Estimation of photovoltaic module parameters based on datasheet: A review and a proposed method

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Abstract This paper is aimed at first to present a thorough review of published research works for evaluating the photovoltaic module parameters in three categories. In the first category, the parameters were determined successively one-by-one based on several approximations. The second category was an extension to the first category but through one-or two-loops for determining one- or two-parameters. Then, the remaining parameters were obtained one-by-one. In the third category, an iterative procedure was presented for simultaneous solution of the describing equations based on assumed initial values of some parameters. The remaining parameters -if any- were determined in terms of those already obtained by iteration. The present paper proposes a method for determining the parameters based on datasheet values at three key points on the module current-voltage (I-V) curve and solution of describing equations of the module with the same well-defined initial values, which serve solution for single- and double-diode models irrespective of module type and rating by using Matlab "fsolve" routine. To the authors' knowledge, one of the formulated equations includes -for the first time- the value of the module maximum power. This value was never considered before by other approaches reported in the literature for evaluating the module parameters. The obtained results confirmed the superiority of the proposed method in assessing the module parameters with higher accuracy than that of other methods reported in the literature. The root-mean-square-deviation from the describing equations records a value of 0.005 against a range from 0.03 to 2.45 by other methods for the same module. As a second check, the percentage deviation of the slope of I-V curve at maximum-power-point from its nominal value reached 0.07% for the proposed method against a range from 0.22 to 44.5 % by other methods. As a third check, the accuracy is evaluated at points different from the key points of the datasheet. The module current value at open-circuit voltage is 0.0029A and closer to zero on using the module parameters predicted by the proposed method when compared with values in a range from -0.23 to + 0.92A obtained by other methods.

Keywords datasheet values; single-and double- diode models; open-circuit; short-

circuit; maximum power point; photovoltaic.

1. Introduction

The solar photovoltaic (PV) systems contribute continuously in increasing generation of electric power to mitigate burden on using a time-depleting fossil-fuel, which pollutes the environment. PV cells and modules are commonly modelled as circuits defined by cell/module parameters. Finding appropriate circuit model of PV modules is crucial for performance evaluation including efficiency and maximum power point tracking of PV systems as well as prediction of the characteristic I-V curves of the module when installed in a particular area at different weather conditions. The photovoltaic module has a non-linear I–V characteristic that depends on the solar irradiance and the temperature. The most common model to study the performance of the PV module is the so-called single-diode model (SDM) [1], [2] followed by the double-diode model (DDM) [1],[2]. Some authors had proposed triple diode model (TDM) [2]. The equivalent circuit of a PV module includes a photon current source $\mathrm{I_{ph}}$ and a parallel diode with reverse saturation current $\mathrm{I_0}$ and ideality factor A, as well as series $\mathrm{R_s}$ and parallel $\mathrm{R_p}$ resistors. Therefore, the model has five parameters $\mathrm{I_{ph}}$, $\mathrm{I_0}$, A, $\mathrm{R_s}$ and $\mathrm{R_p}$ for SDM. For DDM, the number of parameters increases to seven to express extra two parameters representing I_0 and A of the second diode. For TDM, the number of parameters increases to nine to express extra four parameters representing I_0 and A of the second and third diodes. To utilize the PV module in an application, all parameters must be known to the design engineer.

The I-V output equation for SDM at a specified solar irradiation G and temperature T was expressed using equation (A-1a) [1] in Appendix A. The analogous equation to (A-1a) for DDM was expressed using equation (A-1b). Equations (A-1a) and (A-1b) multiplied by the voltage V determines the power-voltage (P-V) relationship.

Modules' manufacturers usually give at standard test condition (STC) with $1000\ \mathrm{W/m^2}$ solar irradiance, 1.5 air-mass ratio (AM) and 25 °C cell temperature datasheet-information at three key points including current $\mathrm{I_{sc}}$ at short-circuit point, voltage $\mathrm{V_{oc}}$ at open-circuit point and power ($\mathrm{P_{mpp}}$), voltage ($\mathrm{V_{mpp}}$) and current ($\mathrm{I_{mpp}}$) at MPP, the maximum power point. The coefficients $\mathrm{k_v}$, $\mathrm{k_i}$ and $\mathrm{k_p}$ to assess the variations of $\mathrm{V_{oc}}$ (V), $\mathrm{I_{sc}}$ current (A) and $\mathrm{P_{mpp}}$ (W) with cell temperature are provided in some datasheets. Assessment of the performance at other conditions different from those of STC is possible provided that the module parameters at STC are known.

The present paper is aimed at (i) reviewing the work published in the literature on evaluation of the module parameters based on assumed initial values for the problem-solving approach, and (ii) proposing a systematic method for determining these parameters based on datasheet values and module describing-equations with the same set of well-defined initial values that serve the solution for SDM and DDM. Therefore, assessment of module parameters completes the information provided by the manufacture's datasheets.

The predictions of the parameters by the proposed method for modules either of crystalline or thin film type are compared with those published in the literature over the years including those obtained using Lambert function and optimization techniques supported with experimental measurements to find a solution for the parameters' estimation problem.

The structure of the paper is as follows: Section 2 is devoted for a thorough review of the previous published work and for pinpointing its weakness. Section 3 presents the proposed method. Results and discussions are presented in section 4 and section 5 is assigned for the conclusions extracted from the present work.

2. Literature Review of Methods Reported for Assessment of Module Parameters

2.1. Single diode model (SDM)

2.1.1. First category (parameters were obtained one-by-one based on approximate values assumed for some parameters)

The value of diode ideality factor A was selected [1] equals to 1.3. The value of R_s was obtained from the condition $\frac{dP}{dV}$ equals to zero at MPP which ends up by equation (A-2) in Appendix A in terms of A and datasheet values at the three key points [1]. R_p was determined in terms of A, R_s and datasheet values (I_{sc} and P_{mpp}). I_{ph} was calculated in terms of R_p, R_s and datasheet value (I_{sc}). I_0 was calculated in terms of A, R_p, R_s and datasheet values (V_{oc} and I_{sc}). Thus, the unknown parameters were determined one-by-one using equation (A-2).

In a method based on the Serial–Parallel Ratio (SPR), the five parameters were scaled-down to four parameters [3] without losing significant precision on neglecting one resistance. The photon current I_{ph} was assumed equal to short-circuit current I_{sc}. The SPR value was determined in terms of datasheet values (I_{sc}, V_{oc}, V_{mpp} and I_{mpp}) at the three key points. For SPR >1, $R_p = \infty$ and an explicit equation was given for determining R_s in terms of datasheet values at the three key points. For SPR <1, $R_s = 0$ and an explicit equation was given for determining R_p in terms of datasheet values at the three key points. A was calculated in terms of R_p, R_s and datasheet values at the three key points. I_0 was calculated in terms of A, R_p, R_s and datasheet values (V_{oc} and I_{sc}).

In a presented method [4], R_s and A were calculated in terms of datasheet values (I_{sc}, V_{oc}, V_{mpp} and I_{mpp}) at the three key points. I_{ph} was equated to I_{sc} . I_0 was determined in terms of A and datasheet values (V_{oc} and I_{sc}). R_p was determined in terms of A, R_s and datasheet values (V_{oc} and I_{sc}).

In a presented method [5], the value of the diode ideality factor A was chosen equal to 1.2. Initial value of R_p was determined in terms of datasheet values (I_{sc},V_{mpp} and I_{mpp}) while the initial value of R_s was determined in terms of datasheet values (V_{oc}, V_{mpp} and I_{mpp}). I_{ph} was determined in terms of initial values of R_s, R_p and datasheet value (I_{sc}). I_0 was determined in terms of A, I_{ph}, initial value of R_p and datasheet value (V_{oc}). R_s was determined in terms of I_0, A and initial value of R_s and datasheet value (V_{oc}). R_p was determined in terms of I_0, I_{ph}, A, R_s and datasheet value (V_{mpp} and I_{mpp}).

A method was presented before [6], [7], [8] considering R_p equal to infinity with I_{ph} equal to I_{sc}. The saturation current I_0 was determined [6], [7], [8] from the open-circuit and short-circuit conditions using equation (A-3) in Appendix A. A was determined in terms of datasheet values (I_{sc}, V_{oc}, V_{mpp} and I_{mpp}) at the three key points. R_s was determined in terms of A and the datasheet values at the three key points.

The parameters were determined [9] for an ideal cell ($R_p = \infty$, $R_s = 0$) with ($I_{ph} = I_{sc}$) and I_0 estimated was using equation (A-3). An explicit expression for determining A was given in terms of datasheet values at the three key points.

2.1.2 **Second category** (parameters A and R_s were obtained separately, each in a separate loop or determined simultaneously through two {inner and outer} loops)

A method [10] was based on neglecting the influence of R_p, (i.e, $R_p = \infty$). ($I_{ph} = I_{sc}$) and I_0 was determined using equation (A-3). A was assumed in the range 1-2. Satisfaction of the I-V module-characteristic at MPP (I_{mpp} , V_{mpp}) using equation (A-1a) determined R_s in relation to A as dictated by equation (A-4) in Appendix A [10] provided that I_{ph}, I_0 and R_p were known. As A was assumed, the corresponding value of R_s was determined. The procedure was repeated by incrementing value of A until the condition ($\frac{\partial P}{\partial V} = 0$) was satisfied at the MPP. This determines the final values of A and R_s.

In an attempt [11], A was incremented in the range from 0.1 to 2 in steps of value 0.025. For each value of A, the R_s value was determined based on A and datasheet values (V_{oc}, I_{sc}, V_{mpp} and I_{mpp}) at the three key points. With the known value of R_s, R_p was determined based on A , R_s and datasheet values at the three key points. The final values of A, R_s and R_p were selected corresponding to the maximum obtained value of R_p. I_0 was determined based on A, R_p , R_s and datasheet values (V_{oc} and I_{sc}). However, I_{ph} was determined based on R_p , R_s, I_0 and datasheet value (V_{oc}).

The parameters of SDM of a PV module were estimated [12] based on (i) an iterative method for calculating the module ideality factor A and (ii) four equations formulated at the three key points after doing some simplifications and extractions from previous work [1]. The four equations were solved one-by-one using Simulink in Matlab software. The calculated I-V curves using the presented method agreed with those measured experimentally at different cell temperatures without stating how the module parameters are influenced by cell temperature.

In another research work [13], A was chosen equal to 1.3. I_0 was calculated using equation (A-3). R_s was initially assumed equal to zero while R_p was determined in terms of A, I_0 and R_s and datasheet values at (V_{mpp} and I_{mpp}). I_{ph} was determined in terms of R_p and R_s and datasheet value at (I_{sc}). R_s was incremented in an iterative procedure and the values of R_p and I_{ph} were updated. The iterative procedure continued until P_{mppc}; the calculated maximum power became equal to P_{mpp}; the maximum power obtained from datasheet.

