(I_0R_s)} \approx 0 \tag{3}$$

yet another approximation is taken into account which is

$$e^{\frac{k(t+273)(I_{sc}R_s-V_{oc})}{nq}} \approx 0 \tag{4}$$

Here by taking this approximation the n(ideality factor) is deduced and then the $R_s$and consecutively the other parameters are obtained. Following the suggested approachthe number ofparameters that need preliminary estimationis reduced to two parameters only (n, R_s).

De Blas et al. [9] appliedthe single diode model of the solar cell.Their justification for the rejection of the double-diode model is that the recombination incurred by the second diode dominates at low voltage and low irradiance, which are operation conditions having low probability. Here like Phang et al. [7] the analytical method is used, and by the knowledge of some points which are usually included in the technical specifications issued by the manufacturer of the certified solar module, at least for standard temperature and irradiance conditions. Once again some approximations are taken into account,which are as claimed, different fromPhang’s[8], yet these approximations were not mentioned and the explanation for taking them was neglected. Also the requirement of a close approximation of initial parameter values to attain convergence is a must in this approach.

Naguen et al.[10]adopted the application of optimization techniques such that the sums of the squares of the relative or absolute errors are the different objective functions to be minimized. The simplex minimization method is used for finding local minima; it does not require any first or second derivative of the objective function. The problem in this case is that the ideality factor n is taken to be equal 1, which affects the values of series resistance deduced at high illuminations.

In this approach, an accurate value of those parameters is deduced directly from fitting the experimental data using least square method and Lambertω function.

Because the analytic expression derived from the proposed technique, current is only a function of voltage, the fitting is only one-dimensional and, thus, a much easier practice.

The parameters of 36 series cells of type SOLARX (MSX-56) type have been extracted by using the suggested approach.

3. Methodology

3.1 Single diode model

The electric characteristic of a solar cell can be described by the equivalent circuit of the single diode model, the two diode model[11] or the three diode model [12]. Among these circuit models, the single diode model has the simplest form as shown in Figure 2.

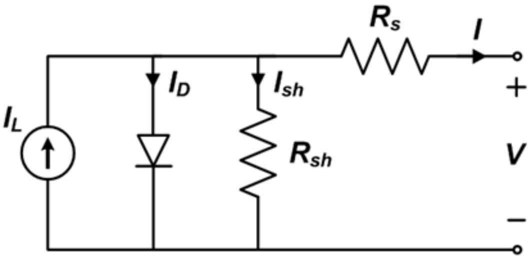

Fig. 2: Single exponential model of solar cell

The solar cell can be represented by: a current generator, a diode indicating the recombination losses, a shunt resistance symbolizing losses from currents that return across the junction and a series resistance denoting resistance losses.

In the single diode model, the relation of the current I and the voltage V is given as:

$$I = I_L - I_o\left(e^{\frac{q(V+IR_s)}{nk(t+273)}} - 1\right) - \frac{V+IR_s}{R_{sh}} \qquad (5)$$

where I_L is the photocurrent, I_o is the saturation current, R_s is the series resistance, $R_{sh}$is the shunt resistance, n is the ideality factor, k is Boltzman's constant (1.4x10^{-23}m^2 kg s^{-2} K^{-1}), $q$is the electron charge (1.6x10^{-19}coulombs), $t$is the temperature in degrees Celsius.

The main issue in most researches is evaluating the cell's parameters and hence predicting energy production. Different techniques have been used which will be elaborated in the next section. In this manuscript an effective fitting method to estimate the parameters of a solar cell from an I-V curve at certain illumination and temperature based on trying to get an explicit form of the current with the aid of Lambertω function. Eq.(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 but there is no separation between the dependent and the independent variables. Therefore, we propose a technique using Lambertωfunction that makes the current a function of voltage only and thus can be dealt with the normal least square methods techniques to derive the parameters with no need for any approximation.

3.2 Lambertω Function:

The Lambertω function[13] is defined as the function $W(z)$ such that $W(z)\, e^{W(z)} = z$ for all complex values z. As log z is the inverse of e^z, $W(z)$ is the inverse of ze^z. Like the complex logarithm, the Lambertω function is multivalued with a countable infinite number of branches. The branches are enumerated by the integers and are conventionally denoted by W_k for the kth branch.

