Solar Cell Parameters Estimation Using Simulated Annealing Algorithm

M. R. AlRashidi, K. M. El-Naggar, M. F. AlHajri

Abstract—This paper presents Simulated Annealing based approach to estimate solar cell model parameters. Single diode solar cell model is used in this study to validate the proposed approach outcomes. The developed technique is used to estimate different model parameters such as generated photocurrent, saturation current, series resistance, shunt resistance, and ideality factor that govern the current-voltage relationship of a solar cell. A practical case study is used to test and verify the consistency of accurately estimating various parameters of single diode solar cell model. Comparative study among different parameter estimation techniques is presented to show the effectiveness of the developed approach.

Keywords—Simulated Annealing, Parameter Estimation, Solar Cell.

I. INTRODUCTION

SOLAR energy is a fundamental energy source for humans as it has been used for heating and lighting since ancient times. Different reasons are promoting serious involvement of environmental friendly energy sources in producing electricity in many countries. Among these reasons are possible depletion and price increase of fossil based fuels, global warming, air pollution, and strict environmental laws. One of the most promising renewable sources that is currently being used worldwide to contribute to meeting rising demands of electric power is solar energy. Solar photovoltaic (PV) is the fastest growing power-generation technology in the world with an annual average increase of 60% between 2004-2009. PV is not only capable of directly converting solar energy to electricity, but also is an environmental friendly distributed generation unit that would provide power at the load location [1].

PV systems convert solar radiation into direct current through a solar panel that typically has arrays of interconnected solar cells. The current-voltage (I-V) curve of a solar cell exhibits non-linear relationship determined by the solar cell parameters that describe its model. Several models have been proposed to describe the current-voltage relationship (I-V) in solar cells [2-4]. To gain better understanding of the solar cell physics, a lumped parameter equivalent circuit model is commonly used to simulate its

M. R. AlRashidi is with the electrical engineering Department, College of Technological Studies, (PAAET), Kuwait, (Phone:965-22314312; email: malrash2002@yahoo.com).

K. M. El-Naggar is with the electrical engineering Department, College of Technological Studies, (PAAET), Kuwait, (Phone:965-22314312; email: knaggar60@hotmail.com).

M. F. AlHajri is is with the electrical engineering Department, College of Technological Studies, (PAAET), Kuwait, (Phone:965-22314312; email: mfalhajri@yahoo.com).

behavior under different operating conditions. In practice, there are two main equivalent circuit models used to describe the non-linear I-V relationship: single and double diode models. The key parameters that describe solar cell models behavior are the generated photocurrent, saturation current, series resistance, shunt resistance, and ideality factor. Valid estimation of these parameters is always required to provide accurate modeling and performance evaluation of a given solar system.

Different techniques have been reported to estimate different parameters of solar cells. Reference [5] proposed a modified non-linear least error squares estimation approach based on Newton's method to determine solar cell parameters. A major shortcoming of this approach is its high dependency on the initial values used in the proposed iterative technique. In addition, this type of optimization method is local optimizer and may reach a local solution rather than a global one if multiple solutions exist. Different analytical solution technique called "Co-content function" which is based on Lambert function has been proposed in reference [6] to extract the solar cell parameters. A comparative study of three different methods, namely curve-fitting method, iterative 5-point method, and analytical 5-point method, for estimating solar cell parameters is presented in reference [7]. Similar analytical solution methods are presented in references [8-10]. However these techniques suffer from necessitating certain modeling conditions to make it applicable such as continuity, convexity and differentiability, heavy computation involvement, tedious algebraic manipulation, and finally curve fitting. Genetic Algorithm (GA) based approach is introduced as a meta-heuristic tool for extracting the solar cell parameters in reference [11]. Drawbacks of reported results are the relatively high percentage of errors associated with the extracted parameters. Particle swarm optimization (PSO) is introduced in references [4, 12] as a nature-inspired optimizer for solar cell parameters extraction. Study results revealed that PSO outperformed GA in providing more accurate parameters of solar cells. Reference [13] proposed Pattern Search (PS) technique for extracting the solar cell parameters.