A method was presented [14] based on determining a range of R_s from 0 to $R_{s,max}$ where $R_{s,max}$ was determined in terms of assumed values for A, I_0 and datasheet values

(I_{sc}, V_{mpp} and I_{mpp}). An initial value of R_s within the assigned range was selected and an arbitrary initial value of A was assumed to form an iterative procedure devoted for incrementing R_s. Initial values of ($I_{ph} = I_{sc}$) and I_0 were determined from equation (A-3). Initial value of R_p was determined in terms of R_s, A, I_{ph}, I_0 and datasheet value (V_{mpp}, I_{mpp}). Updated value of A was determined in terms of R_p, R_s, I_{ph}, I_0 and datasheet values (V_{mpp}, I_{mpp}). Updated value of I_{ph} was determined in terms of R_s, A, R_p and datasheet value (I_{sc}). Updated value of I_0 was determined in terms of I_{ph}, A, R_p and datasheet value (V_{oc}). Updated value of R_p was determined in terms of R_s, A, I_{ph}, I_0 and datasheet values (V_{mpp}, I_{mpp}). R_s was incremented and the iterative procedure was continued until the product of two successive values of $\frac{dP}{dV}$ assumed a negative value.

Based on SDM representation, a hybrid approach was presented for extracting the parameters of PV modules [15]. The hybrid model is a combination of the module ideal model and the resistance-network model. In the ideal model, the parameters I_0, I_{ph} and A were evaluated using an analytical approach one-by-one based on the datasheet values under STC. The parameters R_s and R_p were obtained using a numerical approach similar to a previous one [13]. The calculated I-V and P-V curves using the presented hybrid method agreed with those measured experimentally.

A two-step method was presented [16]. The first step was aimed at determining A and R_s-value where R_p was assumed equal to infinity. In an iterative procedure, A was assumed initially equal to 1 and R_s was determined in terms of A and datasheet values (V_{oc}, V_{mpp} and I_{mpp}). I_0 was determined based on A, R_s and datasheet values (V_{oc} and I_{sc}). I_{ph} was determined in terms of A, I_0 and datasheet value (V_{oc}). Then, the calculated voltage V_{mppc} at MPP was obtained using equation (A-1a) corresponding to current I_{mpp} of the datasheet for comparison against V_{mpp} of the datasheet. The procedure was terminated when the difference between V_{mppc} and V_{mpp} became within a predefined tolerance value. In the second step, the Rp-value was calculated for the first iteration using an explicit equation reported before [13] along with the values of A, R_s, I_{ph} and I_0 as obtained from the first step. The iterative procedure was aimed at incrementing R_p and obtaining accurate values of R_p, I_0 and I_{ph} being dependent on R_p while the values of R_s and A were remained the same as obtained in first step. Then, the current I_{mppc} at the maximum-power point was calculated using equation (A-1a) corresponding to V_{mpp} of the datasheet for comparison against I_{mpp} of the datasheet. The iterative procedure was terminated when the difference between I_{mppc} and I_{mpp} became within a predefined tolerance value.

In a presented method [17], all possible values of R_s in the range from 0 to 2 Ω and A in the range from 1 to 2 were attempted. I_{ph} is equal to I_{sc} of datasheet. R_p was calculated in terms of A, R_s, I_{ph} and datasheet value (V_{mpp} and I_{mpp}). I_0 was calculated in terms of A, R_p, I_{ph} and datasheet value (V_{oc}). The values of R_p, I_0 and I_{ph} were determined for each value of R_s and A. For each value of R_s, the calculated output power P_{mppc} (obtained from equation (A-1a) multiplied by V) was compared against P_{mpp} of datasheet or $P_{measured}$. Then, the mean absolute error in power (MAEP) was considered equal to the difference between the calculated P_{mppc} and P_{mpp} of datasheet (or $P_{measured}$ if available) over the voltage range from zero to open-circuit value. The procedure was repeated for other values of A. The requested solution corresponds to the minimum obtained value of MAEP.

A presented method was developed [18] to follow an iterative procedure with two loops; the inner loop was devoted for incrementing A. The outer loop was devoted for incrementing R_s. R_p was determined in terms of A, R_s and datasheet values (V_{oc} and I_{sc}). I_0 was determined in terms of A, R_p, R_s and datasheet values (V_{oc} and I_{sc}). I_{ph} was determined in terms of A, R_p, I_0 and datasheet value (V_{oc}). The iterative procedure was terminated when the difference between the calculated P_{mppc} and P_{mpp} of datasheet became less than a predefined value.

2.1.3 **Third category** (parameters were obtained directly by simultaneous solution of describing equations)

Five equations were formulated [19–22] by applying equation (A-1a) at the three key points as well as equation (A-2) and equation (A-5) in Appendix A. The five equations were reduced by mathematical manipulation and approximation to three equations for determining three unknown parameters R_p , R_s and A. I_0 was determined based on A, R_p , R_s and datasheet values (V_{oc} and I_{sc}). I_{ph} was determined in terms of A, R_p , I_0 and datasheet value (V_{oc}). The equations' solution was performed using Newton-Raphson method [19–21] and Gauss–Seidel method [22].

In a method [23], five equations were formulated based on datasheet values at the three key points using equation (A-1a) as well as equation (A-2) and a supplementary condition concerned with equating derivative of power with respect to current to zero. The five equations were reduced to three equations and solved simultaneously to determine A, R_p and R_s by applying Newton-Raphson with initial values of parameters estimated using simplified explicit equations. I_0 was calculated based on A, R_p , R_s and datasheet values (V_{oc} and I_{sc}). I_{ph} was calculated based on A, R_p, I_0 and datasheet value (V_{oc}).

In a presented method [24], I_0, R_s , R_p and A were obtained based on datasheet values at the three key points using equation (A-1a) as well as equation (A-5) and a supplementary condition concerned with equating derivative of current with respect to voltage at open circuit to $-\frac{1}{R_s}$. $I_{ph}$was determined based on A, R_p , I_0 and datasheet value (V_{oc}).

A method was presented [25], [26] based on formulating a set of five nonlinear equations whose simultaneous solution determines I_{ph}, I_0 , R_p, R_s and A using non-linear least square algorithm [25] and Levenberg–Marquardt algorithm based fsolve [26]. Three out of these five equations were formulated based on datasheet values at the three key points using equation (A-1a) in addition to equations (A-2) and (A-5).

A method was presented [27] based on formulating a set of five nonlinear equations whose simultaneous solution determines the unknown five parameters. Three out of five equations were formulated based on datasheet values at the three key points using equation (A-1a) and the two other equations were formulated at two additional points on I-V curve (I_x current at V_x=0.5V_{oc} and I_{xx} current at V_{xx}=0.5(V_{oc}+V_{mpp}). I_x and I_{xx} were obtained from manufacturer I-V curve.

A method was presented [28] where five equations were formulated based on datasheet values at the three key points using equation (A-1a) as well as equations (A-2) and (A-5) to determine I_0, R_s, I_{ph} , R_p and A using Newton-Raphson method based on guessed initial values to solve the equations.

A method was presented [29] following the same procedure in [23] but the five equations were solved simultaneously using fsolve.

In a method [30], four equations were formulated based on datasheet values at the three key points using equation (A-1a) as well as equation (A-2). The fifth equation was not formulated but claimed to be selected from infinite I-V curves of the module with no explanation.

In an attempt [31], five equations were formulated; two of them obtained by applying equation (A-1a) at open- and short-circuit key points. The 3rd, 4th and 5th equations were obtained from the slope $-\frac{dV}{dI}$ being equal to (i) R_p at the short-circuit point, (ii) R_s at the open-circuit point (iii) $\frac{V_{mp}}{I_{mp}}$ at maximum-power point. After mathematical manipulation, the five equations were transformed into another five explicit equations; each evaluated a parameter. The explicit equations depend on I_{sc}, V_{oc}, P_{mpp}, V_{mpp} and I_{mpp} being extracted from datasheet as well as the slopes $-\frac{dV}{dI}$ at open and short circuit conditions. However, these slopes were not defined.

The parameters of SDM of a PV module were estimated [32] based on measuring the entire I-V curve of the module over the voltage range from zero to Voc. The parameters were obtained by fitting the I-V curve with reference to the basic equation (A-1a), which describes the curve. A portion of the I-V curve around the MPP was utilized for fitting purpose to determine the parameters. Optimal selection of the portion of the I-V curve for parameters' estimation was investigated. Correct choice of that portion of the I-V curve can provide a promising online detection of module aging.

The parameters of SDM of a PV module were estimated [33], [34] using both iterative/numerical and analytical methods. Parameters' prediction using the analytical approaches was compared satisfactorily with those obtained by the iterative methods. The calculated I-V and P-V curves using the analytical and iterative methods agreed with those measured experimentally, even the predicted values of module parameters varied over a wide range. For Shell SP70 module, the parameters R_s, R_p , I_0, and A for SDM varied within the ranges of 0.2 - 0.48, 84 -302, 6.9x10^{-10} - 8.7x10^{-8}, and 1.02 -1.82, respectively.

2.2 Double diode model (DDM)

2.2.1. First category

There is no publish work in the literature on obtaining the module parameters one-by-one as described for the SDM.

2.2.2. Second category

A method was presented [35] for determining parameters of DDM assuming equal reverse-saturation current for both diodes ($I_{01} = I_{02} = I_0$). The ideality factor of one diode was assumed equal to 1 whereas A_2 was calculated from the relationship [$\frac{A_1+A_2}{P}=1$] with the variable p chosen arbitrarily ≥2. I_{ph} was equated to I_{sc} of datasheet. I_0 was determined in terms of A_1 and A_2 and datasheet values (V_{oc} and I_{sc}). The other two parameters R_s and R_p were obtained simultaneously by an iterative method. With iteration, R_s was incremented and subsequently R_p was determined in terms of A_1 and A_2, R_s , I_{ph} and datasheet values (V_{mpp} and I_{mpp}). The iterative procedure continues until P_{mppc} became equal to P_{mpp} of the datasheet within a specified tolerance value.

Assuming that $I_{01}=I_{02}=I_0$ and $A_1=1$ and $A_2=2$, the number of DDM parameters was reduced to four [36]. Firstly, R_p and R_s were correlated by satisfying equation (A-2) at MPP. With iteration, R_s was incremented and subsequently R_p was determined in terms of A, R_s and datasheet values (I_{sc}, V_{oc}, V_{mpp} and I_{mpp}) at the three key points. Secondly, the value of I_{ph} was determined in terms of R_s, R_p and datasheet value (I_{sc}). I_0 was determined in terms of R_s, R_p and datasheet values (I_{sc} and V_{oc}). The iterative procedure was terminated when the value of a pertinent formulated function [36] became less than a predefined value.