If $y = x * e^x$

$$\therefore x = lambertw(y) \tag{6}$$

Figure 3 shows a surface plot of $|W_0(z)|$ in the complex plane, it shows that if $W_0(z)$, is real-valued for $-1/e \leq z$. If $-1/e \leq z < 0$, then the branch $W_{-1}(z)$ is also real-valued.

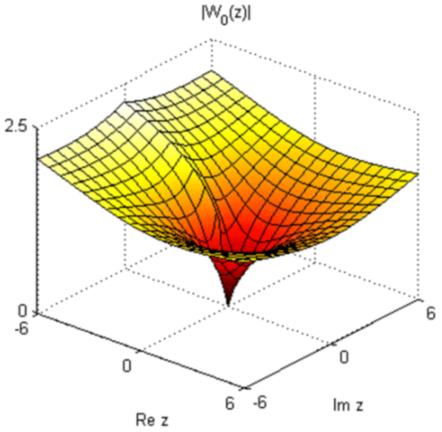

Fig. 3: Surface plot of |W₀(z)| in the complex plane

Eq. (5) gives the most popular description of the I-V characteristics of a solar cell under a given illumination level. With the help of the Lambertω function and according to Eq. (6), Eq.(5) is transformed to:

$$I = -((1/(a+b))V - (b(c+d)/(a+b)) + (e/a) * \text{lambertw}(((adb)/(e(a+b)))\exp\left(\left(\frac{b}{e(a+b)}\right)((ca)+(da)+V)\right))) \tag{7}$$

Where: $a = R_s, b = R_{sh}, c = I_L, d = I_o, e = (nk(t+273))/q$

3.3 Least Square Method

The Curve Fitting Toolbox[14]uses the least squares formulationto fit a nonlinear model to data. For example, Gaussians, ratios of polynomials, and powerfunctions are all nonlinear.

For some nonlinear models, a heuristic approach is provided that producesreasonable starting value. For other models, random values are provided.The direction andmagnitude of the coefficient adjustment depend on the fitting algorithm. Here the trust-region algorithm is used since coefficient constraints are specified.

$$\frac{d\delta^2(\theta)}{d\theta} = 0 \tag{8}$$

Where the set of unknown parameters □= (I_L, I_o, n, R_s, R_{sh}), δ is the difference between the predicted response and the observed one.

After fitting data with one or more models, the goodness of fit should be evaluated. A visual examination of the fitted curve displayed in Curve Fitting Tool is the first step. Beyond that, the toolbox provides these methods sum to assess goodness of fit for both linear and nonlinear parametric fits:

- The Sum of Squares due to error (SSE)
- R-square
- Root mean square error (RMSE)

3.4 Goodness of fit statistics

The performance of the proposed model was measured using two quantitative, standard statistical performance evaluation measures:

- The Sum of Squares due to error (SSE) [14] which is computed according to Eq. (9).

$$SSE = \sum_{i=1}^{n} (I_i - \hat{I}_i)^2 \tag{9}$$

Where $\hat{I}$is the deduced current, I is the observed current

- Refined Willmott's index (d_r) [15] which is calculated according to Eq. (10) or Eq. (11) depending on the specified constraints.

$$d_r = 1 - \frac{\sum_{i=1}^{n} |\hat{I}_i - I_i|}{2\sum_{i=1}^{n} |I_i - \bar{I}|} \tag{10}$$

When: $\sum_{i=1}^{n} \left|\hat{I}_i - I_i\right| \leq 2\sum_{i=1}^{n} |I_i - \bar{I}|$

or

$$d_r = \frac{\sum_{i=1}^{n} |\hat{I}_i - I_i|}{2\sum_{i=1}^{n} |I_i - \bar{I}|} - 1 \tag{11}$$

When: $\sum_{i=1}^{n} \left|\hat{I}_i - I_i\right| > 2\sum_{i=1}^{n} |I_i - \bar{I}|$

The range of d_r is from -1 to 1. A $d_r$of 1 indicates perfect agreement between model and experimental data, a dr of -1 indicates either lack of agreement between the model and observations or insufficient variation in observations to adequately test the model [15].

3.5 Deducing the parameters using the proposed model

The proposed approach is used to analyze solar cells polysilicon array of 36 series cells of type SOLARX (MSX-56).

Various types of solar cells have different properties. To test the validity of our proposed method, we will apply our method to extract the parameters from theexperimental I-V curves [16]at different illumination levels and over various temperature ranges.

