Accurate Expressions for Single-Diode-Model Solar Cell Parameterization

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***Abstract*—The performance of a photovoltaic (PV) module is represented by a single-diode-model circuit with the five parameters for a given environmental condition. However, the model characteristic equation which is implicit in nature makes the parameters' extraction computationally complex. In addition, for finding the five parameters from the specifications of the PV module datasheet, one can formulate only four equations. To complete the solution, the formulation of the fifth equation is really tricky. Therefore, the researchers have attempted several approximations to complete the problem formulation, but the obtained results have low accuracy in many cases. This paper specifically focuses on the formulation of the fifth equation without any approximation, which considers an exact area under the current–voltage (*I–V*) curve of a PV cell/module. The method is employed for different cells as case study-I and for the experimental data of a silicon cell and a module as case study-II commonly available in the literature. The numerical results are highly accurate with respect to the existing methods.**

***Index Terms*—Area under *I–V* curve, curve fitting, *I–V* characteristic, photovoltaic module, single-diode-model, solar cell parameters estimation.**

I. Introduction

DURING the decade 2006–2016, the photovoltaic (PV) installations in the world have increased from 7 to 300 GW [1]. The main reason for such a huge increase in the installations is the dropping PV system prices by 2.5–3.5 times during the same time. The basic principle of the PV technology is to capture the sunlight through a PV module and to convert directly into the electricity. The electrical output of a PV module, a strong function of the climatic conditions (the irradiance and temperature), is represented by a single-diode-model and a double-diode-model in form of an electrical circuit [2].

The single-diode-model reproduces highly accurate output characteristics of different kinds of PV cells and modules in any climatic conditions. In the PV analysis, this model is mostly preferred over the other one as it has less number of parameters and less computational complexity. For this model (see Fig. 1), the relation between the cell current (I) and voltage (V) is defined as follows:

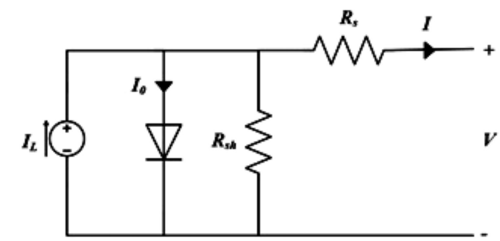

Fig. 1. Equivalent circuit of a solar cell.

$$I = I_L - I_0\left(e^{\frac{q(V+IR_s)}{nKT}} - 1\right) - \frac{V+IR_s}{R_{\rm sh}} \quad (1)$$

where $q =$ electric charge on an electron $= 1.602176487 * 10^{-19}$, $K =$ Boltzmann's constant $= 1.3806504 * 10^{-23}$, $T =$ temperature in Kelvin. The five parameters to be determined are $I_L =$ light generated current, $I_0 =$ reverse saturation current, $R_s =$ series resistance, $R_{\rm sh} =$ shunt resistance, $n =$ ideality factor.

In (1), I is an implicit function, i.e., $I = f(V, I)$. Hence, a direct analytical solution of I is not possible and the solution is obtained by the iterative techniques, such as Newton–Raphson, Gauss–Seidel [3]. In order to formulate an explicit function ($I = f(V)$) and to ease the solution procedure, several explicit analytical expressions exist in the literature. They utilize the approximations such as polynomial [4], Taylor series [5], Padé [6], and Chebyshev [7]. Recently, Lambert W function is extensively used in the literature to express I as an explicit function of V and vice-versa [8], [9]. This special function is not available in form of an elementary function, but it can be represented in a complex series [10]. On one hand, the expressions obtained by previously mentioned approximations drastically reduce the computational time and complexity. On the other hand, the Lambert W function-based expressions are tradeoff between the computation speed and accuracy [8].

In the analytical expressions, the solutions are very sensitive to the initial guesses. A closeness of the guesses to the real values of the parameters successfully converges, otherwise diverges or may result in unphysical parameters. In [11], the five parameters problem is split into two independent and three dependent variables, and thus the solution search space is reduced. In addition, a systematic way for selecting the initial guesses for the two independent variables makes the solution always feasible. In an alternative approach, the analytical problem can be transformed into a nonlinear optimization problem with constraints [12]. This approach gives highly accurate solution without much

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bothering about the initial guesses. In one more approach, the soft-computing techniques are used to find the five parameters from the experimental data, such as pattern search [13], particle swarm optimization [14], and teaching learning based optimization [15]. They first generate many random solutions for the five parameters and then arrive to the final values in an optimized way. The accuracy of the techniques is very high irrespective of the initial guesses. However, they are time consuming as a large number of iterations are required to obtain the final solutions.

