Estimation of Photovoltaic Cell Parameters Using Piecewise Linear Approximation

Helal Al-Hamadi

Abstract**—**This paper focuses on the estimation of the parameters of single-diode photovoltaic cell using piecewise approximation. A lumped circuit current-voltage characteristics model is used to represent photovoltaic cell. No direct general analytical solution exists for such model. The model is approximated by a piecewise linear function that relates the cell current and voltage with some parameters to be estimated. Using the input-output characteristic data of the solar cell, a linear programming technique is developed to solve a set of linear equations to optimally estimate the solar cell parameters.

Keywords**—**I–V characteristics, Linear programming, Optimization, Parameter estimation, Photovoltaic, Silicon solar cell.

I. Introduction

A SOLAR PV system is a renewable energy source. It is an important emerging alternative to supply electricity for long-term sustainability. This system is not only providing reliable and environmentally friendly energy but also could economically visible for rural and remote areas as a source the only source of energy. In many countries, connecting every remote village and isolated islands to the power utility grid system is very expensive and not cost effective. The flexibility solar PV system for such areas will makes it appealing despite its initial cost.

Despite the challenges of variability of electricity generation, life duration of solar photovoltaic devices and economic feasibility of deployment, it is gaining significant attention. This is due to the fact that solar photovoltaic is a semiconductor device that produces DC electricity when sunlight shines on the photovoltaic. It is static, quite, and free of moving parts system without any gas or toxic emissions and therefore requires little operation and maintenance costs.

The solar cell is the elementary building block of the photovoltaic device. Solar photovoltaic cells are normally arranged into arrays called panel or a module which directly converts sun radiation into electricity. Solar cells are made of semiconductor material with a p-n junction that has the property of, when exposed to sunlight, produces direct-current electricity proportional to the solar radiation. Several models have been proposed to describe the solar cell characteristics. [3]-[6]. A Double-diode solar cell model is considered in this project with the same identity factor.

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A lumped parameter equivalent circuit with to model the solar cell. The main parameters to simulate the I-V terminal characteristics of the solar cell are, photo current, saturation current, shunt resistance, series resistance, and diode identity factor. The electrical current produced by a solar cell depends on the intensity of the incident light and on its intrinsic properties. An accurate estimation of the cell parameters required for accurate performance evaluation [3].

Several estimation techniques have been proposed to approximate solar cells model parameters. A pattern search optimization technique for extracting the parameters of single diode, double diode, and photovoltaic module models is discussed in [4]. A Simulated annealing based approach is proposed in [5] for optimal estimation of solar cell model parameters. In [6], [12] numerical curve fitting procedures are used to estimate the cell model parameter: a non-linear two-point interval division and particle swarm optimization algorithm were then applied to extract local parameters from the current-voltage data at search measurement point. An extraction method that avoids the measurements of the peak power point and I-V curve slope which is based on the power law I-V model is proposed in [7]. The method extracts the four model parameters simultaneously from just four simple measurements of the bias points on the illuminated J-V curve, using closed-form expressions. In [8],[11] a real-time estimation method of maximum power point tracking is proposed. The method uses polynomials to demonstrate the power-voltage relationship of PV panels and implements the recursive least-squares method and Newton-Raphson method to identify the voltage of the optimal operating point. Particle swarm optimization (PSO) was applied to extract the solar cell parameters in [9]-[10].

In this paper a mathematical programming approach is used to estimate a set of five parameters of the solar photovoltaic cell. The approach optimally extracts the parameters of interest in order to fit a given experimental current-voltage characteristics using diode lumped circuit models.

The remainder of this paper is organized as follows. For complete presentation, the traditional PV models together with the linear PV current versus voltage (I-V) characteristics are described in Section II. Section III demonstrates the formulation of the nonlinear programming for estimating the PV model parameters. Section IV presents testing and simulation results compared with other results from the literature. Finally, brief conclusions and summary of our findings are presented in Section V.

II. Theory And Analysis

Solar photovoltaic power generation employs solar panels also called modules that composed of a number of solar cells containing semi-conductor photovoltaic diode(s) which converts solar radiation into electric current. Mathematically, the solar photovoltaic cell is modeled by current voltage relationship (I-V) which exhibits a non-linear relationship due to the semi-conductor behavior of the cell. This (I-V) characteristic of the solar cell can be presented by a single diode model [2], [3] and V_L shown in Fig. 1, and mathematically presented by Eqs. (1) and (2).