By applyingEq. (7) which is a normal explicit equation where I lies on only one side of the equal symbol, the parameters can be deduced by the normal least squares method. The introduced equation is applied to the data deduced experimentally which were taken to apply fuzzy modeling to simulate photovoltaic systems [16].

As seen in Figure4(temp: 0 $^{\circ}$, illumination: 0.2 sun) after applying the model to the experimental datataking the 'Voltage'as the independent variable and the current as the dependent variable (the response) using cftool toolbox in Matlab, the SSE was in the order of 10^{-3}amp. The five parameters are then deduced using least square method and applying Eq. (4) without going through the complexity of trying to solve the implicit equation. The same approach is repeated at 0.599, 0.866 and 1sun over four temperature levels ranging from 0 °C to 75 °C and the d_r reached 0.98 in most cases.

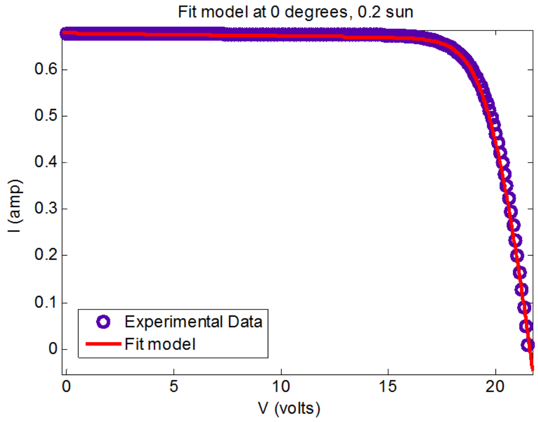

Fig. 4 Single exponential fit model for parameter deduction at 0° and 0.2 sun

After extracting all the parameters, a comparison between the introduced approach and the five parameter method is then presented parameterwise and goodness of fit wise after fitting to the original experimental I-V curve [16].

3.6 Analysis Of Variance (ANOVA) based comparisonof the parameters obtained by the two methods

The parameters derived by the two models were compared using one way ANOVA [14] repetitively for each parameter. The purpose of one way ANOVA is to find out whether several data samples have a common mean. That is to determine the groups are coming from the same population. For each parameter the twelve values deduced from the two models (groups) at different temperature levels (0°, 25°, 50°, 75°) and three illumination intensities (0.599 sun, 0.86 sun, 1 sun). The level of illumination of 0.2 sun is excluded since the ‘five parameter model’ does not yield physically correct values of the parameters. Accordingly one way ANOVA is carried out five times at significant level 0.05.

4. Results

Results have shown the proposed method to model the performance curve of the solar cell with acceptable limits especially at high temperature and high illumination levels, where the ‘five parameter method’ was not feasible as seen in Table 1.It has been demonstrated that the parametersobtained not only fit almost perfectly to the I-V data but the parameters show the physical applicability of the used theory unlike other methods that produce negative values of parameters at low illumination levels. Series resistance (R_s)decreases as the temperature increases and the illumination increases; which is logical since the efficiency of the cell increases. Ideality factor (n) showed to maintain constancy all along operating conditions, it ranged from 0.9 to 1.3. Photocurrent (I_L) increased as the illumination increased and the temperature increases. The shunt resistance(R_{sh}) was in the order of $10^3$and the diode current(I_o) in the order 10^{-6} which is applicable.As depicted in Figure5 at illumination 0.2 sun and temperature 75° only the curve deduced by our approach is present since the R_s and R_{sh}give negative values when deduced by the other method. Moreover the d_r reached 0.9873 for the proposed approach. At normal illumination levels (0.599 sun) the proposed approach outreached the ‘five parameter method’in the goodness of fit over all temperature levels, this is apparent explicitly in Figure6 the SSE= 0.03963 amp and d_r=0.9814 for the proposed method whereas for the ‘five parameter method’ the SSE=1.8492 ampand d_r= 0.9172.The ‘five parameter method’ performance decreases as the illumination level increases at all temperature ranges as shown in Figure7, the $d_r$decayed to 0.6838, yet the proposed method still maintained its level with d_r0.9806.One way ANOVA tests indicated that there is no significant difference in the three parameters (I_L, I_o, R_s) extracted from both models, as for $R_{sh}$and n the two treatments (models) showed significant variance. So these two parameters are the main parameters that affected the models.