A combination between numerical and analytical method was made [37], [38] to determine the seven parameters. At first, initial values of A_1, A_2 and R_s were assumed arbitrary. The values of I_{01} and I_{02} were determined in terms of A_1, A_2, R_s and datasheet values (I_{sc}, V_{oc}, V_{mpp} and I_{mpp}) at the three key points. R_p was determined in terms of A_1, A_2, R_s, I_{01}, I_{02} and datasheet values at the three key points. I_{ph} was determined in terms of A_1, A_2, R_p, R_s, I_{01}, I_{02} and datasheet values at the three key points. R_s was incremented and the iterative procedure was terminated when P_{mppc} became equal to P_{mpp} within a specified tolerance value. For the defined value of R_s, a second iterative procedure was presented by incrementing A_1 and A_2 instead of incrementation of R_s. The iterative procedure was repeated and terminated at P_{mppc} became equal to P_{mpp} of the datasheet within a specified tolerance value. The numerical approach of the method was related to the two iterative procedures. However, the analytical approach of the method was related to the solution of the equations describing I_{01}, I_{02} , R_p and I_{ph}.

2.2.3. Third category

The paper in [39] presented an analytical solution for determining the parameters of a PV module where the unknown parameters was reduced in number from seven to four by assuming $A_1=1$ and A_2 =2 and I_{ph}= I_{sc} of datasheet. I_{01}, I_{02}, R_s and R_p were determined by simultaneous solution of four equations using Newton–Raphson method. These equations were formulated based on datasheet values at the three key points using equation (A-1a) as well as equation (A-5).

Estimation of the seven parameters for PV module was made [40] for the solution by formulating seven equations and using Newton Raphson iterative method. The solution was started by choosing suitable initial values for determining the seven parameters describing the DDM. The initial values of R_s, A_1 and A_2 were assumed arbitrary. The initial values of I_{01}, I_{02} and R_p were obtained by applying equation (A-

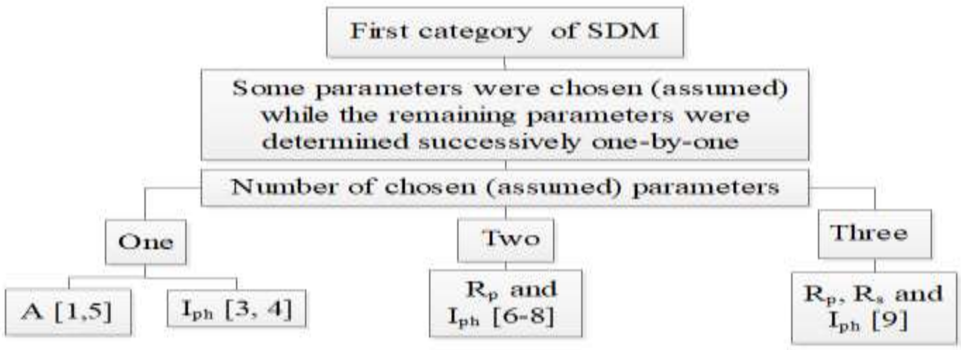
1b) at the three key points provided that R_s, A_1 and A_2 are known. The initial value of I_{ph} was left undefined. Seven equations were formulated; three of them were obtained by applying equation (A-1b) at the three key points. Moreover, the 4th, 5th and 6th equations were obtained from the slope $-\frac{dV}{dI}$ being equal to (i) R_p at the short-circuit point, (ii) R_s at the open-circuit point (iii) $\frac{V_{mp}}{I_{mp}}$ at MPP. The 7th equation was obtained from diode ideality factors whose summation $A_1 + A_2$ was assumed equal to 3 for multi-crystalline and thin film solar cells against 4 for amorphous solar cell. The seven equations were solved simultaneously to determine the unknown parameters.

Estimation of the seven parameters for PV module was made [41] by formulating seven equations using the following initial values of the parameters. The initial values of R_s, A_1 and A_2 were assumed equal to 0, 1, and 2, respectively for determining the seven parameters. The initial value of I_{02} was derived in terms of R_s, A_1 and A_2 as well as datasheet values at the three key points. The initial value of I_{01} was derived in terms of I_{02}, A_1, A_2 as well as datasheet values (V_{oc} and I_{sc}). The initial value of R_p was derived in terms of R_s, A_1 and A_2 as well as datasheet values (V_{oc} and I_{sc}) [41]. The initial value of I_{ph} was derived in terms of I_{01}, I_{02}, R_p, A_1 and A_2 as well as datasheet values (V_{oc} and I_{sc}). Six equations were formulated in the same way as in [40]. The 7th equation was obtained from diode ideality factors whose summation $A_1 + A_2$ was assumed equal to 3 only. The seven equations were solved simultaneously to determine the unknown parameters by using fsolve.

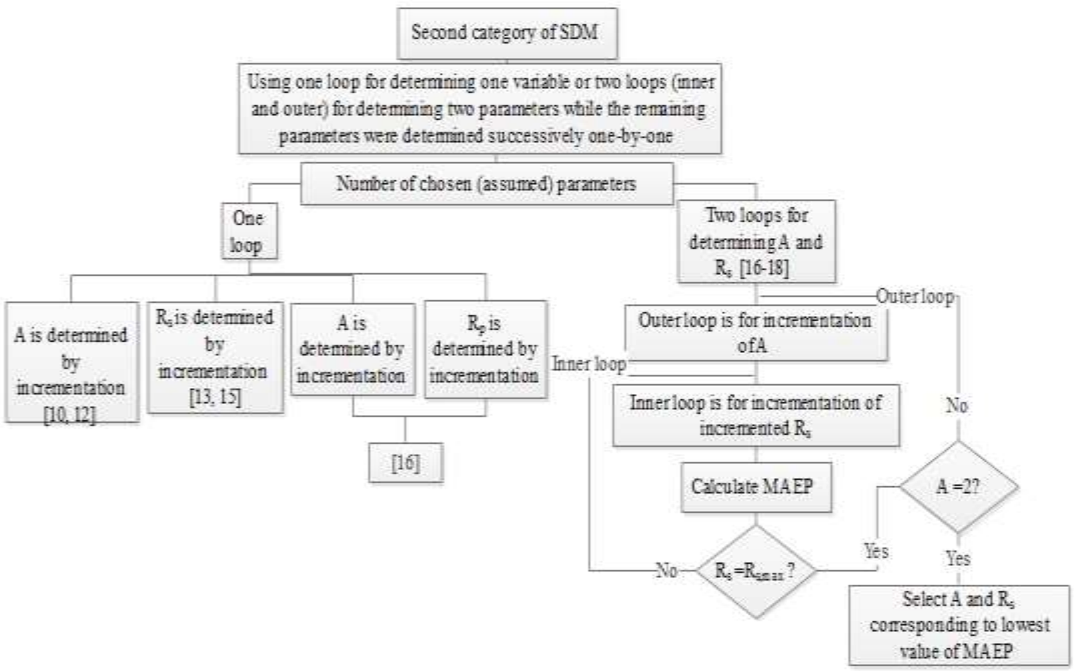
2.3 Research gaps

It is quite clear from the above literature survey that the estimation of the module parameters of SDM and DDM is divided into three categories, Fig. 1, with assumed initial values and use of unjustified explicit equations[3], [30]. No unique approach was reported for determining the parameters of the PV modules in the three categories. To the authors' knowledge, the present paper is aimed at proposing -for the first time- a unique systematic approach based only on the manufacturer's datasheet at the three key points and the solution of the describing-equations of the module with the same well-defined initial-values, which serve solution for SDM and DDM irrespective of module type and rating with no need for conducting expensive experimental measurements.

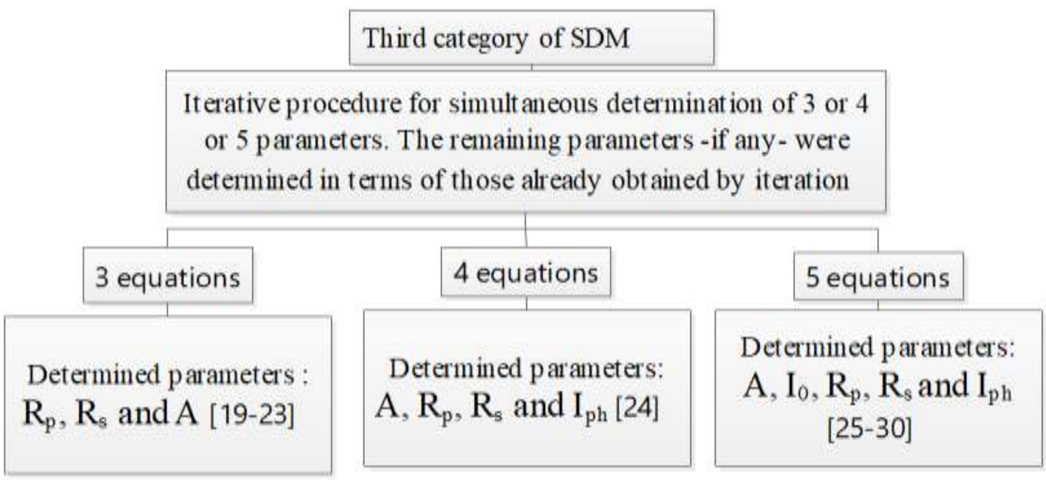
The superiority of the proposed approach in assessing the module parameters with higher accuracy than that of the other approaches reported in the literature is confirmed through three different checks at the three key points and at points different from the key ones on the I-V characteristic curve.


First category of SDM
Some parameters were chosen (assumed) while the remaining parameters were determined successively one-by-one
Number of chosen (assumed) parameters
One
Two
Three
A [1,5]
I_{ph} [3, 4]
R_p and I_{ph} [6-8]
R_p, R_s and I_{ph} [9]

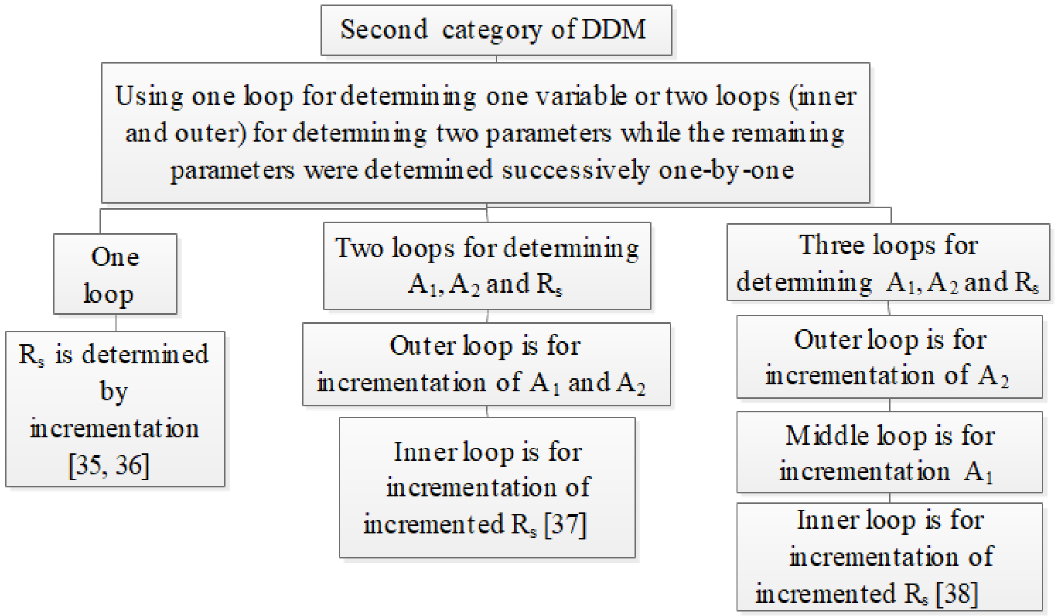
(a)