Five unknown parameters of the single-diode-model decide the performance of a PV module in any climatic conditions. There are two ways to find the parameters: 1) from an experimental data; and 2) from the key-points mentioned in the manufacturer's datasheet. The main issue with the key-points in the datasheet is that they can formulate only four equations against the five parameters to be solved. To simplify this issue, a fixed value of n is assumed to solve the four equations [16], but the obtained parameters may not be correct. To formulate the fifth equation, Desoto *et al*. [17] have used the open-circuit (OC) condition at a temperature other than the standard test condition (STC). However, the final solution is sensitive to a selected temperature range. An improved fifth equation is derived in [18] which correlates n and the OC voltage ($V_{\rm OC}$). In [19], the slope of the *I–V* curve (dI/dV) at the short-circuit (SC) condition is considered as the fifth equation which is equal to negative inverse of $R_{\rm sh}$, but this condition is only true when $R_{\rm sh} \gg R_s$ and is mostly valid for silicon modules and it may fail for thin-film solar cells. Therefore, the problem is still open to select the fifth equation to complete the solution procedure. In this work, a method to estimate the five parameters of the single-diode-model is presented. The key feature of the method is the formulation of the fifth equation using an exact area under the *I–V* curve along with other four equations based on datasheet information. The proposed method considers an *I–V* dataset of a PV cell/module since it needs the area under the curve. The method also illustrates a systematic way to consider initial guesses for the five parameters. The proposed method is implemented on previously reported few cells [silicon, dye-sensitized (DS), copper indium gallium selenide (CIGS), and perovskite]. Further, the proposed parameters extraction procedure is performed for the commonly cited silicon cell and module using their experimentally measured *I–V* data points. The obtained results are compared with the published data and in terms of the root–mean–square–error (*RMSE*) in currents. The proposed method is accurate.

The organization of the paper is as follows. Section I contains the introduction of the paper. The theme of the proposed method is described in Section II. The Section III discusses two case studies wherein previously reported cells and a module are included. Finally, the conclusions are derived in Section V.

II. Theoretical Background

A. Formulation of the Five Equations

The performance of a PV cell in any climatic conditions can be derived from the five parameters of the single-diode-model. Hence, it is essential to solve for the five parameters using five equations. Here, the cell datasheet key-points, the SC (0, $I_{\rm SC}$), the OC ($V_{\rm OC}$, 0), the maximum power point (MPP) (V_M, I_M) are used to formulate four equations. The first equation is obtained using the SC condition, i.e., the voltage across the cell terminals becomes zero, and $I_{\rm SC}$ can be expressed using (1) as follows:

$$I_{\rm sc} = I_L - I_0 \left(e^{\frac{q I_{sc} R_s}{nKT}} - 1 \right) - \frac{I_{\rm sc} R_s}{R_{\rm sh}}. \tag{2}$$

The second equation is expressed using the OC, i.e., the current through terminals of the cell becomes zero, and (1) is written as follows:

$$0 = I_L - I_0 \left(e^{\frac{q V_{oc}}{nKT}} - 1 \right) - \frac{V_{\rm oc}}{R_{\rm sh}}. \tag{3}$$

The third equation is expressed at the MPP on the *I–V* curve of the cell as follows:

$$I_M = I_L - I_0 \left(e^{\frac{q(V_M + I_M R_s)}{nKT}} - 1 \right) - \frac{V_M + I_M R_s}{R_{\rm sh}}. \tag{4}$$

The fourth equation is also written at the MPP, but in this case, the slope (dI/dV) is considered. The cell power is given by $P = V \times I$, and at the MPP, the rate of change of P with respect to V is zero, i.e., $dP/dV = 0$. Differentiating P with respect to V yields the following:

$$I + V\frac{dI}{dV} = 0. \tag{5}$$

Substituting the MPP condition in (5), the expression is generated as follows:

$$\left(\frac{dI}{dV}\right)_{(V_M, I_M)} = -\frac{I_M}{V_M}. \tag{6}$$

Differentiating (1) with respect to V, the expression is represented as follows:

$$\frac{dI}{dV} = -\left(1 + \frac{dI}{dV} R_s\right)\left(\frac{I_0 q}{nKT} e^{\frac{q(V_M + I_M R_s)}{nKT}} + \frac{1}{R_{\rm sh}}\right). \tag{7}$$

Substituting (6) in (7), the final expression is generated as follows:

$$I_M = (V_M - I_M R_s)\left(\frac{I_0 q}{nKT} e^{\frac{q(V_M + I_M R_s)}{nKT}} + \frac{1}{R_{\rm sh}}\right). \tag{8}$$

Thus, the four equations (2), (3), (4), and (8) can easily be derived from the datasheet information. It is noticed that these equations are dependent on the five parameters.