Table 1: Extracted parameters by the suggested method and the ‘Five Parameter Method’ of a polysilicon array, 36 series cells, SOLARX (MSX-56)

Illumin. in sun	Temp. in °C	Parameters extracted by the suggested method					Parameters extracted by the ‘Five Parameter Method’				
		I_L (amp)	I_o(amp) $*10^{-10}$	$R_s(\Omega)$	$R_{sh}(\Omega)$	n	I_L (amp)	I_o(amp) $*10^{-10}$	$R_s(\Omega)$	$R_{sh}(\Omega)$	n
0.2	0	0.678	$3.271*10^{-4}$	1.856	1623	0.8190	0.6761	3.7505	1.312	4428.1	1.2074
	25	0.758	105.4	1.702	23480	1.1750	0.7585	10313	0.546	4407.2	1.5921
	50	0.8373	160.8	1.658	14430	0.9907	0.8395	$162.62*10^4$	-0.1865	3598.3	2.1279
	75	1.166	1805	1.356	20960	1.0637	0.9118	$24*10^6$	-0.9325	-4773.2	2.549
0.599	0	2.027	277.4	0.6043	4262	1.4478	2.025	0.007	0.8142	1964.4	0.9413
	25	2.109	78.63	0.4948	1409	1.1377	2.1076	0.9802	0.7828	1832.7	0.9532
	50	2.191	10430	0.3637	1693	1.2777	2.1907	849.49	0.6303	1024.9	1.1251
	75	2.271	350500	0.3674	20090	1.4067	2.2734	6202.7	0.6307	911.0701	1.0586
0.866	0	2.905	269.9	0.3126	22630	1.4361	2.9052	0.1879	0.4945	1399.2	0.9689
	25	2.985	510.2	0.2609	18750	1.2528	2.9876	29.79	0.3579	1135	1.1051
	50	3.069	17750	0.2565	2505	1.3160	3.0704	722.19	0.3421	998.5698	1.0958
	75	3.152	374000	0.1585	2061	1.3948	3.1529	38990	0.2573	721.3854	1.1899
1	0	3.2	293.3	0.1981	43900	1.4408	3.378	0.688	0.3116	1209.4	1.105
	25	3.278	317.9	0.2627	3124	1.2208	3.46	219.9	0.2237	1128.5	1.2158
	50	3.363	18270	0.1751	1834	1.3190	3.543	16621	0.1228	1050.4	1.3278
	75	3.449	244700	0.1099	730.2	1.3346	3.625	340770	0.0396	991.2368	1.4056

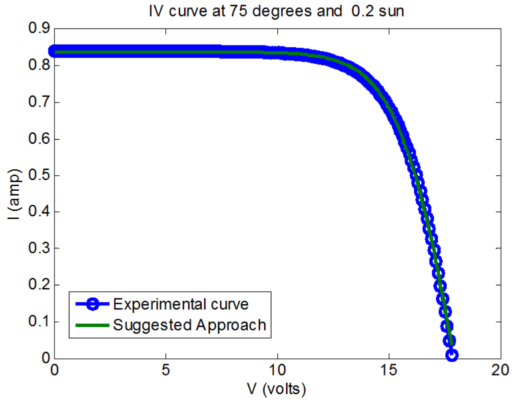

Fig. 5 IV curve deduced by this approach and experimental curve at 75° and 0.2 sun, with SSE=0.003577, d_r=0.9873

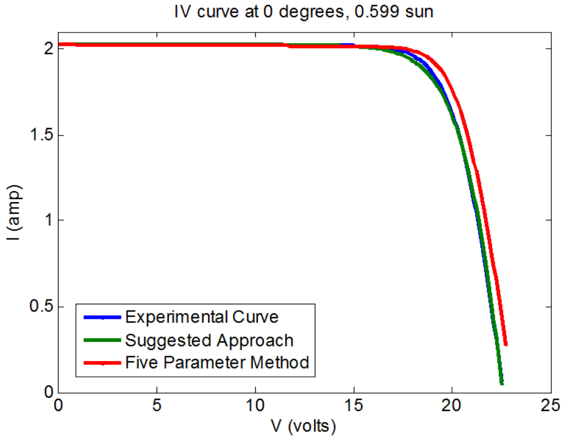

Fig. 6 IV curves deduced by this approach, five parameter method and experimental curve at 0° and 0.599 sun