II. SOLAR CELL MODELING AND PROBLEM FORMULATION

It is important to develop a mathematical model that accurately represents the electrical characteristics of solar cell and the PV module. Many equivalent circuit models have been developed and proposed to describe the solar cell's behavior. The two main models are:

A. Double Diode Model:

Solar cell can be modeled as a current source connected in parallel with a rectifying diode. However, in practice the current source is also shunted by another diode that models the space charge recombination current and a shunt leakage resistor to account for the partial short circuit current path near the cell's edges due to the semiconductor impurities and non-idealities. Moreover, solar cell metal contacts and semiconductor material bulk resistance are represented by a resistor connected in series with the cell shunt elements [14]. The equivalent circuit for this model is shown in Fig. 1.
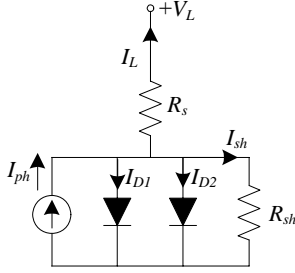

Fig. 1 Equivalent circuit of a double diode model

In this double-diode model, the cell terminal current is calculated as follows:

$$I_L = I_{ph} - I_{D1} - I_{D2} - I_{sh} \qquad (1)$$

where

I_L : the terminal current,

I_{ph} : the cell-generated photocurrent,

I_{D1}, I_{D2} : the first and second diode currents,

I_{sh} : the shunt resistor current.

I_{D1} and I_{D2} are expressed by Shockley equation as illustrated respectively in Eqs (2) and (3), while the leakage resistor current I_{sh} is formulated as shown in Eq.(4).

$$I_{D1} = I_{SD1}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_1 kT}\right) - 1\right] \qquad (2)$$

$$I_{D2} = I_{SD2}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_2 kT}\right) - 1\right] \qquad (3)$$

$$I_{sh} = \frac{V_L + I_L R_s}{R_{sh}} \qquad (4)$$

where R_s and R_{sh} are the series and shunt resistances respectively; I_{SD1} and I_{SD2} are the diffusion and saturation currents respectively; V_L is the terminal voltage; n_1 and

n_2 are the diffusion and recombination diode ideality factors; k is Boltzmann's constant; q is the electronic charge and T is the cell absolute temperature in Kelvin. Substituting Eqs. (2), (3) and (4) into Eq. (1), the cell terminal current is now rewritten as shown in Eq. (5).

$$I_L = \left\{\begin{array}{l} I_{ph} - I_{SD1}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_1 kT}\right) - 1\right] \\ -I_{SD2}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_2 kT}\right) - 1\right] \\ -\left[\frac{(V_L + I_L R_s)}{R_{sh}}\right] \end{array}\right\} \qquad (5)$$

The seven parameters to be estimated that fully describe the I-V characteristics are R_s, R_{sh}, I_{ph}, I_{SD1}, I_{SD2}, n_1, and n_2.

B. Single Diode Model:

Diffusion and recombination currents are often combined together under the introduction of a non-physical diode ideality factor to represent the single diode model. This is the most commonly used model and it has been used successfully to fit experimental data. The single diode model equivalent circuit is shown in Fig. 2.
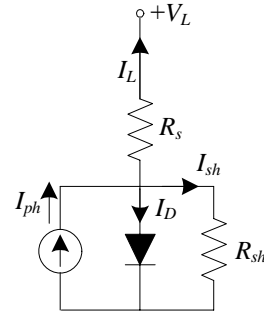

Fig. 2 Equivalent circuit of a single diode model

In this model, Eq. (5) is reduced to the following equation:

$$I_L = I_{ph} - I_{SD}\left[\exp\left(\frac{q(V_L + I_L R_s)}{nkT}\right) - 1\right] - \left[\frac{V_L + I_L R_s}{R_{sh}}\right] \qquad (6)$$

In this case, the parameters to be estimated are:

R_s, R_{sh}, I_{ph}, I_{SD}, and n.