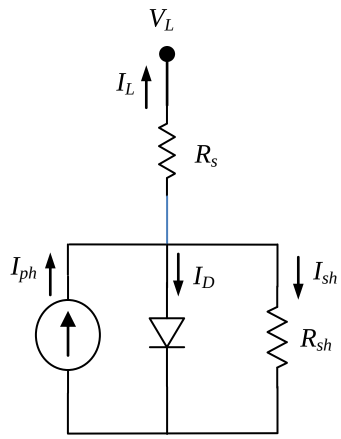

Fig. 1 Equivalent circuit for a single diode lumped circuit.

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

$$I_L = I_{ph} - I_{SD}\left[e^{\left(\frac{q(V_L+I_LR_s)}{nkT}\right)} - 1\right] - \left[G_{sh}(V_L + I_LR_s)\right] \tag{2}$$

Where $I_{ph}, I_{SD}, n, R_s, G_{sh} = (1/R_{sh})$ being the photocurrent, the diode saturation current, the diode identity factor, the series resistance and the shunt conductance, respectively. IL and VL are the terminal Current and voltage respectively; (q/kT) is the inverse thermal voltage, where k is Boltzmann's constant (1.3806503 x 10-23 J/K); q is the electronic charge (1.602176565 x 10-19 C) and T is the cell absolute temperature in Kelvin.

The photovoltaic solar module consists of series and parallel solar cells arranged as Np parallel lines; each line consists of Ns diodes connected in series. The relation between the terminal current and voltage is mathematically expressed in eq. (3):

$$I_L = I_{ph}N_p - I_{SD}N_p\left[e^{\left(\frac{q\left(\frac{V_L}{N_s}+I_L\frac{R_s}{N_p}\right)}{nkT}\right)} - 1\right] - \left[G_{sh}\left(V_L\frac{N_p}{N_s} + I_LR_s\right)\right] \tag{3}$$

Basically, due to presence of device diode(s) in circuit models the photovoltaic solar cell (I-V) characteristics is nonlinear. The models exhibit transcendental functions of the overall current and voltage. The models have 5 parameters ($I_{ph}, I_{SD}, n, R_s, and\ G_{sh}$) that determine the behavior of the cell. Accurate estimation of the model parameters is crucial for providing precise modeling and accurate performance evaluation of the cell. In the next section a mathematical programming approach for estimating the 5 solar photovoltaic cell parameters is addressed.

III. Mathematical optimization model

The mathematical programming model is based on minimizing the difference between the model and the measured values. Artificial variables $x_i\ and\ y_i\ for\ i = 1, \dots, N$ are employed to compensate for positive and negative variations; where N is the number of the measured terminal current and voltage pairs (V_{Li}, I_{Li}). Moreover, practical bounds on the variables have been introduced. Mathematical programming techniques modeling presented in [13] and [14] are used to evaluate the parameters.

Objective function

$$\min \sum_{i=1}^{N}(x_i + y_i) \tag{4}$$

Satisfying measurement data:

$$I_{Li} - I_{ph} + I_{SD}\left[e^{\left(\frac{q(V_{Li}+I_{Li}R_s)}{nkT}\right)} - 1\right] + \left[G_{sh}(V_{Li} + I_{Li}R_s)\right] = x_i - y_i \quad for\ i = 1, \dots, N \tag{5}$$

Artificial variables are positive:

$$\begin{aligned} x_i &\geq 0 \qquad for\ i = 1, \dots, N \\ y_i &\geq 0 \qquad for\ i = 1, \dots, N \end{aligned} \tag{6}$$

Practical bounds on the 5 parameters

$$\begin{aligned} &0.7 \leq I_{ph} \leq 0.8 \\ &0.0000001 \leq I_{DS} \leq 0.000001 \\ &0.03 \leq R_s \leq 0.04 \\ &0.01 \leq G_{sh} \leq 0.03 \\ &1 \leq n \leq 2 \end{aligned} \tag{7}$$

For each measurement data pair $(I_L, V_L),\ for\ L = 1, \dots, N,$ the associated exponential function $E_L = e^{(T_L)}$ is approximated using piecewise linearization technique developed based on mixed-integer zero-one piecewise-linear function [12]. The piecewise-linear function has m affine segments, defined by (m+1) points, $l_L = t_{L1} \leq t_{L2} \leq \cdots \leq t_{L(m+1)} = u_L$ as illustrated in Fig. 2.