Here, for the first time, the fifth equation is derived using the concept of the area under the *I–V* curve. It is possible to calculate an accurate area under the curve using the numerical integration method such as the trapezoid rule. The area under the curve is shown with the shaded region in Fig. 2. For calculating the area $\int I dV$, the entire curve is divided into N number of equidistant data points (V_i, I_i), where $i = 1, 2, 3, \ldots N$. For the application of the trapezoid rule, the N data points from the SC to the OC conditions are obtained with equal step-size h ($= V_{\rm OC}/N$). The numerical value of an area A can be obtained using the following

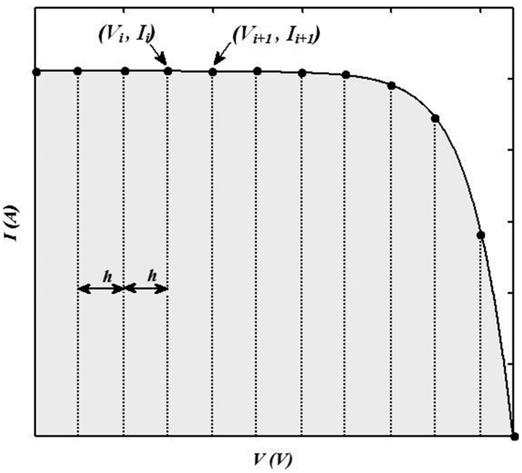

Fig. 2. Area under the *I–V* curve.

expression [20]:

$$A = \frac{h}{2}\left(I_1 + 2\sum_{i=2}^{i=N-1} I_i + I_N\right) \tag{9}$$

where $I_1\ (= I_{\mathrm{SC}})$ is the SC current and I_N is the OC current which is equal to zero.

In order to establish the relation between the area *A* and the five unknown parameters, the trapezoid rule is used again. Here, the value of *A* obtained using (9) is equated to the formula of the trapezoidal rule [20] for the *I–V* curve. But, this time *I* is replaced with its nonlinear implicit expression as in (1). Finally, after simplification, the relation between *A* and the five parameters is generated as the fifth equation represented by (13). The form of this equation can easily be used in the computer programming. Equation (9) can be written as follows after the simplifications:

$$A = \frac{hI_{\mathrm{sc}}}{2} + h\sum_{i=2}^{i=N-1} I_i. \tag{10}$$

In order to change the summation limit from (2, *N*–1) to (1, *N*), the term hI_{SC} is added and subtracted in the right-hand side of (10) and the expression is yielded as follows:

$$A = \frac{hI_{\mathrm{sc}}}{2} - hI_{\mathrm{sc}} + hI_{\mathrm{sc}} + h\sum_{i=2}^{i=N-1} I_i + 0. \tag{11}$$

Simplifying (11), the expression is as follows:

$$A = -\frac{hI_{\mathrm{sc}}}{2} + h\sum_{i=0}^{i=N} I_i. \tag{12}$$

Substituting for I_i in (12) from (1), the final equation relating area *A* and the five parameters is as under

$$A + \frac{hI_{\mathrm{sc}}}{2} - h\sum_{i=0}^{i=N}\left(I_L - I_0\left(e^{\frac{q(V_i + I_i R_s)}{nKT}} - 1\right) - \frac{V_i + I_i R_s}{R_{\mathrm{sh}}}\right) = 0. \tag{13}$$

Thus, (2)–(4), (8), and (13) are the five equations as a function of five unknown parameters. This set of simultaneous equations can be solved using iterative techniques. The prior requirements for the solution are as follows:

1) the datasheet values;
2) *N* data points (V_i, I_i);
3) initial guesses for the five parameters.

B. Evaluation of the Initial Guesses

As previously mentioned, the solution requires initial values for the five parameters. In this procedure, first, the initial values of R_{sh}, *n*, and R_s are derived. Subsequently, the initial values of I_0 and I_L are found using the initial values of the previous three parameters.

Differentiating (1) with respect to *I* and simplifying, the following expression is yielded [21]:

$$-\frac{dV}{dI} = \frac{nKT/q}{I_{\mathrm{sc}} - I - \left\{V - R_s\left(I_{\mathrm{sc}} - I\right) - \frac{nKT}{q}\right\}/R_{\mathrm{sh}}} + R_s. \tag{14}$$

Expressing (14) at the SC condition yields the following:

$$-\frac{dV}{dI} = R_{\mathrm{sh}0} + R_s \approx R_{\mathrm{sh}0}. \tag{15}$$

The assumption $R_s \ll R_{\mathrm{sh}0}$ is generally valid for different cells and modules [22]. Hence, the negative reciprocal of the slope near the SC region gives initial guess value $R_{\mathrm{sh}0}$ for R_{sh}.

For the initial guess values of *n* and R_s, (14) is revisited. The assumptions, $R_s \ll R_{\mathrm{sh}}$ and $\frac{nKT}{q} \ll R_{\mathrm{sh}}$ are generally valid for different cells and modules. Equation (14) can be reduced in the following form after considering the assumptions:

$$-\frac{dV}{dI} \approx \frac{nKT/q}{\left(I_{\mathrm{sc}} - I - \frac{V}{R_{\mathrm{sh}}}\right)} + R_s. \tag{16}$$

A plot of –*dV*/*dI* as a function of $(I_{\mathrm{SC}} - I - V/R_{\mathrm{sh}})^{-1}$ with the knowledge of a few (*V*, *I*) data points near the OC region can be constructed. The plot is a straight line. The slope is nKT/q and *Y*-intercept is R_s. Thus, the initial values n_0 and R_{s0} are obtained from the slope and the *Y*-intercept, respectively.