Second category of SDM
Using one loop for determining one variable or two loops (inner and outer) for determining two parameters while the remaining parameters were determined successively one-by-one
Number of chosen (assumed) parameters
One loop
Two loops for determining A and R_s [16-18]
A is determined by incrementation [10, 12]
R_s is determined by incrementation [13, 15]
A is determined by incrementation
R_p is determined by incrementation
[16]
Outer loop
Outer loop is for incrementation of A
Inner loop
Inner loop is for incrementation of incremented R_s
Calculate MAEP
$R_s = R_{smax}$?
No
Yes
A =2?
No
Yes
Select A and R_s corresponding to lowest value of MAEP

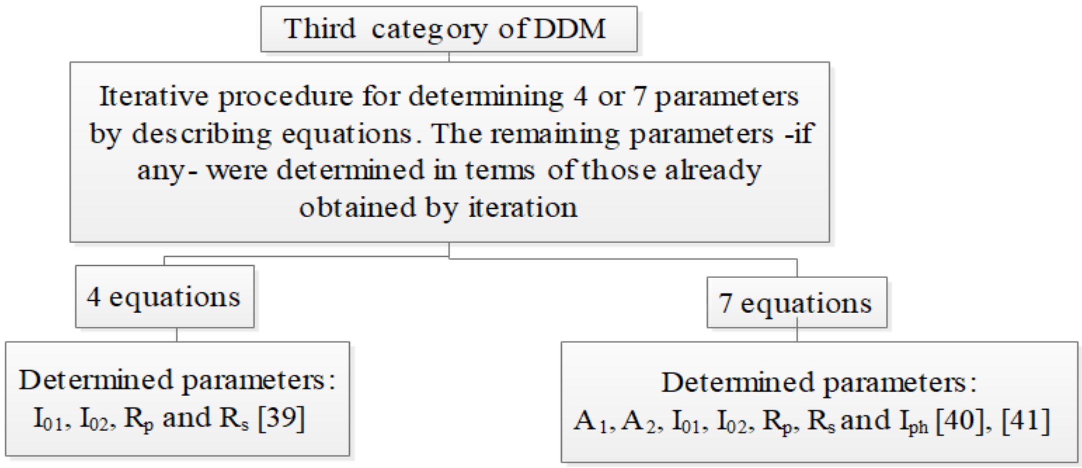
(b)


Third category of SDM
Iterative procedure for simultaneous determination of 3 or 4 or 5 parameters. The remaining parameters -if any- were determined in terms of those already obtained by iteration
3 equations
4 equations
5 equations
Determined parameters : R_p, R_s and A [19-23]
Determined parameters: A, R_p, R_s and I_{ph} [24]
Determined parameters: A, I_0, R_p, R_s and I_{ph} [25-30]

(c)

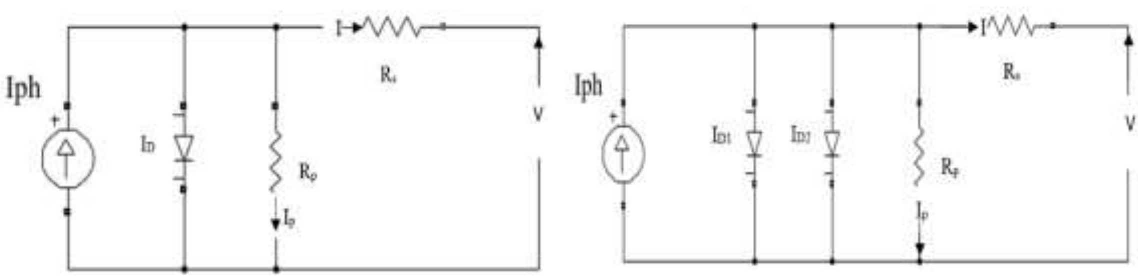


(d)



(e)

Fig.1: Evaluation of module parameters classified in three categories (a) SDM-First category, (b) SDM-Second category, (c) SDM-Third category, (d) DDM-Second category and (e) DDM-Third category



(a) (b)

Fig.2 Equivalent circuit of (a) single- and (b) double- diode model of PV modules

3. Proposed Method for Determining Module Parameters

3.1. Single diode model

3.1.1. Model describing equations

As stated above, the SDM for a PV module is described by an equivalent circuit, Fig. 2. a, with the five parameters I_{ph}, I_0 , A, R_s and R_p. These parameters of the module are determined from the available information provided in manufacturer's datasheets. This calls for formulating five equations to determine the unknown parameters. Four of the five equations are formulated based on datasheet values at the three key points using equation (A-1a) as well as equation (A-2). The fifth equation is formulated to include the maximum power P_{mpp} in the solution:

1- Open-circuit condition with I = 0 at V = V_{oc}

$$I_{ph} - I_0\left[e^{\frac{qV_{oc}}{NAkT}} - 1\right] - \frac{V_{oc}}{R_p} = 0 \quad (1)$$

2- Short circuit condition with I = I_{sc} and V = 0,

$$I_{sc} = I_{ph} - I_0\left[e^{\frac{q(R_s I_{sc})}{NAkT}} - 1\right] - \frac{R_s I_{sc}}{R_p} \text{ or } I_{ph} - I_0\left[e^{\frac{q(R_s I_{sc})}{NAkT}} - 1\right] - \frac{R_s I_{sc}}{R_p} - I_{sc} = 0 \quad (2)$$

3- Maximum-power point at $I = I_{mpp}, V = V_{mpp}$

$$I_{ph} - I_0\left[e^{\frac{q(V_{mpp}+R_s I_{mpp})}{NAkT}} - 1\right] - \frac{V_{mpp}+R_s I_{mpp}}{R_p} - I_{mpp} = 0 \quad (3)$$

4- $\frac{dP}{dV} = 0$ where P=VI. This ends up obtaining equation (A-2)

$$\frac{qI_0}{NAkT}\left(1 - \frac{I_{mpp}}{V_{mpp}}R_s\right)\left[e^{\frac{q(V_{mpp}+I_{mpp}R_s)}{NAkT}}\right] + \frac{1}{R_p} - \frac{R_s}{R_p}\frac{I_{mpp}}{V_{mpp}} - \frac{I_{mpp}}{V_{mpp}} = 0 \quad (4)$$

5- The output power at the MPP, i.e $P = P_{mpp}$ at $I = I_{mpp}, V = V_{mpp}$

$$V_{mpp}\{I_{ph} - I_0[e^{\frac{q(V_{mpp}+R_s I_{mpp})}{NAkT}} - 1] - \frac{V_{mpp}+R_s I_{mpp}}{R_p}\} - P_{mpp} = 0 \quad (5)$$

Equation (5) is another version of equation (3) but it includes -for the first time- the power value P_{mpp} at MPP. This value is never considered before by other approaches reported in the literature for evaluating the module parameters. Equation (5) is requested to form a fifth equation as the Matlab "fsolve" routine calls for it in order to generate a solution for equations (1)-(5). Such solution determines the five parameters pending well-defined initial values.

The describing equations (1) - (5) are formulated to form five nonlinear equations with two of them are dependent on each other. Each equation must be written in the form F(x) = 0, i.e., $F_i(x) = 0$, i = 1, 2.., n (with n equal 5) for simultaneous solution using Matlab "fsolve" routine to determine the unknowns five parameters. The "fsolve" routine has the capability to predict accurate values of the five parameters from five equations with two of them depend on each other [42] pending well-defined initial conditions.

3.1.2. Initial values

The initial values for simultaneous solution of the five formulated equations are expressed as:

$$I_{ph} = I_{sc} \quad , I_0 = \frac{I_{sc}}{\left[e^{\frac{qV_{oc}}{NAkT}} - 1\right]}, \quad R_p = \frac{100 \times V_{oc}}{I_{sc}}, \quad R_s = \frac{0.1 \times V_{oc}}{I_{sc}} \text{ and } \quad A=1.5.$$

3.2. Double diode model

3.2.1. Model describing equations

The equivalent circuit describing the double diode model is composed of a photogenerated current source, two diodes, series and parallel resistances as shown in Fig.2.b and defined by seven unknown parameters.

3.2.2. Simplifying assumptions

The reverse saturation current for both diodes is assumed the same, i.e, $I_{01} = I_{02} = I_0$ in agreement with others [35], [36]. On adopting this simplifying assumption, the number of equations describing the DDM in the present work is reduced from seven to six.

3.2.3. Solution methodology

To evaluate the six unknowns of the DDM, six equations have to be formulated; five of them are equations (1) - (5) of the SDM being applicable for DDM. The seventh equation is to relate the diode ideality factors A_1 and A_2 together.

Reference is made to the above literature review, ideality factors $A_1$and A_2 were related together so $A_1 + A_2 \geq 2$ [35], $A_1 + A_2 = 3$ [40], [41] and $A_1 + A_2 = 4$ [40]. The number of equations were reduced from 7 to 4 [36], [39] and from 7 to 5 [35]. Therefore, the ideality factors in the present work are assumed to follow equation (6):

$$A_1 + A_2 = 2.5 \tag{6}$$

The sum 2.5 in equation (6) is chosen midway between values adopted before [35], [40].

For completeness, the initial values for solution of the DDM describing equations are the same as those of the SDM with $A_1 = 1.5$ and A_2=1 for DDM.

4. Results and Discussion

4.1.Single diode model

The accuracy of the proposed method in satisfying the five formulated equations at the three key points on the I-V characteristic of the PV module is determined by evaluating the root-mean-square deviation (RMSD). The latter is determined based on how the obtained parameters result in a deviation from satisfaction of the describing equations (1) – (5) of the module as expressed by equation (7):

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n} |F_i{}^2|}{n}} \tag{7}$$

The use of RMSD for SDM to assess the accuracy of determining the module parameters is extended to the DDM.

For a second check on the accuracy of the proposed method, the slope $\frac{dI}{dV}$ at the maximum power point is compared against the nominal value $\frac{I_{mpp}}{V_{mpp}}$ according to equation (A-2) and the difference is normalized with respect to $\frac{I_{mpp}}{V_{mpp}}$, expressed as a percentage of the nominal value and assigned a symbol dev $\frac{I_{mpp}}{V_{mpp}}$.

For a third check, the accuracy of the parameters' estimation is evaluated at points other than the three key points on the I-V curve over all the whole voltage range from zero to V_{oc}. The current value at V_{oc} is selected as a check point for comparison purpose to assess the accuracy of the parameters' estimation methods.