With each point $(t_{Li}, e^{t_{Li}})$ associate complex combination weights $(\lambda_{L,i\bar{L}}, \lambda_{L,i\bar{R}})$, $i = 1, \cdots, m+1$. Where $\bar{L}$ and $\bar{R}$ indicates left and right weights. For the first and the last points, the left and right variables are zeros, respectively (i.e. $\lambda_{1L} = \lambda_{mR} = 0$). Furthermore, for selection of only one of the affine segment a binary (0, 1) variable z_i is associated with segment i, $i = 1, \cdots, m$. Subsequently, the resulting formulation is given as follows:

For each measurement data pair (I_L, V_L),

substitute: $\left(\sum_{i=1}^{m+1} t_{Li}(\lambda_{L,i\bar{L}} + \lambda_{L,i\bar{R}}) \right)$ for T_L

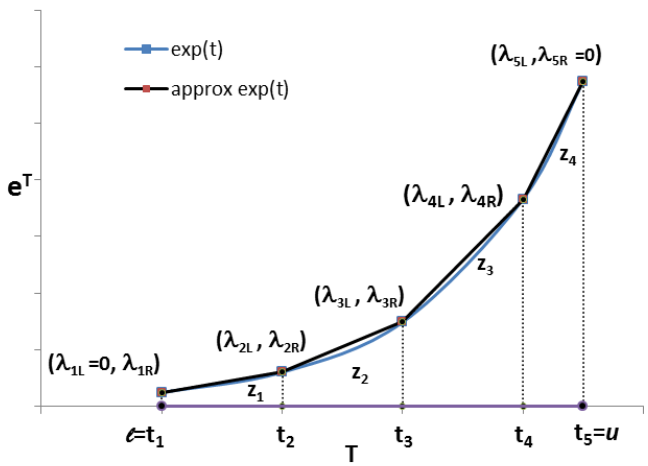

Fig. 2 Piecewise linearization with m=4

and

substitute: $\left(\sum_{i=1}^{m+1} e^{t_{Li}}(\lambda_{L,i\bar{L}} + \lambda_{L,i\bar{R}}) \right)$ for E_L

only one segment is selected: $\sum_{i=1}^{m+1} z_{Li} = 1$

for each segment: $\lambda_{L,i\bar{L}} + \lambda_{L,i\bar{R}} = z_{Li}$ for $i = 1, \cdots, m$

z_{Li} is binary; $i = 1, \cdots, m$

IV. Results And Discussion

The above mathematical model is employed to estimate the 5 photovoltaic solar cell parameters. Real photovoltaic solar cell terminal data $(V_{Li}, I_{Li})\ for\ i = 1, \dots, N$ are considered in this testing [5]. The resulting parameters with comparison with previous work using other techniques are presented in Table I. The comparison is based on the Absolute Mean Error (AME). For each method the estimated resulting parameters along with current the measured terminal are used to calculate the terminal voltage. The AME of the calculated and measured voltages are computed and presented in Table I.

Table I
Comparisons Of Estimated Parameters

	Ref. [11]	**Ref. [12]**	**Using Nonlinear Optimization**	**Using Linear Optimization**
Iph	0.7617	0.7707	0.762113	0.76200
Isd	9.98 E-07	3.267E-07	4.6E-07	4.798E-07
Rs	0.0313	0.0364	0.034653	0.04798
Ghs	0.0156	0.0166	0.023	0.0232000
n	1.6	1.4816	1.518082	1.5172000
Error (MAE)	**0.10295**	**0.1171**	**0.089003**	**0.088926**

V. Conclusion

In this paper photovoltaic solar cell is modeled as a lumped circuit with nonlinear mathematical model. Piecewise linear approximation is used to approximate the model. The model parameters are estimated using linear 0-1 mathematical programming. Without loss of generality, a double diode model is used in the formulation, other models such as single diode and photovoltaic module could be applied similarly. The proposed algorithm gives almost the same result of that of the estimation of the parameters using nonlinear model.

Acknowledgment

The research is supported by Kuwait University Research Sector under grant WI01/13. The author would like to thank Kuwait Foundation for the advancement of science of their financial support for attending the conference.

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