C. Problem Formulation:

It is noted that equations (5) and (6) are nonlinear transcendental functions that involve the overall output current produced by the solar cell in both sides of the equation. Furthermore, the parameters R_s, R_{sh}, I_{ph}, I_{SD}, and n

vary with temperature, irradiance and depend on manufacturing tolerance. Such functions have no explicit analytical solutions for either I_L or V_L. Various techniques such as Numerical methods, curve fitting techniques, and different optimization methods are often utilized to solve such functions. The simulated annealing (SA) optimization technique is employed to estimate the parameters by minimizing the total error. In order to form the objective function, the I-V relationships given in any of equations (5) and (6) are rewritten in the following homogeneous equations:

$$f(V_L, I_L, I_{ph}, I_{SD1}, I_{SD2}, R_s, R_{sh}, n_1, n_2) = 0$$

for the double diode model

$$f(V_L, I_L, I_{ph}, I_{SD}, R_s, R_{sh}, n) = 0$$

for the single diode model

The new objective function that sums the individual absolute errors (IAEs) for any given set of measurements is defined as:

$$f = \sum_{i=1}^{N} \left| f(V_{Li}, I_{Li}, R_s, R_{sh}, \dots) \right| \qquad (7)$$

where N is the number of data points, I_{Li} and V_{Li} are i[th] measured current and voltage pair values, respectively.

III. SIMULATED ANNEALING

SA mimics the physical gradual cooling process that produces high quality crystals in metals. There are two major steps in SA: transition mechanism between states and cooling schedule with the objective being finding the state with minimum energy. Forming a perfect crystal is simply done by properly controlling temperature in the cooling (or annealing) process. In SA, a new solution candidate is randomly generated at each iteration. A probability distribution with a scale proportional to the control parameter, i.e. temperature, governs the distance of the new solution candidate from the existing solution. In SA, an objective function is used to measure solutions' goodness and the temperature parameter decreases based on a cooling schedule as it converges to the optimal solution [1].

This optimization technique was proposed independently by Kirkpatrick et al. in 1983 [15] and by Cerny in 1985 [16]. They have noted that alternative physical states of the matter resemble the solution space of an optimization problem and the objective function of an optimization problem corresponds to the free energy of the material. Forming a perfect crystal corresponds to finding the optimal solution whereas a crystal with defects corresponds to finding a local solution. In both papers, SA was introduced to solve combinatorial problems by adapting the crystallization process model developed by Metropolis et al. [17, 18]. This model generates a sequence of states of a solid and assumes that the probability for a physical system to have a certain energy level E is proportional to Boltzmann factor $e^{\frac{-E}{k_B *T}}$, where k_B denotes the Boltzmann constant, when the thermodynamic equilibrium is reached at a given temperature T. Assuming a solid in initial state S_i with energy level E_i and the next state S_j with energy E_j, if the difference between the two energy levels is less than or equal to zero, the new state S_j is accepted. Otherwise, if the difference is greater than zero, the new state is accepted with probability.

$$P(E, T) = e^{\left(\frac{E_i - E_j}{k_B *T} \right)} \qquad (8)$$

IV. SIMULATION RESULTS

Measured I-V data of solar cell are used to test and validate SA performance in estimating solar cell model parameters [5]. In this case, solar cell data is employed to extract its parameters using the single diode model. The extracted parameters for the single diode model using SA are shown in Table I along with the same parameters estimated using other estimation methods reported in the literature. Based on the extracted parameters, the I-V data set is reconstructed. This is simply done by back substitution in equation (6) with Ia is considered as unknown while Va is known. The current is then calculated using Newton method as it involves solving a set of nonlinear equations. The resultant IAE for each data point is shown in Table II. The obtained IAE values are compared with those obtained using three other techniques [5, 13, 19].

Table II shows that, the summation of the IAE obtained using the parameters estimated via SA technique is 0.03712. A reduction in IAE summation is clear when SA results are compared with other reported outcomes which are 0.055993, 0.367349 and 0.212223 respectively. It is obvious that the parameters extracted using SA generated the best IAE profile when compared to reported work.