The proposed calculation method is tested in Matlab environment for different modules with datasheet values of the crystalline modules Kyocera KC200GT [1], Suntech STP-280 [21], [30], Sunpower SPR-315 [21], [30], Atersa A-120 [21], [30], Atersa A-130 [21], [30], Isofoton I-110 [21], [30] and DP Solar MSX60 [19]. The parameters obtained by the proposed method are compared with those reported before [1], [4], [10], [11], [13], [16], [17], [19], [20], [25], [26], [35] as given in Table 1 for the same module. Also, the parameters predicted by the proposed method are compared with those presented before [13], [19], [21], [30], [43–47] as reported in Table 2 for different modules.

Table 1 A comparison of the proposed method against other methods for the same polycrystalline module KC200GT

Method	Parameters					RMSD	dev $\frac{I_{mpp}}{V_{mpp}}$
	I_{ph}	I_0	R_s	R_p	A		
Proposed	8.2176	1.6296e-08	0.2702	290.6308	1.1838	0.0050	0.069174
[1]	8.2132	9.7631 e-08	0.2308	597.3855	1.3	0.0462	0.578368
[4]	8.212	171e-09	0.217	951.932	1.34	0.0413	0.519268
[4]	8.21	410e-09	0.194	640.771	1.41	0.4904	0.219344
[10]	8.193	1.61e-07	0.1634	∞	1.346	2.119	27.24558
[11]	8.184	1.675e-08	0.212	388.6	1.192	1.7624	28.06936
[13]	8.214	9.825e-08	0.221	415.405	1.3	0.0331	3.275490
[16]	8.196	3.27 e-09	0.2185	164.2	1.1	1.4483	34.12718
[16]	8.22	5.14 e-09	0.2656	144.9	1.12	0.0674	10.77966
[17]	8.193	0.3e-09	0.271	171.2	1	2.4514	44.51799
[19]	8.211	171e-09	0.217	951.92	1.342	0.1268	1.699611
[20]	8.21	171 e-09	0.22	951.93	1.34	0.1427	1.587918
[20]	8.16	150 e-09	0.18	951.9	1.34	1.1024	22.29557
[25]	8.22	9e-08	0.2	600	1.3	1.4006	17.78918
[26]	8.21	4.31e-08	0.2484	396.9	1.24	0.4312	4.778346
[35]	8.22	9.825e-08	0.23	601.34	1.3	0.1033	0.286356

It is quite clear from Table 1 that the RMSD on using the proposed method records a value of 0.005 against high values that reach up to 2.45 as predicted by other methods [1], [4], [10], [11], [13], [16], [17], [19], [20], [25], [26], [35] for the same module. The value of dev $\frac{I_{mpp}}{V_{mpp}}$ reached 0.069% for the proposed method against higher values up to 44.5% for the same other methods.

Table 2 dictates that the RMSD on using the proposed method records values of 0.0018, 2.1842×10^{-4}, 0.0026, 7.63×10^{-4}, 0.0016 and 0.0017 for different crystalline modules against 0.007, 0.05, 0.008, 0.003, 0.0017 and 0.49 for other methods [13], [19], [21], [30], [43–47]. The values of dev $\frac{I_{mpp}}{V_{mpp}}$ reached 0.023608, 0.0011, 0.035, 0.012 and 0.054% by the proposed method against 0.07, 0.65, 0.13, 0.05 and 17.7% by the same other methods.

Also, the proposed method is examined for two different polycrystalline modules (RTC France and STP6 120/36) at two different cell temperature 33 and 45°C. The parameters obtained by the proposed method are compared with those obtained by different optimization techniques [48–56], [57–66], [67–75], [76–84], [85–92]. The RMSD values on using the proposed method record value of 2.06×10^{-4} for RTC France against 0.43 as obtained by optimization techniques.

The RMSD values on using the proposed method record value of 0.003 for STP6 120/36 against values up to 7.495 as obtained by optimization techniques [48], [49], [56], [58], [59], [60], [61], [63], [64], [65], [92] as give in Table 3.

Therefore, the RMSD values on using the proposed method show the superiority of the proposed method in assessing the module parameters with higher accuracy than that of methods reported in the literature [1]-[47] and other methods using optimization techniques [48]-[92]. The superiority is referred to the well-defined initial conditions given in section 3.1.2, which guided Matlab "fsolve" routine to predict highly accurate values of the module parameters irrespective of the module type and rating.

Table 2 A comparison of the proposed method against other methods for different crystalline modules

Model	Method	Parameters					RMSD	dev $\frac{I_{mpp}}{V_{mpp}}$
		I_{ph}	I_0	R_s	R_p	A		
STP-280 (Poly)	Proposed	8.3388	1.1150e-15	0.7098	670.6813	0.66247	0.0018	0.02361
	[21]	8.3329	4.4492E-14	0.6704	1939	0.7367	0.0072	0.07235
SPR-315 (Mono)	Proposed	6.1403	1.8663e-08	0.0803	1.7083e+3	1.3354	2.184e-4	0.00115
	[30], [13]	6.140507	1.086506E-8	0.11092	1342.357	1.3	0.0421	0.49139
	[30], [43]	6.140594	9.014765E-9	0.12120	1252.904	1.288098	0.0422	0.49531
	[30], [44]	6.140138	3.02301 E-8	0.05176	2294.489	1.369340	0.0415	0.46985
	[30], [45]	6.144464	4.35853E-11	0.36286	499.144	1.020959	0.0451	0.60912
	[30], [46]	6.146165	6.35991E-12	0.43117	429.4011	0.949809	0.0461	0.65049
		6.146176	6.28389E-12	0.43157	429.0516	0.949395	0.0461	0.65069
	[21]	6.1434	1.5295E-10	0.3142	566	1.0731	0.0105	0.10302
A-120 (Mono)	Proposed	7.7026	4.0450e-07	0.1126	329.6987	1.3546	0.0026	0.03506
	[21]	7.7033	2.97E-07	0.1185	278	1.3302	0.0077	0.12736
A-130 (Mono)	Proposed	4.5496	2.3230e-04	-0.0640	745.4956	2.2665	7.627e-04	0.01235
	[21]	4.5595	4.53E-06	0.3797	181	1.6246	0.0029	0.04881
MSX 60	Proposed	3.8017	1.5101e-07	0.1882	430.6600	1.3392	0.0017	0.05446
	[19]	3.801	329e-09	0.169	637.5	1.404	0.0383	1.63508
	[47]	3.859	1.2654 E-09	0.33	117.99	1.0365	0.4851	17.7358

Also, the proposed method is examined for different thin-film modules (RTC France and STP6 120/36) at STC. The parameters obtained by the proposed method are compared with those obtained by different optimization techniques reported before [93]-[94] as given in Table 4. The table dictates that the RMSD on using the proposed method records values of 7.6e-04 for ST40 (CTS), 0.002 for ASP-S4-77(CdTe) and 7.6e-06 for PVM 752 (GaAs) against 0.98, 0.17 and 0.04 for other methods**.**

Table 3 A comparison of the proposed method against other methods based on different optimization techniques for the same polycrystalline STP6 120/36 PV module.

Method	Parameters					RMSD
	I_{ph}	I_0	R_s	R_p	A	
Proposed	7.4851	8.3520e-07	0.1832	269.6704	1.1790	0.0026
[48]	7.4757	3.01e-06	0.1600	827.5815	1.2816	0.1290
[49]	7.4672	2.2536e−06	0.0046	27.5925	1.2571	1.1951
[56]	7.4725	2.335e−06	0.0046	22.2199	1.2601	2.0461
[58]	7.4725	0	0.0046	22.2184	1.2601	2.9681
[59]	7.4725	2.335e−06	0.0046	22.2199	1.2601	2.0461
[60]	7.4782	1.9194e−06	0.0047	13.2688	1.244	4.9738
[61]	7.4725	2.335e−06	0.0046	22.2199	1.2601	2.0461
[63]	7.4725	2.335e−06	0.0046	22.2199	1.2601	2.0461
[64]	7.4725	2.3349e−06	0.0046	22.2117	1.2601	2.0476
[65]	7.4725	2.335e−06	0.0046	22.2199	1.2601	2.0461
[92]	7.4838	1.2e−06	0.0049	9.745	1.2072	7.4950

Table 4 A comparison of the proposed method against other methods for different thin-film modules

Manufacturer / Supplier	Model	Method	Parameters					RMSD
			I_{ph}	I_0	R_s	R_p	A	
Shell solar	ST40 (CIS)	Proposed	2.6854	9.3174e-08	1.4439	719.0865	1.2575	7.5525e-04
		[93]	2.695131	1.0777e-08	0.8545173	70.816	1.289332	0.9760
		[95]	2.675591	1.530652e-06	0.026495	8.591956	1.500355	12.8424
Advanced Solar Power	ASP-S4-77 (CdTe)	Proposed	3.9161	6.0072e-12	1.1065	711.8718	0.6677	0.0016
		[93]	3.930204	2.054211e-6	0.483427	633.505182	1.261012	0.1749
---	PVM 752 (GaAs)	Proposed	0.1002	4.6040e-12	0.6895	676.8461	1.6234	7.6098e-06
		[94]	0.099985	19.4231e-12	0.616566	684.519	1.73411	0.0059
			0.103903	84.90e-12	0.5	100	1.858574	0.0067
		[96]	0.103312	32e-12	0.5	100	1.774159	0.0095
			0.115016	0	0.159052	14.42950	1.768590	0.0367

All methods based on optimization techniques for estimating the parameters of the PV module were aimed at fitting the measured I-V characteristic curve of the PV module with no attention to satisfy the pertinent conditions at the three key points of the module. Therefore, the estimated module parameters depend on the accuracy of the measured I-V characteristic curve. Meanwhile, the measured I-V curve is usually not available. This adds more to the superiority of the proposed method for estimation of module parameters with no need for conducting measurements with excessive cost to build the experimental set up.

Concerning the third check on the accuracy of the proposed method, a global comparison of it is made against other methods for the same PV module at specific points on the I-V curve other than the three key points over the voltage range from zero to V_{oc} . Table 5 gives the module current calculated by the proposed method and the methods listed in Table 1 at voltages zero, $V_{oc}/4$, $V_{oc}/2$, $3V_{oc}/4$ and V_{oc} for PV module KC200GT. It is quite clear that the current value at V_{oc} is 0.0029A and closer to zero on using the module parameters predicted by the proposed method when compared with the current values obtained in Table 5 by other method in the range from -0.23 to + 0.92A. This confirms the superiority of the proposed method in predicting the module parameters when compared with other methods.