Finally, the initial values for I_{00} and I_{L0} are obtained using (2) and (3), respectively, by substituting $R_{\mathrm{sh}0}$, n_0, and R_{s0}. The expressions for I_{00} and I_{L0} are as follows:

$$I_{00} = \frac{I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}0}} + \frac{I_{\mathrm{sc}}R_{s0}}{R_{\mathrm{sh}0}}}{e^{\frac{qV_{oc}}{n_0KT}} - e^{\frac{qI_{\mathrm{sc}}R_{s0}}{n_0KT}}} \tag{17}$$

$$I_{L0} = \left(\frac{I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}0}} + \frac{I_{sc}R_{s0}}{R_{\mathrm{sh}0}}}{e^{\frac{qV_{oc}}{n_0KT}} - e^{\frac{qI_{\mathrm{sc}}R_{s0}}{n_0KT}}}\right)\left(e^{\frac{qV_{oc}}{n_0KT}} - 1\right) + \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}0}}. \tag{18}$$

Thus, the procedure cited above establishes a systematic way to find the initial values of the five parameters, which can be helpful for the other parameters extraction algorithms as well.

TABLE I
FIVE PARAMETERS FOR THE BLUE SILICON CELL (SAT) WITH $N = 1\ 000\ 000$

Parameters	Reference	Initial guess	Solution A
I_L (A)	0.1023	0.1023	0.102307
I_0 (A)	$1.045\text{x}10^{-7}$	$1.0327\text{x}10^{-7}$	$1.0450\text{x}10^{-7}$
R_s (Ω)	0.0695	0.0696	0.069499
R_{sh} (Ω)	1003.2	1000.0	1003.207
n	1.5051	1.5038	1.505102

III. Application of the Proposed Method

A. Case Studies-1

The proposed method is first validated on different PV cells described in the previous literature. A detailed analysis is carried out on a high quality blue silicon cell (SAT) [23] in MATLAB. To test the method, the reference values of the five parameters of the cell at the STC (1000 W/m^2 and 25 °C) were taken from [24] and are listed in Table I. The (V, I) data points of the cell are reproduced using the reference values of five parameters and the Runge–Kutta fourth-order method, which is used for the solution of an ordinary differential equation [25]. Equation (7) can be represented as follows:

$$\frac{dI}{dV} = f\left(V,\ I\right) = -\frac{\frac{I_0 q}{nKT} e^{\frac{q(V+IR_s)}{nKT}} + \frac{1}{R_{\mathrm{sh}}}}{1 + \frac{R_s}{R_{\mathrm{sh}}} + \frac{I_0 q R_s}{nKT} e^{\frac{q(V+IR_s)}{nKT}}}. \quad (19)$$

The following iterative steps are used to generate the N data points (V, I) at an equal step-size h of the I–V curve [25]

$$K_1 = f\left(V_i, I_i\right) \quad (20)$$

$$K_2 = f\left(V_i + \frac{h}{2}, I_i + K_1 \frac{h}{2}\right) \quad (21)$$

$$K_3 = f\left(V_i + \frac{h}{2}, I_i + K_2 \frac{h}{2}\right) \quad (22)$$

$$K_4 = f\left(V_i + h, I_i + K_3 h\right) \quad (23)$$

$$I_{i+1} = I_i + \frac{h}{6}\left(K_1 + 2K_2 + 2K_3 + K_4\right). \quad (24)$$

Thus, for this cell, $N = 1\ 000\ 000$ data points are generated using the set of (20)–(24), subsequently, the SC, the OC, and the MPP are extracted. The initial guesses are calculated using the procedure shown in Section II-B and are listed in Table I. The plot of $-dV/dI$ as a function of $(I_{\mathrm{SC}} - I - V/R_{\mathrm{sh}})^{-1}$ is displayed in Fig. 3. The area A is computed using the data points and *trapz* function in MATLAB. The *trapz* is an inbuilt function to compute the area A using (9). The set of equations (2)–(4), (8), and (13) for the cell is solved using *fsolve* command in MATLAB. The five parameters obtained using the proposed method are listed in Table I as a solution A. The solution A is extremely close to the reference parameters. This indicates that the proposed method accurately calculates the parameters of the cell.

