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Parameters Estimation of Double Diode Solar Cell Model

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

***Abstract*—**A new technique based on Pattern search optimization is proposed for estimating different solar cell parameters in this paper. The estimated parameters are the generated photocurrent, saturation current, series resistance, shunt resistance, and ideality factor. The proposed approach is tested and validated using double diode model to show its potential. Performance of the developed approach is quite interesting which signifies its potential as a promising estimation tool.

***Keywords*—**Solar Cell, Parameter Estimation, Pattern Search.

I. Introduction

RECENT awareness of the harmful effects of pollutants emitted as a result of fossil-based power generation and strict environmental laws imposed on electricity producers are leading factors that resulted in rapid growth in using renewable energy sources as alternatives to electricity production. Solar energy is one of the most promising renewable energy source that has been receiving added attention. Photovoltaic (PV) systems consist of different parts centered around a solar panel that typically has arrays of interconnected solar cells. Various models were developed to explain the non-linear characteristics of the current-voltage (I-V) curve of a solar cell [1-3]. A lumped parameter equivalent circuit model is commonly used to simulate the solar cell 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 modelse. Main parameters that describe solar cell models behavior are the generated photocurrent, saturation current, series resistance, shunt resistance, and ideality factor. Accurate estimation of these parameters is always required to provide better modeling and efficient performance evaluation of a given solar system.

Different estimation techniques have been developed to approximate different parameters of solar cell models. Reference [4] presented a modified non-linear least error squares estimation approach based on Newton's method to estimate solar cell parameters. This approach suffers from its dependency on the initial values used in the proposed iterative technique. In addition, this type of optimization method is local in nature and may converge to local extreme if multiple solutions exist. An analytical solution technique uses the so called "Co-content function" which is based on Lambert function, has been proposed in reference [5] to extract the solar cell model parameters. A comparative study of three different estimation methods for extracting solar cell model parameters is provided in reference [6]. Similar analytical solution methods are presented in references [7-9]. However, these techniques necessitate certain modeling conditions to make it applicable such as continuity, convexity and differentiability. A Genetic Algorithm (GA) is presented as a new population based tool for extracting the solar cell parameters in reference [10]. Reported results suffer from the relatively high percentage of errors associated with the extracted parameters and the binary conversion pertaining to GA implementation. Particle swarm optimization (PSO) is introduced in reference [3] as a different evolutionary optimizer for solar cell parameters extraction. A comparative study highlighted that PSO outperformed GA in extracting more accurate parameters of solar cell model.

In recent years, Pattern Search (PS) has been receiving a considerable attention as new optimization technique. Unlike deterministic methods, PS is a derivative free method which gives the PS the flexibility to deal with objective functions that are not necessarily continuous, convex or differentiable. Key Advantages of this optimization algorithm are concept simplicity, ease of implementation, and computational efficiency [11]. This paper presents an efficient PS technique for estimating the solar cell where the goal is to minimize the error associated with the estimated parameters.

II. Solar Cell Modeling

Although many equivalent circuit models have been developed and proposed over the past four decades to describe the solar cell's behavior, only two models are used practically. In this section the two common models are briefly presented.

A. Double Diode Model:

In this model, the solar cell is 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. In addition, the solar cell metal contacts and the semiconductor material bulk resistance are represented by a resistor connected in series with the cell

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).

shunt elements [12]. The equivalent circuit for this model is shown in Fig. 1.

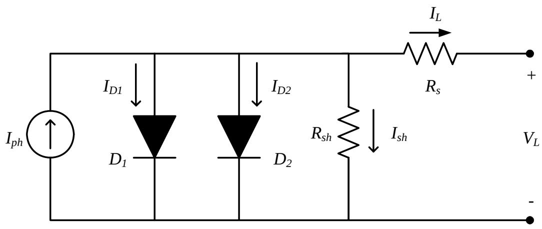

Fig. 1 Equivalent circuit of a double diode model

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

$$I_L = I_{ph} - I_{D1} - I_{D2} - I_{sh} \tag{1}$$

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.

The two diodes currents 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).

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

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

$$I_{sh} = \frac{V_L + I_L R_s}{R_{sh}} \tag{4}$$

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).

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

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:

Despite the fact that the diffusion and recombination currents are linearly independent, it is common to combine them together under the introduction of a non-physical diode ideality factor n. Recently, the use of this single diode model to describe the static I-V characteristic has been considered widely, and it has been used successfully to fit experimental data. The single diode model equivalent circuit is shown in Fig. 2.

