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Parameters extraction of solar cells – A comparative examination of three methods

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ABSTRACT

This paper deals with the extraction of the parameters of the single-diode solar cell model from experimental I–V characteristics of Si and Multi-junction solar cells. The extraction is carried out by three different optimization methods in an attempt to judge which method surpasses the others in terms of data-to-model fitting. The first and the second methods are a variation of the Newton-Raphson method and the Levenberg–Marquardt algorithm, respectively. Both methods are based on the gradient descent approach. The third method is a global-search method based on a Genetic-Algorithm. The extraction of the parameters was done in two stages. On the first stage, empirical I–V characteristics of solar cells that contained measurement errors were used, whereas on the second stage the parameters were re-extracted using a smooth synthetic I–V data. In the absence of true measured parameter values of the cells, it was left to rate the performance of the three optimization methods by the extraction error alone. Although no definitive conclusions could be drawn from the results of the noisy data, results of the smooth data are far more pronounced in terms of the extraction error, and tend to favor the Newton-Raphson method.

1. Introduction

Formulating an equation that describes the performance of photovoltaic cells under illumination or in dark conditions, one from which the cell's physical parameters can be restored, is of great value in the field of photovoltaic engineering. The single-diode model that describes the cell's current–voltage relationship is basically derived from the semiconductor equations that govern the physics of solar cells. Once a solar cell model has been established, optimization methods can be employed to extract the unknown model parameters. Each parameter accounts for a different component that constitutes the electrical circuitry of the model. The one-diode model shown in Fig. 1(a), is composed of 5 such parameters, namely the series and the shunt resistance, R_s and R_{sh}, respectively, the diode ideality factor n, the diode reverse-saturation current I_0, and the photogenerated current I_L.

Although the one-diode model is considered accurate, it is oftentimes elaborated in order to follow the behavior of solar cells more adequately. Ben-Or et al. [1] extended the set of conventional parameters in the one-diode model, to include 8 parameters instead of 5. By adding to the model α, V_{br} and m – the cell's correction coefficient, breakdown voltage and exponent-power, respectively, the model was extended to cover the cell's negative-voltage operation mode.

The act of parameters extraction, may be perceived as being subjected to two opposing aspects, mathematical and physical. On the one hand, the problem of combining a model with an experimental data so as to extract its parameters is purely mathematical. From the mathematical point of view, it is apparently favorable to employ a model that consists of a small number of parameters, one which reduces the complexity level of optimization. On the other hand, from the physical point of view it may be unrealistic to confine ourselves to the one-diode model, since parametric-wise, an extended model covers a larger number of phenomena that underlie the physics of solar cells. This in turn enhances the accuracy of the model. (See: Fig. 1(b) - the two-diode model)

The parameters extraction has an extensive reference in the related literature. It can be claimed that the extraction procedures are distinguished by the amount of the data samples that participate in the extraction procedure, by the type of model being used, and by the mathematical approach that is employed. Focusing on the mathematical aspect, the parameters extraction of solar cells is generally divided into two categories – numerical methods and analytical methods. Numerical methods rely on curve fitting algorithms to find an optimized fit between theoretical and experimental I–V characteristics of solar cells. These curve fitting methods are said to have an overall higher level of confidence in

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Nomenclature

ACT	algorithm conversion time
I_0	diode reverse saturation current
I_L	solar cell's photogenerated current
I_{sc}	solar cell's short-circuit current
n	diode ideality factor
R_{sh}	solar cell model's shunt resistance
R_s	solar cell model's series resistance
V_{oc}	solar cell's open-circuit Voltage
V_T	thermal voltage
GA	Genetic-Algorithm
LMA	Levenberg–Marquardt Algorithm
MJ	multi-junction
NRM	Newton–Raphson Method

terms of the resulting values of the parameters, since the majority or the entire set of I–V samples are used throughout the extraction procedure. On the other hand, the accuracy of the fitting methods depends on the type of the method, the objective function to be minimized, and the starting values of the parameters that are introduced prior to the running of the algorithm. In addition, curve fittings that are based on gradient-descent methods may tend to converge to local rather than global extrema on account of an inappropriate choice of initial values. Also, these methods may require a relatively long computation time. In contrast, analytical methods only require a limited set of I–V points corresponding to a finite set of equations whose solution are the parameter values. In that sense, analytical methods are characterized by a straightforward algebraic approach. Bearing in mind, however, that experimental I–V samples may contain measurement errors makes it vital to choose an appropriate set of points in order to avoid inaccuracy.