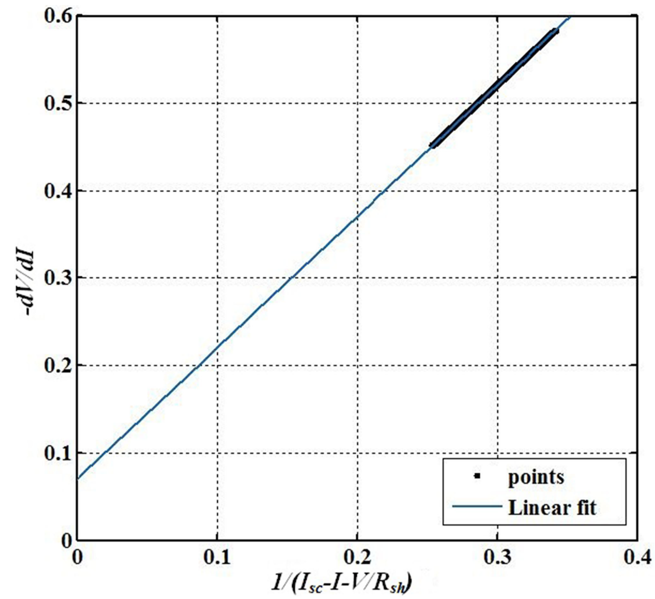

Fig. 3. Plot of $-dV/dI$ as a function of $(I_{\mathrm{SC}} - I - V/R_{\mathrm{sh}})^{-1}$ for the blue silicon cell.

TABLE II
ACCURACY IN THE FIVE PARAMETERS AS A FUNCTION OF DATA POINTS N

N	I_L (A)	I_0 (A)	R_s (Ω)	R_{sh} (Ω)	n	A
10^2	0.102308	$1.045\text{x}10^{-7}$	0.045532	578.7056	1.519746	0.050421
10^3	0.102308	$1.189\text{x}10^{-7}$	0.065965	901.1235	1.507066	0.050426
10^4	0.102307	$1.063\text{x}10^{-7}$	0.069815	1018.24	1.505008	0.050426
10^5	0.102307	$1.044\text{x}10^{-7}$	0.069433	1005.124	1.505208	0.050426
10^6	0.102307	$1.046\text{x}10^{-7}$	0.069499	1003.207	1.505102	0.050426
10^7	0.102307	$1.045\text{x}10^{-7}$	0.069499	1003.207	1.505102	0.050426

TABLE III
ESTIMATED PARAMETERS OF THE BLUE SOLAR CELL WITH RANDOMLY CHOSEN INITIAL GUESSES

Parameters	Initial guesses	Solution B
I_L (A)	1	0.102307
I_0 (A)	0.001	$1.045\text{x}10^{-7}$
R_s (Ω)	0.5	0.069499
R_{sh} (Ω)	100	1003.207
n	1	1.505102

The area under the curve estimated using the trapezoid rule is usually erroneous if N is too small (in other words large h). To improve the accuracy in the parameters, large N has to be chosen (small h). Thus, the accuracy in the five parameters is greatly influenced by the number of selected data points N. Table II illustrates how the accuracy is improved in the five parameters with an increase in number of N data points. As seen in Table II, the large N data points increase the precision in A, and thus, the accuracy in the estimated parameters increases.

Even if the initial guesses are chosen randomly within boundary values of the parameters [26] as shown in Table III, the proposed method gives solution B which is exactly the same as

TABLE IV
ESTIMATED AND PREVIOUSLY REPORTED PARAMETERS OF THIN-FILM CELLS [8], [21], [27]

Name of cell		V_{oc} (V)	I_{sc} (A)	I_L (A)	I_0 (A)	R_s (Ω)	R_{sh} (Ω)	n	A	T (K)
DSSC(C4)	**Previous work [21]**	0.704	0.002	-	3.05x10^{-8}	43.8	3736	2.5	-	293
	Present work	0.693683	0.002	0.002024	3.05x10^{-8}	43.79868	3736.157	2.500053	1.15x10^{-3}	
Silicon	**Previous work [8]**	-	0.0418	0.0418	1.73x10^{-14}	0.163	929.5	1	-	300
	Present work	0.736364	0.0418	0.041807	1.73x10^{-14}	0.162975	929.4773	1.000006	0.029292	
CIGS	**Previous work [27]**	0.692	0.0352	0.0352	3.60x10^{-11}	0.22	5882.3	1.3	-	298
	Present work	0.6907	0.0352	0.0352	3.60x10^{-11}	0.22	5882.6	1.3	0.023	
Perovskite	**Previous work [8]**	-	0.01937	0.01937	4.17x10^{-13}	2.923	2676.5	2.098	-	300
	Present work	1.330073	0.01937	0.019391	4.17x10^{-13}	2.922767	2676.562	2.098045	0.023893	
Perovskite-b	**Previous work [8]**	-	0.0193	0.0193	8.80x10^{-13}	2.078	∞	2.473	-	300
	Present work	1.521721	0.0193	0.0193	8.81x10^{-13}	2.077991	3.99x10^{10}	2.473025	0.027749	

solution A. This proves that the proposed method could be tried with different initial guesses which may give correct parameters.