Table 5 Calculated module-current values obtained by module's parameters predicted by the proposed method and other methods for the same polycrystalline module KC200GT at V equal to 0, $1/4V_{oc}$, $1/2V_{oc}$, $3/4V_{oc}$ and V_{oc}

	module current I (A) at V equal to				
Method	0	$1/4V_{oc}$	$1/2V_{oc}$	$3/4V_{oc}$	V_{oc}
Proposed	8.209967	8.181684	8.152032	7.925651	0.002999
[1]	8.210028	8.196239	8.179971	7.934626	0.028011
[4]	8.210128	8.201453	8.189767	7.934814	-0.02839
[4]	8.207515	8.194622	8.177727	7.90069	-0.02418
[10]	8.193	8.192973	8.190802	8.016166	0.625992
[11]	8.179538	8.158377	8.136241	7.976436	0.433191
[13]	8.209632	8.189818	8.167621	7.924905	-0.0088
[16]	8.185108	8.135081	8.084562	7.928898	0.251607
[17]	8.180051	8.132084	8.083913	7.961584	0.921514
[19]	8.209128	8.200454	8.188813	7.938917	0.081275
[20]	8.208103	8.199427	8.187702	7.929728	-0.02922
[20]	8.158457	8.149791	8.138892	7.945515	0.526099
[25]	8.217261	8.203536	8.187822	7.986574	0.377816
[26]	8.204865	8.184138	8.161464	7.915252	-0.23108
[35]	8.216857	8.203158	8.186972	7.940881	0.006323

With the aid of the module parameters, one can determine the I-V characteristic curve by applying the basic equation (A-1a) using either Simulink or Lambert function. Figure 3 shows that I-V and P-V characteristic curves of polycrystalline module KC200GT from Kyocera at STC as obtained by the proposed method and by one of the published works [17] using Simulink. The percentage deviation of I_{sc} and V_{oc} from the datasheet value reaches 0.006 % by the proposed method against 1.28% [17] at open-circuit condition and 0.0004% by the proposed method against 0.36% [17] at short-circuit condition. The percentage deviation of P_{mpp} from the datasheet values reaches 0.004% by the proposed method against 3.2% [17] at MPP.

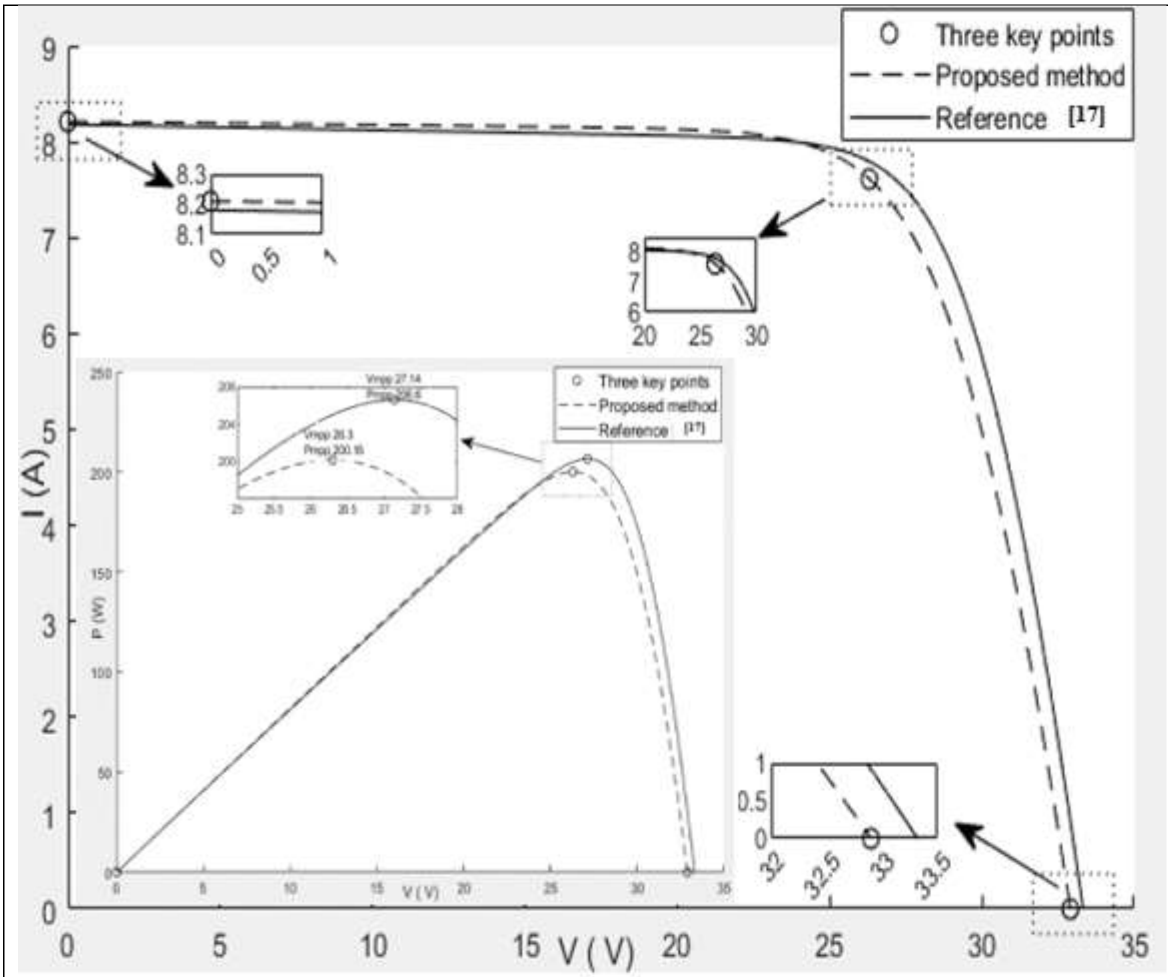


Fig.3 I-V and P-V characteristic curves of polycrystalline module KC200GT at STC

4.2.Double diode model

The parameters obtained by the proposed method for crystalline modules with datasheet values of Kyocera KC200GT [38], [40], DP Solar MSX60 [37], [38] and UniSolar US-64 [40] are compared with those obtained before [36] ,[38] as well as those obtained by different optimization techniques [48]-[92].

The RMSD on using the proposed method records values of 12×10^{-4} for KC200GT 5.79×10^{-5} for MSX60 and 9.27×10^{-4} for US-64 against 0.3, 4.82 and 0.58 for different modules as given in Table 6.

The RMSD on using the proposed method records a value of 2.62×10^{-6} for R.T.C France silicon solar cell against high values that reach up to 1.58 for the same module on using different optimization techniques as given in Table 7.

4.3.Single-diode and double-diode models

It is quite clear from Table 8 that the RMSD on using the proposed method for different modules records values of 12×10^{-4} for KC200GT, 6.1$\times 10^{-4}$ for Atersa A-120, 4.57×10^{-5} for Isofoton I-110 and 5.79×10^{-5} for MSX60 for DDM against 0.005, 0.003, 0.0016 and 0.0017 for SDM. It is quite clear that RMSD values for DDM are smaller than those of SDM pointing that the DDM is more accurate than SDM in determining the module parameters as dictated before [48]-[55], [91].

Table 6 A comparison of the proposed method against other methods for different modules.

model	Method	Parameters							RMSD
		I_{ph}	I_{01}	R_s	R_p	A_1	A_2	I_{02}	
KC200GT	Proposed	8.2141	3.3391e-08	0.2396	481.7504	1.2731	1.2731	3.3391e-08	12e-04
	[40]	8.2237	4.1437e-10	0.3305	196.500	1.0003	1.9997	1.9032e-6	0.2965
	[38]-Analytical	8.3277	3.3130e-10	0.29127	279.6013	1	2	1.0867e-05	0.2919
	[38]-Numerical	8.2194	3.3513e-10	0.31944	279.1899	0.99574	2.0041	4.5971e-06	0.1176
MSX-60	Proposed	3.8008	2.1704e-07	0.1466	719.1986	1.4272	2.1704e-07	1.4272	5.79e-05
	[40]	3.8084	4.8723e-10	0.3692	169.0471	1.0003	1.9997	6.1528e-10	0.1528
	[37]	3.80634	2.59262e-10	0.33329	199.59354	0.97899	2.021001	3.757882e-5	4.8218
	[38]-Analytical	3.8752	3.8752e-10	0.3084	280.6449	1	2	9.3773e-6	0.0766
	[38]-Numerical	3.8046	3.9901e-10	0.3397	280.2171	0.99859	2.0014	4.033e-6	0.0461
US-64	Proposed	4.9748	5.2273e-08	1.0401	28.5637	2.4059	5.2273e-08	2.4059	9.27e-04
	[40]	4.96	1.3736e-18	0.9449	34.5665	1.0175	2.9825	2.7404e-06	0.5808

Table 7 A comparison of the proposed method against other methods based on different optimization techniques for the same R.T.C France silicon solar cell.

Method	Parameters							RMSD
	I_{ph}	I_{01}	R_s	R_p	A_1	A_2	I_{02}	
Proposed	0.7606	3.1789e-07	0.0319	80.7946	1.5518	1.5518	3.1789e-07	2.6e-06
[48]	0.7608	2.183e–07	0.03675	54.5464	1.450	1.820	3.681e–07	0.0037
[49]	0.7601	5.0445e–09	0.0376	77.8519	1.2186	1.6247	7.5094e–07	0.0028
[50]	0.76176	1.2545e–07	0.03545	46.82696	1.49439	1.49989	2.547e–07	0.0027
[52]	0.76078	2.335e–07	0.03671	55.2997	1.45374	2	6.8372e–07	0.0040
[53]	0.76078	8.4161e–07	0.03679	55.72835	2	1.44705	2.1545e–07	0.0043
[54]	0.76083	5.9115e–07	0.03664	55.0494	2	1.45798	2.4523e–07	0.0046
[55]	0.760781079	7.49349e–07	0.036740432	55.48543807	1.451016656	2	2.25974e–07	1.5799
[91]	0.76078	2.25974e-07	0.03674	55.48544	1.451017	2	7.4935e-07	0.0041

Table 8 SDM versus DDM for parameters' assessment for different modules by the proposed method

Manufacturer / Supplier	Model	Type model	Parameters					RMSD
			I_{ph}	I_0	R_s	R_p	A	
Kyocera	KC200 GT	SDM	8.2176	1.6296e-08	0.2702	290.6308	1.1838	0.0050
		DDM	8.2141	3.3391e-08	0.2396	481.7504	1.2731	12e-04
Atersa Electricidad Solar	A-120	SDM	7.7026	4.0450e-07	0.1126	329.6987	1.3546	0.0026
		DDM	7.7105	6.8013e-09	0.1675	122.5078	1.1273	6.1 e-04
Sofoton	I-110	SDM	3.3812	3.7177e-09	0.8013	2.1897e3	1.1320	0.0016
		DDM	3.3823	5.2102e-10	0.8766	1.2897e3	1.0664	4.57e-05
BP Solar	MSX60	SDM	3.8017	1.5101e-07	0.1882	430.6600	1.3392	0.0017
		DDM	3.8008	2.1704e-07	0.1466	719.1986	1.4272	5.79e-05

5. Conclusions

1- A comprehensive literature survey for estimating of the module parameters is made. The survey dictates that the parameters' estimation methods has been divided into three categories based on how the parameters were evaluated.
2- A method is proposed for assessing the parameters of modules either of crystalline or thin film type using Matlab "fsolve" routine. The method is based on the datasheet values and the describing equations (1)-(5) for SDM and (1)-(6) for DDM of the module at the three key points with the same set of well-defined initial values that serve the solution irrespective of the module type or rating.
3- The accuracy of the proposed method is determined by checking how the module describing-equations using the predicted parameters are satisfied at the three key points on the I-V characteristics. Therefore, the RMSD is assessed based on the deviation of the calculated values from those of the datasheet. The percentage deviation of the slope of I-V characteristic at maximum power point from its nominal value is also evaluated. A global comparison is made between the proposed method and other methods for the same module at points on the I-V curve other than the three key points over the voltage range from zero to V_{oc}.
4- The obtained results by the proposed method shows the superiority of the proposed method in assessing the module parameters with higher accuracy than that of other methods reported in the literature.
5- The RMSD from the describing-equations is defined to record a lower value for the proposed method when compared with that obtained by other methods reported in the literature for modules either of crystalline or thin-film type and represented by SDM and DDM whatever the type or rating of the module.
6- The RMSD values for DDM are smaller than those of SDM pointing that the DDM is more accurate than SDM in agreement with others. Of course, the accuracy of PV panel/array modeling depends on the accuracy of module parameters estimation.