TABLE I
SINGLE DIODE MODEL PARAMETERS ESTIMATION

Case	Item	Ref. [13]	Ref. [5]	Ref. [19]	SA
Solar Cell Parameter	I_{ph}	0.7617	0.7608	0.7607	0.7620
	I_{SD} (µA)	0.9980	0.3223	0.3267	0.4798
	R_s (Ω)	0.0313	0.0364	0.0364	0.0345
	G_{sh} (S)	0.0156	0.0186	0.0166	0.0232
	n	1.6000	1.4837	1.4816	1.5172

TABLE II
COMPARISON OF IAES ASSOCIATED WITH DIFFERENT ESTIMATION TECHNIQUES

Measurment	Va (V)	Ia (A)	IAE based on Ref. [13]	IAE based on Ref. [5]	IAE based on Ref. [19]	IAE based on SA
1	-0.2057	0.7640	0.00054	0.00011	0.00035	0.00098
2	-0.1291	0.7620	0.00134	0.00069	0.00038	0.00171
3	-0.0588	0.7605	0.00175	0.00088	0.00072	0.00204
4	0.0057	0.7605	0.00074	0.00032	0.00035	0.00097
5	0.0646	0.7600	0.00031	0.00092	0.00083	0.00049
6	0.1185	0.7590	0.00045	0.00093	0.00074	0.00058
7	0.1678	0.7570	0.00162	0.0012	0.00041	0.00172
8	0.2132	0.7570	0.00074	0.00083	0.00045	0.00084
9	0.2545	0.7555	0.00115	0.00037	0.0008	0.00132
10	0.2924	0.7540	0.00103	0.00026	0.00025	0.00138
11	0.3269	0.7505	0.00182	0.00104	0.00158	0.00250
12	0.3585	0.7465	0.00100	0.00118	0.00169	0.00225
13	0.3873	0.7385	0.00063	0.00231	0.00268	0.00266
14	0.4137	0.7280	0.00304	0.00078	0.00084	0.00005
15	0.4373	0.7065	0.00341	0.00307	0.00258	0.00055
16	0.4590	0.6755	0.00522	0.00433	0.00293	0.00056
17	0.4784	0.6320	0.00658	0.00617	0.00343	0.00177
18	0.4960	0.5730	0.00575	0.01024	0.00568	0.00148
19	0.5119	0.4990	0.00248	0.01685	0.00999	0.00055
20	0.5265	0.4130	0.00011	0.02287	0.01326	0.00111
21	0.5398	0.3165	0.00269	0.03006	0.01732	0.00191
22	0.5521	0.2120	0.00391	0.03681	0.02060	0.00123
23	0.5633	0.1035	0.00359	0.04344	0.02359	0.00050
24	0.5736	-0.0100	0.00542	0.05419	0.03064	0.00094
25	0.5833	-0.1230	0.00033	0.05915	0.03167	0.00453
26	0.5900	-0.2100	0.00034	0.06944	0.03917	0.00250
Total IAE			0.05599	0.36735	0.21222	0.03712

V. CONCLUSION

SA algorithm is presented for estimating solar cell single diode model parameters. The solution methodology is implemented and tested using actual recorded data. Results obtained using SA algorithm, especially when compared to other competing methods, are quite promising and deserve serious attention. It sheds light on the SA potential as a valuable new method for parameters estimation and system identification as it relieves system modeling from the regular oversimplifying assumptions such as continuity, convexity, and differentiability required by other traditional estimation techniques.