In this case study, a few more thin-film cells with high and low R_s in comparison with R_{sh} are analyzed [8], [21], [27]. A dye-sensitized solar cell (DSSC) from the top in Table IV has very high R_s in comparison with the remaining cells. The same procedure is adopted to find the five parameters for these cells with number of data points $N = 1\ 000\ 000$. Table IV lists the estimated parameters and the previously reported parameters.

The estimated parameters are in excellent agreement with those reported in the literature. Therefore, it is concluded that the proposed method performs excellently with the cells having low to high values of R_s.

B. Case Studies-2

Here, the proposed method is also employed for the measured experimental *I–V* data of 1) the module PWP 201 (36 polycrystalline silicon cells connected in series) tested under 1000 W/m^2 and 45 °C [28] and 2) the 57 mm diameter commercial silicon cell (RTC France) tested under 1000 W/m^2 and 33 °C [28]. Twenty six experimental data points of both the cases are taken from [11] and listed in Table V.

1) Silicon Module: For this case, the experimental data points shown in Table V are with an unequal distance and separated by a large voltage difference on the *V*-axis. As in (9), the computation of the accurate area (A) requires equidistant points with very small h, i.e., large data points N. Therefore, the accurate computation of A is not possible using a few experimental data points ($N = 26$) for the module. In order to generate a set of large data points with an equal distance, the experimental data are fitted with a suitable polynomial. Here, the experimental data are optimally fitted using section-wise polynomial curve fitting [29], which results in minimum RMSE in I. A set of few data near the SC region are fitted with sixth-order polynomial, and the remaining dataset near the OC region are fitted with ninth-order polynomial. The *cftool* command in MATLAB is used for both the fittings and total data points $N = 1\ 000\ 000$ are generated. Subsequently, area A (see Table VI) is computed using the data points and *trapz* function in the MATLAB. The SC, the OC, and the maximum power points are also obtained from the generated data points. The initial guesses for the five parameters are evaluated using the systematic approach described in Section II-B and are listed in Table VI. Finally, the five parameters are computed by solving (2)–(4), (8), and (13) using the *fsolve* function in MATLAB. The estimated parameters are shown in Table VI. Fig. 4 illustrates the experimental data and the simulated *I–V* curve obtained by the estimated parameters. It is clearly observed that the

TABLE V
EXPERIMENTAL DATA AND THE ABSOLUTE ERROR IN I FOR THE SILICON MODULE AND THE SILICON CELL

Silicon module			Silicon cell		
I_n (A)	V_n (V)	$\lvert\Delta I\rvert$(A)	I_n (A)	V_n(V)	$\lvert\Delta I\rvert$(A)
1.0345	-1.9426	5.8127x10^{-4}	0.7640	-0.2057	3.5242 x10^{-4}
1.0315	0.1248	1.2479 x10^{-5}	0.7620	-0.1299	8.7471 x10^{-4}
1.0300	1.8093	5.0617 x10^{-4}	0.7605	-0.0588	9.8852 x10^{-4}
1.0260	3.3511	1.6304 x10^{-3}	0.7605	0.0057	2.6945 x10^{-4}
1.0220	4.7622	3.8182 x10^{-3}	0.7600	0.0646	9.2016 x10^{-4}
1.0180	6.0538	5.8921 x10^{-3}	0.7590	0.1185	9.8047 x10^{-4}
1.0155	7.2364	6.0176 x10^{-3}	0.7570	0.1678	2.5938 x10^{-5}
1.0140	8.3189	4.0651 x10^{-3}	0.7570	0.2132	9.5930 x10^{-4}
1.0100	9.3097	2.4395 x10^{-3}	0.7555	0.2545	5.3965 x10^{-4}
1.0035	10.2163	5.8871 x10^{-4}	0.7540	0.2924	4.7223 x10^{-4}
0.9880	11.0449	9.4913 x10^{-4}	0.7505	0.3269	7.6684 x10^{-4}
0.9630	11.8018	1.1230 x10^{-3}	0.7465	0.3585	7.7986 x10^{-4}
0.9255	12.4929	1.1394 x10^{-3}	0.7385	0.3873	1.6299 x10^{-3}
0.9120	12.6490	1.2828 x10^{-3}	0.7280	0.4137	4.1323 x10^{-4}
0.8725	13.1231	2.2612 x10^{-4}	0.7065	0.4373	8.4278 x10^{-4}
0.7265	14.2221	3.4224 x10^{-3}	0.6755	0.4590	4.0556 x10^{-4}
0.6345	14.6995	4.8842 x10^{-3}	0.6320	0.4784	3.0749 x10^{-4}
0.5345	15.1346	6.8068 x10^{-3}	0.5730	0.4960	2.8962 x10^{-5}
0.4275	15.5311	6.7841 x10^{-3}	0.4990	0.5119	1.4954 x10^{-3}
0.3185	15.8929	6.9280 x10^{-3}	0.4130	0.5265	1.4714 x10^{-3}
0.2085	16.2229	5.7255 x10^{-3}	0.3165	0.5398	1.6035 x10^{-3}
0.1010	16.5241	4.8668 x10^{-3}	0.2120	0.5521	8.4683 x10^{-4}
-0.0080	16.7987	1.1257 x10^{-3}	0.1035	0.5633	1.9657 x10^{-4}
-0.1110	17.04990	5.3255 x10^{-3}	-0.0100	0.5736	1.1675 x10^{-3}
-0.2090	17.2793	9.4896 x10^{-3}	-0.1230	0.5833	1.1260 x10^{-3}
-0.3030	17.4885	1.5068 x10^{-3}	-0.2100	0.5900	9.5296 x10^{-4}