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Appendix A: Some Basic Equations Describing Performance of a PV Module

Equation A-1expresses the I-V curve of the module represented by SDM and DDM[1]:

$$I = I_{ph} - I_0 \left[e^{\frac{q(V+R_S I)}{NAkT}} - 1 \right] - \frac{V+R_S I}{R_p} \qquad \text{(A -1a)}$$

The number of series cells forming the module is N, Boltzmann's constant is k (=1.38 × 10^{-23} J/K), the electron charge is q (=1.6 × 10^{-19} C) and cell temperature in kelvin is T (K).

$$I = I_{ph} - I_{01} \left[e^{\frac{q(V+R_S I)}{NA_1kT}} - 1 \right] - I_{02} \left[e^{\frac{q(V+R_S I)}{NA_2kT}} - 1 \right] - \frac{V+R_S I}{R_p} \qquad \text{(A -1b)}$$

where I_{01} and I_{02} are diode reverse saturation currents and A_1 and A_2 are diode ideality factors of DDM

Equation A-2 expresses the derivative of current I with respect to voltage V at MPP [1]:

$$\frac{dI}{dV}\Big|_{MPP} = -\frac{I_{mpp}}{V_{mpp}} \quad \text{(A-2)}$$

Equation A-3 determines I_0 in terms of I_{sc}, V_{oc} and A [6], [7], [8]:

$$I_0 = \frac{I_{sc}}{\left[e^{\frac{qV_{oc}}{NAkT}}-1\right]} \quad \text{(A-3)}$$

Equation A-4 determines R_s in terms of $I_{mpp}, I_{ph}, V_{mpp}, V_{oc}$ and A [10]:

$$R_s = \frac{\frac{NAkT}{q}\ln\left[\left(1-\frac{I_{mpp}}{I_{ph}}\right)e^{\frac{qV_{oc}}{NAkT}}+\frac{I_{mpp}}{I_{ph}}\right]-V_{mpp}}{I_{mpp}} \quad \text{(A-4)}$$

Equation A-5 expresses the derivative of current I with respect to voltage V at short circuit condition [19–22]:

$$\frac{dI}{dV}\Big|(\text{at } I = I_{sc}) = -\frac{1}{R_p} \quad \text{(A-5)}$$

References

1. Cubas J, Pindado S, Victoria M (2014) On the analytical approach for modeling photovoltaic systems behavior. J Power Sources 247:467–474
2. Sarkar MNI (2016) Effect of various model parameters on solar photovoltaic cell simulation: a SPICE analysis. Renewables Wind Water, Sol 3:1–9. https://doi.org/10.1186/s40807-016-0035-3
3. Cannizzaro S, Di Piazza MC, Luna M, Vitale G (2014) Generalized classification of PV modules by simplified single-diode models. In: 2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE). pp 2266–2273
4. Hejri M, Mokhtari H, Azizian MR, Söder L (2016) An analytical-numerical approach for parameter determination of a five-parameter single-diode model of photovoltaic cells and modules. Int J Sustain Energy 35:396–410
5. Senturk A, Eke R (2017) A new method to simulate photovoltaic performance of crystalline silicon photovoltaic modules based on datasheet values. Renew energy 103:58–69
6. Sera D, Teodorescu R, Rodriguez P (2008) Photovoltaic module diagnostics by series resistance monitoring and temperature and rated power estimation. In: 2008 34th annual conference of IEEE industrial electronics. pp 2195–2199
7. Silva FA (2013) Power electronics and control techniques for maximum energy harvesting in photovoltaic systems (Femia, N. et al; 2013)[Book News]. IEEE Ind Electron Mag 7:66–67
8. Aldwane B (2014) Modeling, simulation and parameters estimation for Photovoltaic module. In: 2014 First International Conference on Green Energy ICGE 2014. pp 101–106
9. Saloux E, Teyssedou A, Sorin M (2011) Explicit model of photovoltaic panels to determine voltages and currents at the maximum power point. Sol energy 85:713–722
10. Xiao W, Dunford WG, Capel A (2004) A novel modeling method for photovoltaic cells. In: 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No. 04CH37551). pp 1950–1956
11. Muhammadsharif FF (2022) A new simplified method for efficient extraction of solar cells and modules parameters from datasheet information. Silicon 14:3059–3067
12. Lidaighbi S, Elyaqouti M, Hmamou D Ben, Saadaoui D, Assalaou K, Arjdal E (2022) A new hybrid method to estimate the single-diode model parameters of solar photovoltaic panel.

Energy Convers Manag X 15:100234
13. Villalva MG, Gazoli JR, Ruppert Filho E (2009) Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans power Electron 24:1198–1208
14. Nguyen-Duc T, Nguyen-Duc H, Le-Viet T, Takano H (2020) Single-diode models of PV modules: A comparison of conventional approaches and proposal of a novel model. Energies 13:1296
15. Elyaqouti M, Saadaoui D, Lidaighbi S, Chaoufi J, Ibrahim A, Aqel R, Obukhov S, others (2022) A novel hybrid numerical with analytical approach for parameter extraction of photovoltaic modules. Energy Convers Manag X 14:100219
16. Stornelli V, Muttillo M, De Rubeis T, Nardi I (2019) A new simplified five-parameter estimation method for single-diode model of photovoltaic panels. Energies 12:4271
17. Silva EA, Bradaschia F, Cavalcanti MC, Nascimento AJ (2015) Parameter estimation method to improve the accuracy of photovoltaic electrical model. IEEE J Photovoltaics 6:278–285
18. Manda S, Chaubey P, Yelisetti S, Kuralla SK, kumar Yadav N, Meena NK (2019) Exact parameter identification of photovoltaic panel by using datasheet details. Energy Procedia 158:972–977
19. Atay BK, Ulaş Eminoğlu (2019) A new approach for parameter estimation of the single-diode model forphotovoltaic cells/modules. Turkish J Electr Eng Comput Sci 27:3026–3039
20. Hejri M, Mokhtari H (2016) On the comprehensive parametrization of the photovoltaic (PV) cells and modules. IEEE J Photovoltaics 7:250–258
21. Carrero C, Ramírez D, Rodríguez J, Platero CA (2011) Accurate and fast convergence method for parameter estimation of PV generators based on three main points of the I-V curve. Renew Energy 36:2972–2977
22. Chatterjee A, Keyhani A, Kapoor D (2011) Identification of photovoltaic source models. IEEE Trans Energy Convers 26:883–889
23. Mohamed MA, Osman MH, others (2014) Evaluation of a PV model based on a novel parameter estimation procedure for different manufacturers module. Int J Eng Res \& Technol 3:1–7
24. Khan F, Baek S-H, Park Y, Kim JH (2013) Extraction of diode parameters of silicon solar cells under high illumination conditions. Energy Convers Manag 76:421–429
25. Nayak BK, Mohapatra A, Mohanty KB (2013) Parameters estimation of photovoltaic module using nonlinear least square algorithm: A comparative study. In: 2013 Annual IEEE India Conference (INDICON). pp 1–6
26. Hemza A, Abdeslam H, Rachid C, Aoun N (2019) Simplified methods for evaluating the degradation of photovoltaic module and modeling considering partial shading. Measurement 138:217–224
27. Karatepe E, Boztepe M, Colak M (2007) Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells. Sol energy 81:977–992
28. Phang JCH, Chan DSH, Phillips JR (1984) Accurate analytical method for the extraction of solar cell model parameters. Electron Lett 10:406–408
29. ALQahtani AH (2012) A simplified and accurate photovoltaic module parameters extraction approach using matlab. In: 2012 IEEE International Symposium on Industrial Electronics. pp 1748–1753
30. Toledo FJ, Blanes JM, Galiano V, Laudani A (2021) In-depth analysis of single-diode model parameters from manufacturer's datasheet. Renew Energy 163:1370–1384
31. Bai J, Cao Y, Hao Y, Zhang Z, Liu S, Cao F (2015) Characteristic output of PV systems under partial shading or mismatch conditions. Sol Energy 112:41–54. https://doi.org/10.1016/j.solener.2014.09.048
32. Kalliojärvi H, Lappalainen K, Valkealahti S (2022) Feasibility of Photovoltaic Module Single-Diode Model Fitting to the Current--Voltage Curves Measured in the Vicinity of the Maximum Power Point for Online Condition Monitoring Purposes. Energies 15:9079
33. Lidaighbi S, Elyaqouti M, Assalaou K, Hmamou D Ben, Saadaoui D, H'roura J (2022) Parameter estimation of photovoltaic modules using analytical and numerical/iterative approaches: A comparative study. Mater Today Proc 52:1–6
34. Hamid N, Elyaqouti M, Boulfaf N, Feddaoui M, Agliz D (2022) Modelling and characterisation

