



Comparison of Different Extraction Methods for the Simulation of Thin-Film PV Module

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Abstract. This paper investigates and compares three different methods commonly employed in solving current–voltage equation of single diode and two diode solar PV models using manufacturer’s data sheet based on three parameter estimation methods are employed: an iterative method, method of the slope at point and an analytical method based on the Lambert W function. These three existing mathematical methods are implemented to estimate the parameters of thin-film PV module under changing environmental conditions.

The results reveal that no single method performs best in all the metrics and there will always be a trade-off in the choice of the method based on the user’s focus.

The present work can be a potential tool for researchers and designers working in the area of photovoltaic systems, to make decisions related to the selection of the best possible method for the extraction of the characteristic parameters of thin-film PV modules.

Keywords: Thin film PV modules · Numerical methods · Analytical methods · Parameter extraction · Performance I–V curves

1 Introduction

During the last years the international market of thin-film photovoltaic (PV) modules has been increasing considerably mainly due to their simple and low-cost manufacturing process. The various thin-film technologies reduce the amount of light absorbing material that is necessary to produce a solar cell.

Therefore, to ensure the maximum use of the available solar energy by a PV power system, it is important to study its behaviour through modeling, before implementing it in reality. The mathematical model of the PV device is very useful in studying various PV technologies and in designing several PV systems along with their components for application in practical systems.

Some researchers have compared the algorithm used in extracting the parameter of solar PV models. For example, the extraction of the parameters of the single-diode solar cell model using experimental I–V characteristics of Si and Multi-junction solar

cells has been performed by Appelbaum and Peled [1]. In another research, Ciulla et al. [2] compared the I–V and P–V curves at various temperatures and irradiance for a generic PV panel for five different algorithm models which are: Hadj Arab et al. [3] model, De Blas et al. [4], Lo Brano et al. [5], Villalva et al. [6] and De Soto et al. [7] models.

Extensive studies have been conducted to determine the series resistance (R_s) and parallel resistance (R_{sh}). Some authors neglect R_p to simplify the model as the value of this resistance is generally high [8], and sometimes, the R_s is neglected, as its value is very low [9]. The neglect of R_s and R_p has significant impact on the model accuracy. Several algorithms have been proposed to determine both R_s and R_{sh} through iterative techniques [10]. In [11], R_s and R_{sh} are evaluated by using additional parameters which can be extracted from the current versus voltage curve of a PV module.

This present study tends to contribute also along this direction by including other metrics in addition to the accuracy of the models for an encompassing comparison of parameter extraction models. This study therefore evaluates the performances of three extraction methods (iterative method, method of the slope at point and the Lambert W function). These three methods applies the one diode and two diode models and based only on the manufacturer datasheet of ST40 thin film PV panel, whose the objective is to predict the behavior of Shell ST40 panel under real environmental conditions. The Shell ST40 belongs as a copper indium diselenide (CIS) thin film technology, their module size ($W \times L$) is $0.328 \times 1.293 \text{ m}^2$.

2 Materials and Methods

2.1 Lambert W-Function Method

A PV cell of current equation mathematically solved by the Newton's Raphson method is difficult to employ the Large PV structure. This equation gives the relation involving the output current (I) and terminal voltage (V) under the environment condition as:

$$I = I_{pv} - I_0 \cdot \left(\exp\left(\frac{V + R_s \cdot I}{V_T}\right) - 1 \right) - \left(\frac{V + R_s \cdot I}{R_{sh}} \right) \quad (1)$$

Where

- I_{pv} Photocurrent
- I_0 Cell saturation current
- R_{sh} Shunt resistance
- R_s Series resistance
- V_T the thermal voltage ($V_T = a \cdot N_s \cdot k \cdot T / q$)
- N_s Number of cells in series
- a Ideal factor of the PV diode
- q Electron charge ($1.60281 \times 10^{-19} \text{ C}$)
- k Boltzmann's constant = $1.38066 \times 10^{-23} \text{ J/K}$
- T Cell operating temperature

When reach the level of entire PV structure it is difficult to solve Newton’s method because in large PV structure all cell is individually described by a only one equation, so task becomes complicated, rising the convergence issues. To overcome this limitation Lambert W Function is used to the explicit results of current and voltage equations (Fig. 1). The Lambert W Function $W(x)$ is defined as Eq. (3) [13].