TABLE VI
ESTIMATED PARAMETERS OF THE PV MODULE

Parameters	Initial guess	Estimated
I_L (A)	1.032447	1.033285
I_0 (A)	9.07x10^{-6}	1.82x10^{-6}
R_s (Ω)	1.089249	1.357607
R_{sh} (Ω)	1384.033	850.7068
n	52.65237	46.28725
A	-	15.15517
$RMSE$	-	5.181 x 10^{-3}
I_{SC} (A)	-	1.03163
V_{OC} (V)	-	16.7753
I_M (A)	-	0.9162
V_M (V)	-	12.6049

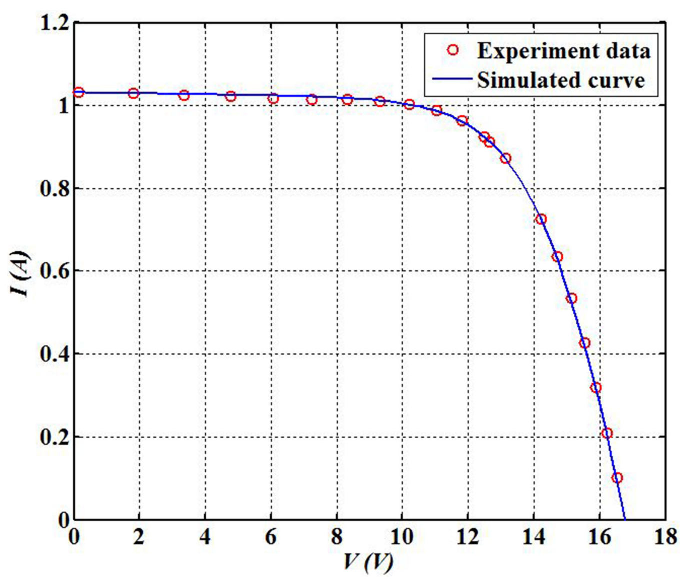

Fig. 4. Experimental data and the simulated *I–V* curves of the PV module.

TABLE VII
ABSOLUTE RELATIVE ERROR (%) IN ESTIMATED PARAMETER WITH 1% TO 5% NOISE LEVEL

Noise	I_L (%)	I_0 (%)	R_s (%)	R_{sh} (%)	n	P_{max} (%)
1%	0.1308	16.4861	1.8218	11.4829	1.3382	0.0337
2%	0.0947	52.1001	4.1743	68.2985	3.2362	0.0302
3%	0.0241	14.0746	3.7296	13.2058	1.1436	0.0622
4%	0.3483	74.9463	9.7694	38.6499	9.3995	2.1539
5%	0.4567	62.9113	28.4097	38.9158.	6.9586	0.1133

simulated curve passes through all the experimental points. In addition, the experimental data together with the absolute error in I are reported in Table V. The maximum error is 1.5068×10^{-3} A and the minimum is 1.2479×10^{-5} A. Furthermore, the RMSE (listed in Table VI) between the experimental (I_i) and the estimated values (I_{est}) is also computed using the following expression:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{i=N} \left(I_i - I_{\text{est}}\right)^2}{N}}. \tag{25}$$

TABLE VIII
ESTIMATED PARAMETERS OF THE SILICON CELL

Parameters	Initial guess	Estimated
I_L (A)	0.760446	0.760883
I_0 (A)	8.068212x10^{-7}	2.96x10^{-7}
R_s (Ω)	0.03343	0.036499
R_{sh} (Ω)	244.2236	51.25965
n	1.579771	1.473194
A	-	0.392972
$RMSE$	-	8.58 x10^{-4}
I_{SC} (A)	-	0.7603
V_{OC} (V)	-	0.5726
I_M (A)	-	0.6894
V_M (V)	-	0.4507

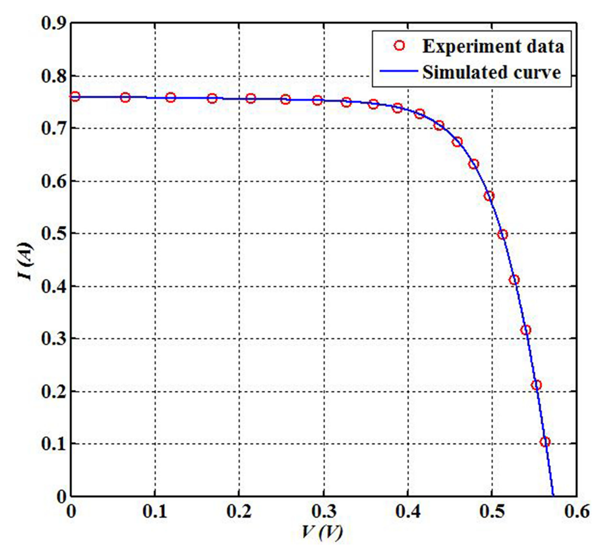

Fig. 5. Experimental data and the simulated *I–V* curves of the silicon cell.