of photovoltaic modules using iterative and analytical methods. Int J Ambient Energy 43:5917–5938
35. Ishaque K, Salam Z, Taheri H (2011) Simple, fast and accurate two-diode model for photovoltaic modules. Sol energy Mater Sol cells 95:586–594
36. Meng Z, Zhao Y, Tang S, Sun Y (2020) An efficient datasheet-based parameters extraction method for two-diode photovoltaic cell and cells model. Renew Energy 153:1174–1182
37. Chennoufi K, Ferfra M, Mokhlis M (2021) An accurate modelling of Photovoltaic modules based on two-diode model. Renew Energy 167:294–305
38. Orioli A, Di Gangi A (2019) A procedure to evaluate the seven parameters of the two-diode model for photovoltaic modules. Renew energy 139:582–599
39. Hejri M, Mokhtari H, Azizian MR, Ghandhari M, Söder L (2014) On the parameter extraction of a five-parameter double-diode model of photovoltaic cells and modules. IEEE J Photovoltaics 4:915–923
40. Elbaset AA, Ali H, Abd-El Sattar M (2014) Novel seven-parameter model for photovoltaic modules. Sol energy Mater Sol cells 130:442–455
41. Kumar M, Kumar A (2017) An efficient parameters extraction technique of photovoltaic models for performance assessment. Sol Energy 158:192–206
42. Hanebeck UD (2014) Truncated Moment Problem for Dirac Mixture Densities with Entropy Regularization. arXiv Prepr arXiv14087083
43. Laudani A, Fulginei FR, Salvini A (2014) Identification of the one-diode model for photovoltaic modules from datasheet values. Sol energy 108:432–446
44. Chan DSH, Phillips JR, Phang JCH (1986) A comparative study of extraction methods for solar cell model parameters. Solid State Electron 29:329–337
45. Accarino J, Petrone G, Ramos-Paja CA, Spagnuolo G (2013) Symbolic algebra for the calculation of the series and parallel resistances in PV module model. In: 2013 International Conference on Clean Electrical Power (ICCEP). pp 62–66
46. De Soto W, Klein SA, Beckman WA (2006) Improvement and validation of a model for photovoltaic array performance. Sol energy 80:78–88
47. Ayang A, Wamkeue R, Ouhrouche M, Saad M, Andy Tameghe T, Deli K, Tchakoua Takoutsing P (2021) Least square estimator and IEC-60891 procedure for parameters estimation of single-diode model of photovoltaic generator at standard test conditions (STC). Electr Eng 103:1253–1264
48. Rezk H, Babu TS, Al-Dhaifallah M, Ziedan HA (2021) A robust parameter estimation approach based on stochastic fractal search optimization algorithm applied to solar PV parameters. Energy Reports 7:620–640
49. Yu K, Liang JJ, Qu BY, Chen X, Wang H (2017) Parameters identification of photovoltaic models using an improved JAYA optimization algorithm. Energy Convers Manag 150:742–753
50. Askarzadeh A, Rezazadeh A (2012) Parameter identification for solar cell models using harmony search-based algorithms. Sol Energy 86:3241–3249
51. Zagrouba M, Sellami A, Boua\"\icha M, Ksouri M (2010) Identification of PV solar cells and modules parameters using the genetic algorithms: Application to maximum power extraction. Sol energy 84:860–866
52. Sheng H, Li C, Wang H, Yan Z, Xiong Y, Cao Z, Kuang Q (2019) Parameters extraction of photovoltaic models using an improved moth-flame optimization. Energies 12:3527
53. Chen X, Yue H, Yu K (2019) Perturbed stochastic fractal search for solar PV parameter estimation. Energy 189:116247
54. Niu Q, Zhang L, Li K (2014) A biogeography-based optimization algorithm with mutation strategies for model parameter estimation of solar and fuel cells. Energy Convers Manag 86:1173–1185
55. Zhanga H, Heidarib AA, Wangd M, Zhange L, Chena H, Lif C (2020) Orthogonal Nelder-Mead moth flame method for parameters identification. Energy Convers Manag 211:112764
56. Liao Z, Chen Z, Li S (2020) Parameters extraction of photovoltaic models using triple-phase teaching-learning-based optimization. IEEE Access 8:69937–69952
57. Rajasekar N, Kumar NK, Venugopalan R (2013) Bacterial foraging algorithm based solar PV

parameter estimation. Sol Energy 97:255–265
58. Yu K, Qu B, Yue C, Ge S, Chen X, Liang J (2019) A performance-guided JAYA algorithm for parameters identification of photovoltaic cell and module. Appl Energy 237:241–257
59. Yu K, Liang JJ, Qu BY, Cheng Z, Wang H (2018) Multiple learning backtracking search algorithm for estimating parameters of photovoltaic models. Appl Energy 226:408–422
60. Guo L, Meng Z, Sun Y, Wang L (2016) Parameter identification and sensitivity analysis of solar cell models with cat swarm optimization algorithm. Energy Convers Manag 108:520–528
61. Yu K, Chen X, Wang X, Wang Z (2017) Parameters identification of photovoltaic models using self-adaptive teaching-learning-based optimization. Energy Convers Manag 145:233–246
62. Chen H, Jiao S, Heidari AA, Wang M, Chen X, Zhao X (2019) An opposition-based sine cosine approach with local search for parameter estimation of photovoltaic models. Energy Convers Manag 195:927–942
63. Chen Z, Wu L, Lin P, Wu Y, Cheng S (2016) Parameters identification of photovoltaic models using hybrid adaptive Nelder-Mead simplex algorithm based on eagle strategy. Appl Energy 182:47–57
64. Chen X, Xu B, Mei C, Ding Y, Li K (2018) Teaching--learning--based artificial bee colony for solar photovoltaic parameter estimation. Appl Energy 212:1578–1588
65. Li S, Gong W, Yan X, Hu C, Bai D, Wang L, Gao L (2019) Parameter extraction of photovoltaic models using an improved teaching-learning-based optimization. Energy Convers Manag 186:293–305
66. Chen X, Tianfield H, Mei C, Du W, Liu G (2017) Biogeography-based learning particle swarm optimization. Soft Comput 21:7519–7541
67. Liang J, Ge S, Qu B, Yu K, Liu F, Yang H, Wei P, Li Z (2020) Classified perturbation mutation based particle swarm optimization algorithm for parameters extraction of photovoltaic models. Energy Convers Manag 203:112138
68. Alam DF, Yousri DA, Eteiba MB (2015) Flower pollination algorithm based solar PV parameter estimation. Energy Convers Manag 101:410–422
69. Oliva D, Abd El Aziz M, Hassanien AE (2017) Parameter estimation of photovoltaic cells using an improved chaotic whale optimization algorithm. Appl Energy 200:141–154
70. Mathew D, Rani C, Kumar MR, Wang Y, Binns R, Busawon K (2017) Wind-driven optimization technique for estimation of solar photovoltaic parameters. IEEE J Photovoltaics 8:248–256
71. Allam D, Yousri DA, Eteiba MB (2016) Parameters extraction of the three diode model for the multi-crystalline solar cell/module using Moth-Flame Optimization Algorithm. Energy Convers Manag 123:535–548
72. Chen X, Yu K (2019) Hybridizing cuckoo search algorithm with biogeography-based optimization for estimating photovoltaic model parameters. Sol Energy 180:192–206
73. Xiong G, Zhang J, Shi D, He Y (2018) Parameter extraction of solar photovoltaic models using an improved whale optimization algorithm. Energy Convers Manag 174:388–405
74. Yuan X, He Y, Liu L (2015) Parameter extraction of solar cell models using chaotic asexual reproduction optimization. Neural Comput Appl 26:1227–1239
75. Lin P, Cheng S, Yeh W, Chen Z, Wu L (2017) Parameters extraction of solar cell models using a modified simplified swarm optimization algorithm. Sol Energy 144:594–603
76. Oliva D, Cuevas E, Pajares G (2014) Parameter identification of solar cells using artificial bee colony optimization. Energy 72:93–102
77. Kang T, Yao J, Jin M, Yang S, Duong T (2018) A novel improved cuckoo search algorithm for parameter estimation of photovoltaic (PV) models. Energies 11:1060
78. El-Fergany AA (2021) Parameters identification of PV model using improved slime mould optimizer and Lambert W-function. Energy Reports 7:875–887
79. El-Naggar KM, AlRashidi MR, AlHajri MF, Al-Othman AK (2012) Simulated annealing algorithm for photovoltaic parameters identification. Sol Energy 86:266–274
80. AlHajri MF, El-Naggar KM, AlRashidi MR, Al-Othman AK (2012) Optimal extraction of solar cell parameters using pattern search. Renew energy 44:238–245
81. Easwarakhanthan T, Bottin J, Bouhouch I, Boutrit C (1986) Nonlinear minimization algorithm for determining the solar cell parameters with microcomputers. Int J Sol energy 4:1–12

82. Hachana O, Hemsas KE, Tina GM, Ventura C (2013) Comparison of different metaheuristic algorithms for parameter identification of photovoltaic cell/module. J Renew Sustain energy 5:53122
83. Wei H, Cong J, Lingyun X, Deyun S (2011) Extracting solar cell model parameters based on chaos particle swarm algorithm. In: 2011 International conference on electric information and control engineering. pp 398–402
84. Askarzadeh A, Rezazadeh A (2013) Artificial bee swarm optimization algorithm for parameters identification of solar cell models. Appl Energy 102:943–949
85. Zhang Y, Jin Z, Zhao X, Yang Q (2020) Backtracking search algorithm with Lévy flight for estimating parameters of photovoltaic models. Energy Convers Manag 208:112615
86. Dkhichi F, Oukarfi B, Fakkar A, Belbounaguia N (2014) Parameter identification of solar cell model using Levenberg--Marquardt algorithm combined with simulated annealing. Sol Energy 110:781–788
87. Jiang LL, Maskell DL, Patra JC (2013) Parameter estimation of solar cells and modules using an improved adaptive differential evolution algorithm. Appl Energy 112:185–193
88. Niu Q, Zhang H, Li K (2014) An improved TLBO with elite strategy for parameters identification of PEM fuel cell and solar cell models. Int J Hydrogen Energy 39:3837–3854
89. Agwa AM, El-Fergany AA, Maksoud HA (2020) Electrical characterization of photovoltaic modules using farmland fertility optimizer. Energy Convers Manag 217:112990
90. Bouali C, Schulte H, Mami A (2019) A high performance optimizing method for modeling photovoltaic cells and modules array based on discrete symbiosis organism search. Energies 12:2246
91. Zhang Y, Ma M, Jin Z (2020) Backtracking search algorithm with competitive learning for identification of unknown parameters of photovoltaic systems. Expert Syst Appl 160:113750
92. Tong NT, Pora W (2016) A parameter extraction technique exploiting intrinsic properties of solar cells. Appl Energy 176:104–115
93. Nnamchi SN, Mundu MM, Busingye JD, Ezenwankwo JU (2019) Extrinsic modeling and simulation of helio-photovoltaic system: a case of single diode model. Int J green energy 16:450–467
94. Muhammad FF, Karim Sangawi AW, Hashim S, Ghoshal SK, Abdullah IK, Hameed SS (2019) Simple and efficient estimation of photovoltaic cells and modules parameters using approximation and correction technique. PLoS One 14:e0216201
95. Huang T, Zhang C, Ouyang H, Luo G, Li S, Zou D (2020) Parameter identification for photovoltaic models using an improved learning search algorithm. Ieee Access 8:116292–116309
96. Jordehi AR (2018) Enhanced leader particle swarm optimisation (ELPSO): An efficient algorithm for parameter estimation of photovoltaic (PV) cells and modules. Sol Energy 159:78–87