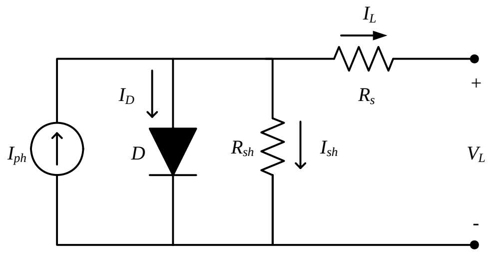

Fig. 2 Equivalent circuit of a single diode model

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

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

Consequently, the parameters to be estimated are:

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

III. Problem Formulation

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 PS optimization technique is employed to estimate the parameters by minimizing a pre-selected objective function. 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:

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

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

IV. Pattern Search Technique

PS as a zero-order method only needs objective function evaluations towards its search for optimality. Sometimes, It is used as an alternative solution method to traditional optimization techniques when the objective function derivative is not available or has a stochastic nature [11]. The salient features of PS optimization method are: It is a non-gradient method that does not construct approximations of the objective function, it is insensitive to choosing the starting initial point, and it utilizes its own past search history in determining the forthcoming new search direction [13]. The solar cell parameter estimation problem is mathematically formulated as a nonlinear optimization problem and is expressed as follows:

$$\min_{\mathbf{x} \in \mathbf{R}^n} f\left(\mathbf{x}\right) \tag{8}$$

where x is the vector of n independent variables and f is a real valued objective function. The optimization solution method starts from an arbitrary initial point, called Base Point (BP) where and serves as the iteration index. It searches for optimality in a sequential technique and has two routines at each iteration: Exploratory search and pattern move routines. Full details of PS algorithm is described in reference [14].

V. Simulation Results and Discussion

Real measured I-V data for solar cell is used to test its performance [4]. In this section, the double diode model is used to characterize a set of I-V data of a solar cell. In this case, two more unknowns are added to the problem (I_{SD2}, n_2). Therefore, the overall unknown parameters become seven rather than five. These unknowns are given in the double diode model described by equation (5). The objective function as illustrated in equation (7) is minimized in order to reach an optimal set of parameters that reflects the solar cell characteristics. Estimated parameters along with curve fitting values are given in Tables I and II respectively.

The parameters extracted using the PS method are substituted in equation (6) to evaluate the fitness. The optimal value is to be zero for each of the 26 equations. Also, the sum of IAEs is 0.0505855, which is quite low; hence, the extracted parameters reasonably describe the solar cell

TABLE I
Parameters Extraction for the Double Diode Model

Parameter	PS Estimation
I_{ph}	0.7602
I_{SD1} (μA)	0.9889
R_s (Ω)	0.0320
G_{sh} (S)	0.0123
n_1	1.6000
I_{SD2} (μA)	0.0001
n_2	1.1920

VI. Conclusion

The problem of solar cell parameters identification using PS algorithm is presented in this study. The double diode model of solar cell is used to validate the performance of the proposed approach in tackling this estimation problem. The proposed approach is implemented and tested using actual recorded data. The outcomes of PS algorithm are quite promising and deserve serious attention. It signifies the PS potential as a valuable new tool 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 competing estimation techniques. In forthcoming study, other solar cell models as well as impact of different operating conditions such as shading on solar cell modeling and parameters estimation will go under rigorous investigations.

TABLE II
Curve Fitting of the Estimated Solar Cell Parameters

Measurement	V_a (V)	I_a (A)	IAE based on PS
1	-0.2057	0.764	0.0015815
2	-0.1291	0.762	0.0005264
3	-0.0588	0.7605	0.000106
4	0.0057	0.7605	0.0006918
5	0.0646	0.76	0.0009248
6	0.1185	0.759	0.0006106
7	0.1678	0.757	0.0007182
8	0.2132	0.757	1.963E-05
9	0.2545	0.7555	0.0005262

10	0.2924	0.754	0.0005259
11	0.3269	0.7505	0.0014101
12	0.3585	0.7465	0.0006727
13	0.3873	0.7385	0.0003336
14	0.4137	0.728	0.0033565
15	0.4373	0.7065	0.0038234
16	0.459	0.6755	0.0058478
17	0.4784	0.632	0.0075294
18	0.496	0.573	0.0071042
19	0.5119	0.499	0.0042714
20	0.5265	0.413	0.0023209
21	0.5398	0.3165	0.0001889
22	0.5521	0.212	0.0012975
23	0.5633	0.1035	0.0011202
24	0.5736	-0.01	0.0034277
25	0.5833	-0.123	0.0015812
26	0.59	-0.21	6.878E-05
Total IAE			0.0505855

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