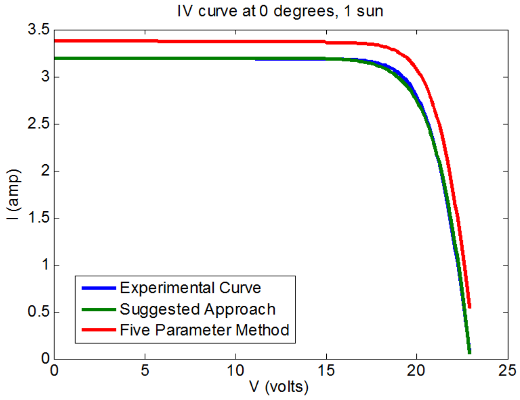

Fig. 7 IV curves deduced by this approach, five parameter method and experimental curve at 0° and 1 sun

4.1 I-V curve shape sensitivity to the parameters

In the following discussion the sensitivity of the curve to the five parameters (R_s, R_{sh}, I_L, I_o, n) due to changes in their values will be thoroughly analyzed; to show their influence on the maximum power point, short circuit current, open circuit voltage, and hence power delivered (area under the curve).

4.1.1 I-V curve shape sensitivity to R_s

The shape of the I-V curve in the voltage source region is shifted leftward with a gradual increase in the value of series resistance from 0 to 2.6Ω as shown in Fig. 8, the power conversion decrease slightly with a steady rise in the value of series resistance. This is physically justified since the series resistance represents resistance losses. Fig. 8 also shows that the series resistance does not affect the values of V_{oc} or I_{sc}.

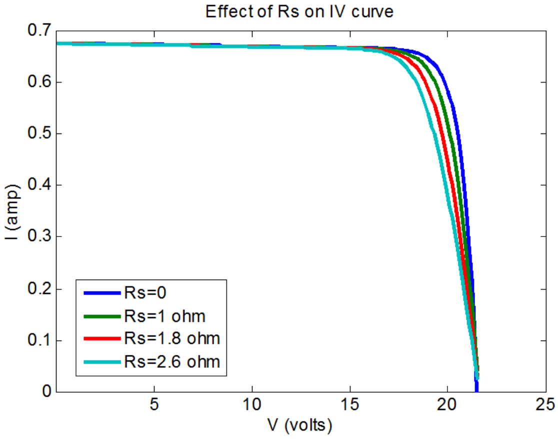

Fig. 8 The effect of R_s on the I-V curve

4.1.2 I-V curve shape sensitivity to Rsh

As shown on Fig. 9 when the shunt resistance decreases from infinity, the shape of the I-V curve in the current source region is depressed, and the power conversion decreases too. This is validated because the shunt resistance characterizes the losses from the currents that return across the junction, when it tends to infinity these currents tend to zero.

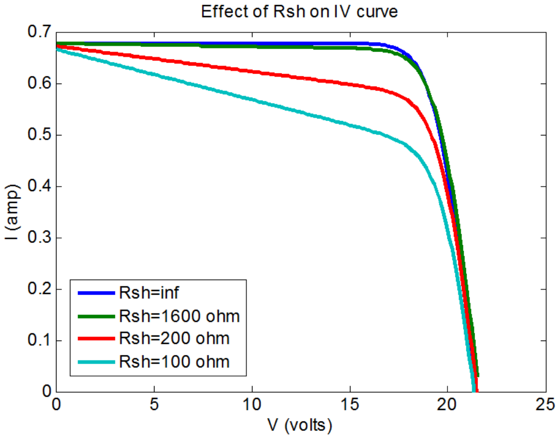

Fig. 9 The effect of R_{sh} on the I-V curve

The figure shows that when R_{sh} is in the order of 10^3, further rise of it up to infinity does not have a significant weight on the curve. The figure also shows that this parameter doesn't alter the values of V_{oc}or I_{sc}.

4.1.3 I-V curve shape sensitivity to I_L

The effect of raising I_L is shown in Fig. 10. The shape of the I-V curve in the current source region is shifted upwards increasing the value of the short circuit current. In the model the I_L represents the illumination on the cell which is a current source, this justifies that raising it increases the power generation.