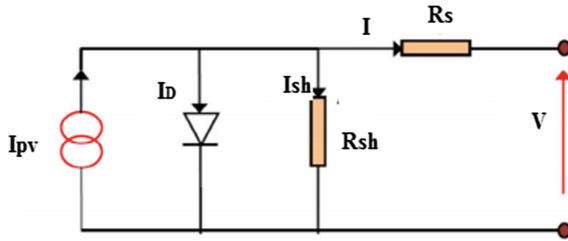


Fig. 1. PV-cell equivalent-circuit models: single-diode model [12].

If we make the following change of variable:

$$x = \frac{V_{mp} + I_{mp} \cdot R_s}{a \cdot N_s \cdot V_T} \tag{2}$$

The analytical solution based on the use of the Lambert W function, which is the solution of the equation:

$$f(x) = x \cdot e^x \tag{3}$$

Then the series and parallel resistances can be written as follows:

$$R_s = \frac{x \cdot a \cdot N_s \cdot V_T - V_{mp}}{I_{mp}} \tag{4}$$

$$R_{sh} = \frac{x \cdot a \cdot N_s \cdot V_T}{I_{PV} - I_{mp} - I_0 [\exp(x) - 1]} \tag{5}$$

Where x 's expression is given in Eq. (6). The value obtained by (6) is substituted in (4) and (5) to deduce the values of R_{sh} and R_s .

$$x = \text{Lambert W} \left[\frac{V_{mp} \cdot (2I_{mp} - I_{PV} - I_0) \left[\exp\left(\frac{V_{mp} \cdot (V_{mp} - 2a \cdot V_T)}{(a \cdot N_s \cdot V_T)^2}\right) - 1 \right]}{a \cdot N_s \cdot V_T \cdot I_0} \right] + 2 \frac{V_{mp}}{a \cdot N_s \cdot V_T} - \left(\frac{V_{mp}}{a \cdot N_s \cdot V_T} \right)^2 \tag{6}$$

The mathematical relation the Eq. (3) is applied to Eq. (1) in order to obtained the equation for the cell gives the explicit results of current and voltage equation. By solving Eq. (1) with the Lambert W method the equation of the output current as the function of output voltage as given in Eq. (7) [14].

$$I = -\frac{V}{R_s + R_{sh}} - \frac{\text{LambertW}\left(\frac{R_{sh}(R_s I_{pv} + R_s I_0 + V)}{a \cdot V_T (R_s + R_{sh})}\right)}{R_s} + \frac{R_{sh}(I_0 + I_{pv})}{R_s + R_{sh}} \tag{7}$$

Where:

$$I_0 = I_{pvn} \cdot \exp\left(-\frac{V_{ocn}}{a \cdot N_s \cdot V_{Tn}}\right) - 1 \tag{8}$$

The ideality factor (a) is calculated by:

$$a = \left(K_V - \frac{V_{oc}}{T_n}\right) / a \cdot N_s \cdot V_{Tn} \left(\frac{K_i}{I_{pvn}} - \frac{3}{T_n} - \frac{E_g}{k \cdot T_n^2}\right) \tag{9}$$

2.2 Method of the Slope at Point

The difference given by this method in comparison of the previous method is in the manner of calculating the series resistance. It is based on the fact that the series resistance influences remarkably the slope of the characteristic curve I-V in the vicinity of the point (Voc, 0).

$$\frac{dI}{dV} = -I_0 \left[\exp\left(q \frac{V + IR_s}{aN_s kT} - 1\right) \right] \frac{q}{aN_s kT} \left(1 + R_s \frac{dI}{dV}\right) \tag{10}$$

$$R_s = -\frac{dV}{dI} \Big|_{V_{oc}} - \frac{1}{\frac{I_0 q}{aN_s kT} \exp\left(q \frac{V_{oc}}{aN_s kT}\right)} \tag{11}$$

The slope $M = \frac{dV}{dI}$ (I = 0) at the point (Vco, 0) is deduced geometrically from experimental data (Fig. 2).

The photocurrent I_{pv} of the PV cell is directly proportional to the solar insolation. The output current I of the cell is equal to photo generated current I_{pv} , minus diode current I_D , minus shunt current I_{sh} .

$$I = I_{pv} - I_D - I_{sh} \tag{12}$$

As $R_{sh} \approx \infty, I_{sh} \approx 0$.