REFERENCES

[1] K. M. El-Naggar, M. R. AlRashidi, M. F. AlHajri, and A. K. Al-Othman, "Simulated Annealing algorithm for photovoltaic parameters identification," Solar Energy, vol. 86, no. 1, pp. 266-274, 2012.
[2] W. Xiao, M. G. J. Lind, W. G. Dunford, and A. Capel, "Real-Time Identification of Optimal Operating Points in Photovoltaic Power Systems," IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1017-1026, 2006.
[3] M. Chegaar, Z. Ouennough, F. Guechi, and H. Langueur, "Determination od Solar Cells Parameters under Illuminated Conditions," Journal of Electron Devices, vol. 2, pp. 17-21, 2003.
[4] M. Ye, X. Wang, and Y. Xu, "Parameter extraction of solar cells using particle swarm optimization," Journal of Applied Physics, vol. 105, no. 9, pp. 094502-094508, 2009.
[5] T. Easwarakhanthan, J. Bottin, I. Bouhouch, and C. Boutrit, "Nonlinear Minimization Algorithm for Determining the Solar Cell Parameters with Microcomputers," International Journal of Solar Energy, vol. 4, pp. 1-12, 1986.
[6] A. Ortiz-Conde, F. J. Garcia Sanchez, and J. Muci, "New method to extract the model parameters of solar cells from the explicit analytic solutions of their illuminated I-V characteristics," Solar Energy Materials and Solar Cells, vol. 90, no. 3, pp. 352-361, Feb.2006.
[7] D. S. H. Chan, J. R. Phillips, and J. C. H. Phang, "A comparative study of extraction methods for solar cell model parameters," Solid-State Electronics, vol. 29, no. 3, pp. 329-337, Mar.1986.
[8] A. Jain and A. Kapoor, "Exact analytical solutions of the parameters of real solar cells using Lambert W-function," Solar Energy Materials and Solar Cells, vol. 81, no. 2, pp. 269-277, Feb.2004.
[9] D. S. H. Chan and J. C. H. Phang, "Analytical methods for the extraction of solar-cell single- and double-diode model parameters from I-V characteristics," IEEE Transactions on Electron Devices, vol. 34, no. 2, pp. 286-293, 1987.
[10] H. Saleem and S. Karmalkar, "An Analytical Method to Extract the Physical Parameters of a Solar Cell From Four Points on the Illuminated J-V Curve," IEEE Electron Device Letters, vol. 30, no. 4, pp. 349-352, 2009.
[11] J. A. Jervase, H. Bourdoucen, and A. Al-Lawati, "Solar cell parameter extraction using genetic algorithms," Measurement Science and Technology, vol. 12, no. 11, pp. 1922-1925, 2001.
[12] M. K. Munji, W. Okullo, E. E. van Dyk, and F. J. Vorster, "Local device parameter extraction of a concentrator photovoltaic cell under solar spot illumination," Solar Energy Materials and Solar Cells, vol. 94, no. 12, pp. 2129-2136, Dec.2010.
[13] M. R. AlRashidi, K. M. El-Naggar, M. F. AlHajri, and A. K. Al-Othman, "A New Estimation Approach for Determining the I-V Characteristics of Solar Cells," Solar Energy, vol. 85, no. 7, pp. 1543-1550, 2011.
[14] M. Wolf, G. Noel, and R. Stirn, "Investigation of the double exponential in the current-voltage characteristics of silicon solar cells," IEEE Transaction on Electron Devices, vol. 24, no. 4, pp. 419-428, Apr.1977.
[15] S. Kirkpatrick, C. D. Gelatt Jr, and M. P. Vecchi, "Optimization by simulated annealing," Science, vol. 220(4598), pp. 671-680, 1983.
[16] V. Cerny, "Thermodynamical approach to the traveling salesman problem: an efficient simulation algorithm," Journal of Optimization Theory and Application, vol. 45(1), pp. 41-51, 1985.
[17] K. Lee and M. El-Sharkawi, Modern Heuristic Optimization Techniques: Theory and Applications to Power Systems, 1st ed. New Jersey: John Wiley & Sons, Inc., 2008.
[18] N. Metropolis, A. W. Rosenbluth, M. N. Rosenbluth, and A. H. Teller, "Equation of state calculation by fast computing machines," Journal of Chemical Physics, vol. 21, pp. 1087-1092, 1953.
[19] K. Bouzidi, M. Chegaar, and N. Nehaoua, "New method to extract the parameters of solar cells from their illuminated I-V curve," 4th International Conference on Computer Integrated Manufacturing, Setif, Algeria, Nov.2007.