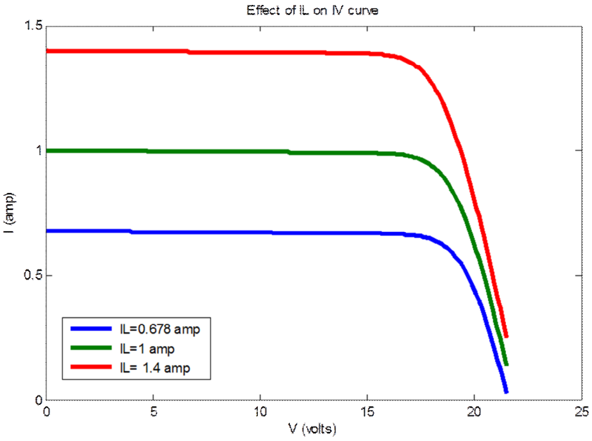

Fig. 10 The effect of $I_L$on the I-V curve

4.1.4 I-V curve shape sensitivity to Io

Figure 11 shows the effect of increasing I_o on the curve. The shape of the I-V curve in the voltage source region is shifted leftward lessening the value of the open circuit voltage. In the model the diode represents the recombination losses this explains that increasing the diode current decreases the power conversion.

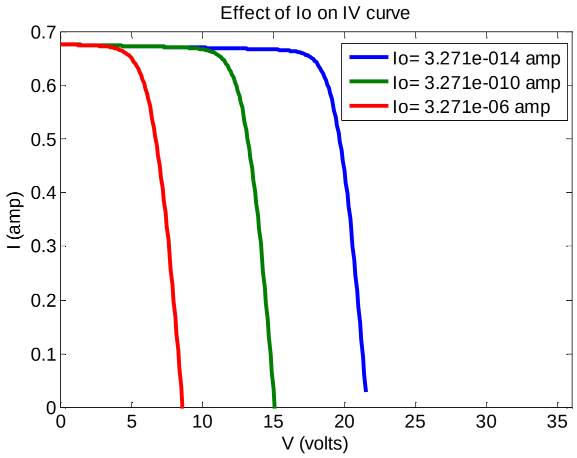

Fig. 11 The effect of I_o on the I-V curve

4.1.5 I-V curve shape sensitivity to n

Figure 12 depicts the effect of increasing the ideality factor of the diode *n* on the I-V curve. The term *n* is referred to as the diode ideality factor. What factors define *n*? In fact, defects drive the recombination process. More defects mean more space-charge recombination [17].If there were no defects present, the total diode current would be diffusion current and n would be 1 [17].

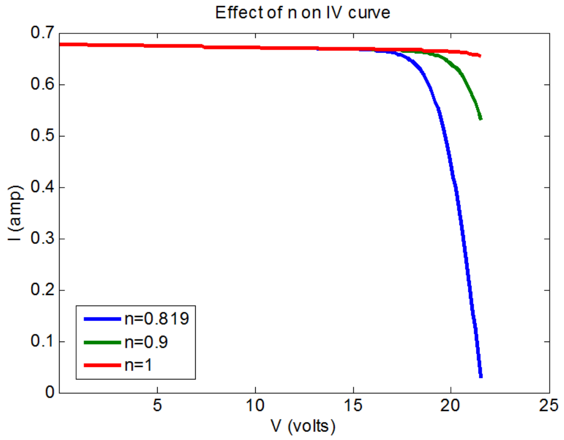

Fig. 12 The effect of *n* on the I-V curve

This would be the “ideal” diode case, in it the shape of the I-V curve is only in the current source region. The shape of the I-V curve in the voltage source region is shifted rightward increasing the value of the open circuit voltage as n increases.

5. Conclusion

An efficient method for the extraction of all the parameters of a solar cell from a single current-voltage (I-V) curve under the constant illumination level is proposed. With the help of the Lambertω function, the explicit analytic expression for I is obtained. This analytic expression is directly used to fit the experimental data and extract the five device parameters (R_s, R_{sh}, n, I_L, I_o) using least square method. Thissolar cell parameter extraction method can be directly applied for all kinds of solar cells whose I-V characteristics follow the single-diode model.It has been shown that the proposed method can be easily used to detectall the parameters at varioustemperature levels over different illuminations.The technique has been successfully applied to a silicon solar module under different illuminations and temperatures.

It has been demonstrated that it is not only sufficient to achieve a numerical agreement between measured and fitted I-V data to verify the validity of the extraction approach; but the values of the parameters have to be in accordance with their physical interpretation.