Various parameters extraction techniques have been proposed in the literature, and since the parameters extraction is a multidimensional numerical optimization problem, different authors have obtained different values of parameters for common sets of I–V data. Therefore it can be argued that no method insures completely reliable results for the extracted parameters. Ghani and Duke [2] proposed an approach whereby only R_s and R_{sh} are extracted, relying solely on the maximum power-point values of the voltage and the current. The experimental I_m and V_m in [2] were retrieved from a relevant manufacturer datasheet. The resistances were extracted by applying the Newton–Raphson technique to find the roots of an equation that was derived from the single-diode model. Chan et al. [3] have also used the Newton–Raphson technique to minimize the error difference, denoted $\Delta Area$, between the areas confined under the empirical and theoretical I–V curves. In [3], two types of extraction are presented – the 5-point method, whereby 5 equations are solved for 5 distinct points along the I–V curve, and a Newton–Raphson based curve-fitting technique, where the entire set of data points is used. Appelbaum et al. [4] have suggested a new approach to sort an array of solar cells based on their performance. The procedure in [4] involved the use of the single and the two-diode models. Parameters extraction via a quasi-Newton based curve fitting was demonstrated in [4] on a batch of 50 silicon solar cells. Yadir et al. [5] used the same error criterion as in [3] but obtained the analytical expression for the area under the I–V curve through derivation of the single-diode model equation.

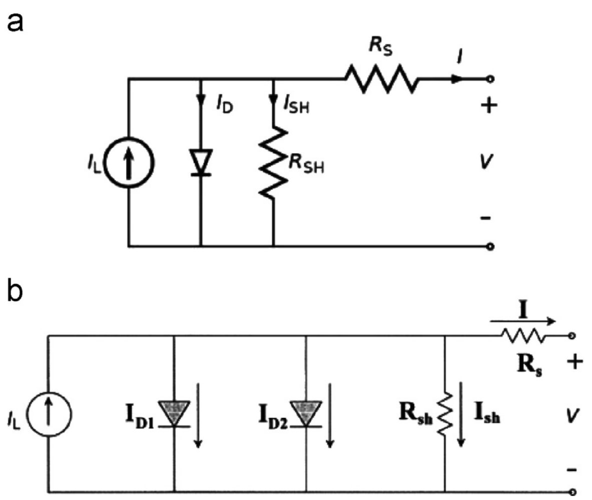

Fig. 1. An equivalent electrical circuit of a solar cell under illumination: (a) The single-diode model, and (b) The two-diode model.

Ye et al. [6] applied the particle swarm optimization and the genetic-algorithm methods on both synthetic and experimental I–V data, using the two-diode and the single-diode models. The second diode in the two-diode model contributes two additional parameters-an ideality factor n_2 and a reverse saturation current I_{02}, The latter is typically 10^5 times smaller than its counterpart, I_{01}. In terms of the objective-function minimization, the results for the two-diode were slightly improved in comparison to the one-diode model. Maoucha et al. [7] too, have used a Trust-Region based optimization to extract the seven parameters of the two-diode model for measured data of organic solar cells. Chan et al. [8] used the two-diode model and applied the Newton–Raphson method to extract parameters from silicon cells. Algebraic substitutions were used in [8] to reduce the number of the extracted parameters.

This paper focuses on three methods of parameters extraction, of which the first two are gradient-descent based techniques, hence local in their search. The third method, a genetic algorithm based extraction, is global in its search and requires no initial values for the parameters. In this work, we restrict ourselves to the single-diode model. We first reduce the cell model to three parameters instead of five, by using some algebraic manipulations. The objective function that is derived from the reduced model is then applied to all three methods. The first Newton–Raphson Method (NRM) that was used in several other works has been altered here by adding an additional stage in between the traditional steps of the algorithm. This variation was carried out in order to overcome some convergence difficulties arising from the complex nature of the objective function. The two other methods, namely the Levenberg–Marquardt Algorithm (LMA) and the Genetic-Algorithm (GA), were left unchanged. All extraction methods were examined on three Si cells as well as on a Multi-junction cell with concentration of 350, 555 and 750 Sun. In the Si cells case, the extraction was mainly performed in order to show that the extracted values bear similarities to the expected physical parameters which characterize Si cells. In the multi-junction cell case, we expected the value of the extracted parameters to show correspondence with the increasing of the concentration level.

2. The single-diode and the two-diode model equations

Under Illumination, the I–V characteristics of a p–n junction solar cell at forward-bias, can be represented by the following