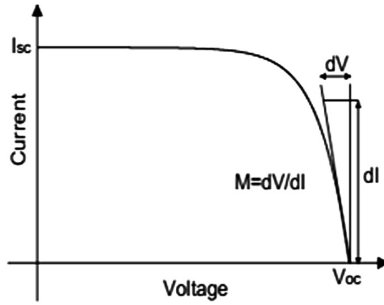


Fig. 2. The slope calculation at the open circuit voltage point

$$I = I_{pv} - LD \tag{13}$$

Thus the equations for the I-V characteristics of the PV cell are:

$$I = I_{pv} - I_0 \left[\exp \left(q \frac{V + IR_s}{a N_s k T} - 1 \right) \right] \tag{14}$$

Hence, to solve Eq. (14) the value of voltage (Voc) and current (Isc) at different temperature T1 & T2 is the Eq. (15) [15]:

$$I_0(T) = I_{0(T1)} \left(\frac{T}{T_1} \right)^3 \exp \left[\left(\frac{q E_g}{a \cdot K} \right) \left(\frac{1}{T_1} - \frac{1}{T} \right) \right] \tag{15}$$

Here, the energy gap of the material is defined as Eg
Where

$$I_{0(T1)} = \frac{I_{pvn}}{\exp \left(\frac{V_{ocn}}{a V_{Tn}} \right) - 1} \tag{16}$$

$$I_{PV} = [I_{PVn} + K_i \cdot (T - T_n)] \cdot G / G_n \tag{17}$$

Where:

$$I_{sc} = I_{PV} \tag{18}$$

$$K_i = [I_{sc(T2)} - I_{sc(T1)}] / (T2 - T1) \tag{19}$$

2.3 Iterative Method

This method appears an improved modeling approach for the two-diode model of photovoltaic (PV) module. The main contribution of this method is the simplification of the current equation. Furthermore the values of the series and parallel resistances are

computed using a simple and fast iterative method. The both reverse saturation currents I_{01}, I_{02} are set to be equal in magnitude

$$I_{01} = I_{02} = \frac{I_{sc} + K_i \cdot \Delta T}{\exp\left(\frac{q \cdot (V_{oc} + K_v \cdot \Delta T)}{kT \cdot (a_1 + a_2)}\right) - 1} \tag{20}$$

Diode ideality factors a_1 and a_2 represent the diffusion and recombination current components, respectively. Ishaque [10] put $\frac{a_1 + a_2}{p} = 1$ and $a_1 = 1$, it follows that variable p can be chosen to be $p \geq 2.2$. This generalization can eliminate the ambiguity in selecting the values of a_1 and a_2 . Equation (20) can be simplified in terms of p as:

$$I = I_{pv} - I_{01} \cdot \left(\exp\left(\frac{V + R_s \cdot I}{V_{T1}}\right) - 1 \right) - I_{02} \cdot \left(\exp\left(\frac{V + R_s \cdot I}{V_{T2}}\right) - 1 \right) - \left(\frac{V + R_s \cdot I}{R_{sh}} \right) \tag{21}$$

The R_s and R_{sh} are calculated simultaneously, similar to the procedure proposed in [10]. From Eq. (21) at maximum power point condition, the expression for R_{sh} can be rearranged and rewritten as:

$$R_{sh} = \frac{V_{mp} + R_s \cdot I_{mp}}{I_{pv} - I_{01} \cdot \left(\exp\left(q \frac{V_{mp} + R_s \cdot I_{mp}}{k \cdot T}\right) + \exp\left(q \frac{V_{mp} + R_s \cdot I_{mp}}{(p-1)k \cdot T}\right) + 2 \right) - \frac{P_{max,e}}{V_{mp}}} \tag{22}$$

The initial conditions for both resistances are given below

$$R_{s0} = 0, R_{p0} = \frac{V_{mp}}{I_{sc,STC} - I_{mp}} - \frac{V_{0c,STC} - V_{mp}}{I_{mp}} \tag{23}$$

3 Results and Discussion

The equations of the previous section were implemented in MATLAB environment to simulate, evaluate and test the three methods mentioned above for ST40 PV modules. The datasheet parameters specified under STC are already given in Table 1.

Table 1. Specification of the PV modules

Modules	Isc(A)	Voc(V)	Imp(A)	Vmp (V)	Ki _(Isc) (mA/°C)	Kv _(Voc) (mV/°C)	Ns
Thin-Film Shell ST40	2.68	23.3	2.41	16.6	0.35	-100	36

Figure 3 show the I-V characteristics compared with measured data extracted from ST40 PV module’s datasheet, for different irradiance levels at 25 °C and for different temperature levels and at 1 kW/m². It is noted that the I-V characteristics of the method of the slope at point show good agreement with the measured data, with the exception of iterative method and the W-function method around V_{OC} for low irradiance.