So the parameters obtained not only fit almost perfectly to the experimental I-V data but they show theoretical physical applicability unlike other methods that produce negative values of parameters at low illumination levels.An ANOVA based comparison of the parameters obtained by the proposed approach and the ‘Five parameters method’ to find out whether several parameter samples deduced by the two models have a common mean.

The sensitivity of the curve to the five parameters (R_s, R_{sh}, I_L, I_o, n) due to changes in their values wasanalyzed. It shows the influence of these parameters on the maximum power point, short circuit current, open circuit voltage, and hence power delivered (area under the curve). A physical justification for the impact of each parameter on the curve is revealed, which in turn affects the performance of the cell and the maximum power point.In order to improve the solar cell efficiency and thus further to simulate, design, fabricate and quality control it, it is necessary to know these parameters accurately from experimental data.

References

[1] Nehaoua N, Chergui Y and Mekki DE. A New Model for Extracting the PhysicalParameters from I-V Curves of Organicand Inorganic Solar Cells. Available from: www.intechopen.com

[2] Technical Information Office, Solar Energy Research Institute, U.S. Department of Energy. *Basic Photovoltaic Principles and Methods.*Technical Information Office, Solar Energy Research Institute, U.S. Department of Energy. Report number: SERI/SP-290-1448, February 1982.

[3] Solar Irrigation System. Available from: http://www.solartech.cn/detail.aspx?cid=725&gclid=CJjP2_Pevr0CFafKtAodl1wAIA- solartech.cn (accessed: Apr. 2014)

[4] ZhangCh, Zhang J, Hao Y, Lin Z, Zhu Ch. A simple and efficient solar cell

parameter extraction method from a single current voltage curve.J. Appl. Phys. 2011; 110(6): 064504-1-064504-7. http://scitation.aip.org/content/aip/journal/jap/110/6/10.1063/1.3632971 (accessed December 2013).doi: 10.1063/1.3632971

[5] Jain A, Kapoor A. A New Approach to Study Organic Solar Cell Using Lambert W-Function.*Sol.Energ Mat. Sol.*2005; 86: 197-205.

[6] Cabestany J, Castaner L. Evaluation of solar cell parameters by nonlinear algorithms. *J. Phys. D: Appl. Phys.*1983; 16: 2547-2558.

[7] Kishore R. Accurate analytical expressions for the parameters of the single exponential model of the solar cells.*Solid-State Electron.*1989; 32(6): 493-495.

[8] Phang JSH, Chan DSH, Phillips JR. Accurate analytical method for the extraction of solar cell model parameters.*Electron.Lett.*1984; 20: 406-408.

[9] De Blas MA, Torres JL, Prieto E, Garcia A. Selecting a suitable model for characterizing photovoltaic devices. *Renew. Energy* 2002; 25: 371-380.

[10] Nguyen PH, Lepley B, Boutrit C, Ravelet S.*Computer-Aided-Characterization of the Illuminated and Dark Current Voltage Characteristics of Solar Cells.* Netherlands: Springer Netherlands; 1982. Fourth E.C. Photovoltaic Solar Energy Conference; p. 492-497.

[11] Araujo GL, Sanchez E and Marti M. Determination of the two-exponential solar cell equation parameters from empirical data.*Sol. Cells*1982; 5: 199-204.

[12] Mazhari B. An improved solar cell circuit model for organic solar cells. *Sol Energ Mat. Sol. 2006*; 90(7): 1021-1033.

[13] Corless RM, Gonnet GH, Hare DFG, Jerey DJ and Knuth DE. On the Lambert W Function: https://cs.uwaterloo.ca/research/tr/1993/03/W.pdf (accessed Mar. 2014).

[14] MATLAB toolbox description. http://www.mathworks.com/access/helpdesk/help/toolbox/curvefit/bq_5ka6-1_1.html (accessed Jan. 2014).

[15] Willmott C, Robeson S, Matsuura K. A refined index of model performance.Int. J.Climatol.2012; 32:2088-94. doi: 10.1002/joc.2419

[16] El-Shatter TFA, *Fuzzy modeling and simulation of photovoltaic systems* [PhD thesis]. Egypt: Cairo University; 1998.

[17] Diode Ideality. http://www.ece.umd.edu/class/enee480.F2005/DiodeIdeality.pdf (accessed Apr. 2014)