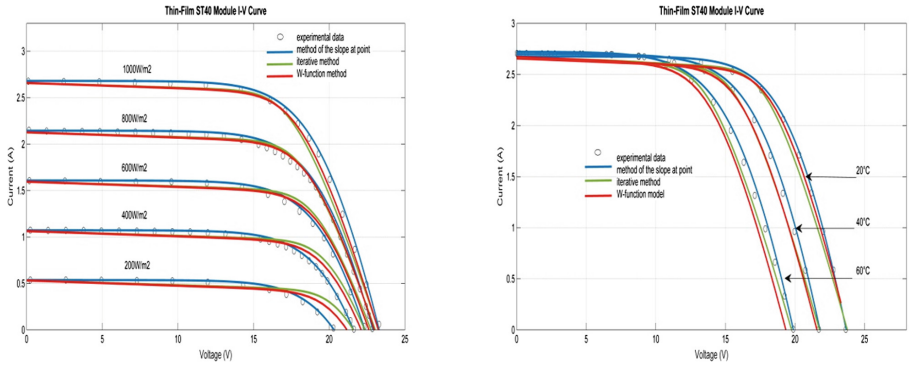


Fig. 3. The I-V characteristics of ST40 module at varying irradiance and temperature.

In the other hand, It is observed that at temperatures around STC, the models have similar behavior for all method. However, as the temperature increases, the Lambert W function method’s characteristics tends to a slight deviate from the other methods.

Table 2 show the parameters estimated for ST40 PV module. The values these parameters (R_s , R_{sh} , a , I_0 and I_{pv}) are estimated using three methods. Certainly, the similarity of the results between these methods is noteworthy and the differences have no appreciable influence on the simulated I-V characteristics at STC.

Table 2. The estimated parameters of ST40 using three models at STC.

Modules	Thin-Film (ST40)		
Models	Method of the slope at point	Iterative method	W-function method
I_{pv}	2.68	2.657	2.68
a_1	2	1	1.23
a_2	–	1.3	–
R_s	0.839	1.71	1.435
R_{sh}	–	198.941	174.531
$I_{o1} = I_{o2}$	$9.122e - 6$	$3.075e - 11$	$3.415e - 09$

To provide thorough evaluation, data corresponding to the above mentioned panels are taken from manufacturer’s datasheet and I-V curves are matched with the simulation results obtained using three models. Further, to know the quality of the curve fit between these models values to the experimental data, statistical analysis is carried out

by measuring Individual Absolute Error (IAE) values. The IAE values are calculated by using the mentioned formula.

$$\text{Individual Absolute Error: } (IAE) = |I_{\text{measured}} - I_{\text{estimated}}| \tag{24}$$

Figure 4 show the absolute errors of I–V characteristic for ST40 PV module. The absolute errors of method of the slope at point are less than that of the other methods at all the conditions.

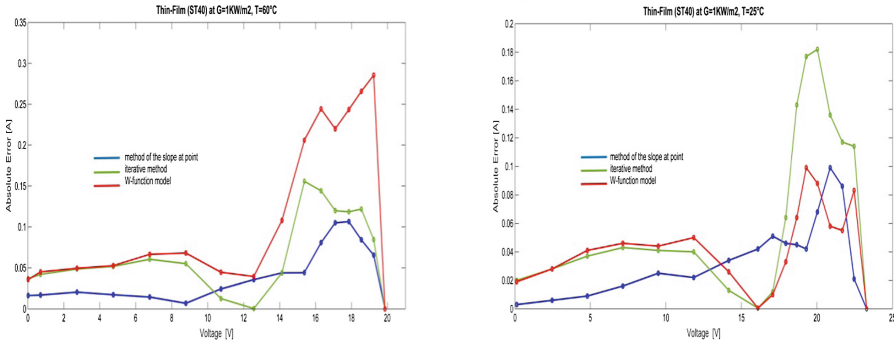


Fig. 4. Absolute error for Thin-Film ST40.

4 Conclusion

In this work, three parameter estimation models existing in the literature are described and have been verified by simulation and measured data, which were extracted from datasheet I–V characteristics. The methods that the most accurate method of parameter estimation given in the PV modules’ datasheets of the ST40 module is method of the slope at point. The differences between the three estimation methods have no appreciable influence on the simulated I–V characteristics under varying environmental conditions. In particular, excellent accuracy exhibited at high irradiance and low temperature conditions for all models.

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