These results indicate that the parameters estimated by the proposed method correctly represent the performance of the PV module.

In order to assess the capability of the proposed method in the presence of noise in the measurements, a possible random error in the experimental data of the PV module is generated as follows [9]:

$$I_{\text{with\_noise}} = I_{\text{without\_noise}}(1 + \text{random} \times \text{percent}). \tag{26}$$

Thus, the data obtained with noise in (26) is further used to extract the parameters. First, the noisy data is smoothed using *smooth* function in MATLAB (This command is based on a moving average filter with a default span 5 in the *V* data.) Subsequently, the data is regressed using *cftool* function. Table VII shows the absolute relative error in the obtained parameters (with noise level 1%–5%) with that of with 0% noise. It can be observed that with a relative intensity 1%–5%, the highest error in R_s is 28.40%, whereas that in *n* is 9.39%. The I_L is not influenced much by adding the noise. However, the errors in R_{sh} and I_0 are relatively large compared with other three parameters.

TABLE IX
ESTIMATED PARAMETERS OF THE SILICON CELL AND MODULE BY THE PROPOSED AND EXISTING METHODS

Case	Methods	I_L (A)	I_0 (A)	R_s (Ω)	R_{sh} (Ω)	n	*RMSE*
PV module PWP-201	**Proposed**	1.033285	1.82x10^{-6}	1.357607	850.7068	1.2857	5.18x10^{-3}
	Ref. [21]	1	2.30x10^{-6}	1.3	830	1.3056	3.26 x10^{-2}
	Ref. [30]	1.03	6.40 x10^{-6}	1.1619	689.65517	1.4164	1.72 x10^{-2}
	Ref. [31]	1.0359	6.77 x10^{-6}	1.146	200	1.4265	4.10 x10^{-2}
	Ref. [34]	1.033774	1.10 x10^{-6}	1.432646	689.0408	1.2391	6.55 x10^{-2}
PV cell RTC France	**Proposed**	0.760883	2.96 x10^{-7}	0.036499	51.25965	1.4731	8.58 x10^{-4}
	Ref. [21]	0.77	2.00 x10^{-7}	0.037	320	1.4	7.78 x10^{-2}
	Ref. [22]	0.7608	3.44 x10^{-7}	0.0356	53.7375	1.4898	3.72 x10^{-3}
	Ref. [29]	0.7608	3.22 x10^{-7}	0.0364	53.76275	1.4837	4.37 x10^{-3}
	Ref. [30]	0.7603	3.37 x10^{-7}	0.0376	106.38298	1.4841	3.86 x10^{-3}
	Ref. [31]	0.7609	4.04 x10^{-7}	0.0364	49.504951	1.5039	3.40 x10^{-3}
	Ref. [32]	0.7632	3.47 x10^{-7}	0.0365	43.0829	1.4909	3.68 x10^{-3}
	Ref. [33]	0.760944	3.46 x10^{-7}	0.036142	49.482205	1.4887154	1.06 x10^{-3}
	Ref. [34]	0.760863	2.78 x10^{-7}	0.036961	49.88866	1.4664564	1.20 x10^{-3}

This is because the current *I* is an exponential function of R_s and *n* as in (1). A strong dependence of *I* on R_s and *n* does not allow to deviate these parameters much with added noise. However, a poor sensitivity of *I* on $R_{\rm sh}$ and I_0 allows larger deviations. The similar results are obtained in [9] and [15] with noise. An application point of view, the maximum power $P_{\max}$ is a significant parameter for a PV module. The extracted value of $P_{\max}$ has a negligible deviation (∼2%) with the noise (see Table VII). Thus, a small deviation in $P_{\max}$ proves the robustness of the algorithm to handle data with measurement noise.

2) Silicon Cell: For this case, the procedure analogous to the silicon module is adopted to estimate the five parameters. For the best data fit, the experimental data are divided into four parts. The first, second, and third parts are fitted using fourth-order polynomial, whereas the fourth part is fitted using fifth-order polynomial using *cftool* function. Total $N = 1\ 000\ 000$ data points are generated.

The estimated initial guesses, the five parameters together with area (*A*) and the RMSE are shown in Table VIII. Fig. 5 illustrates the experimental data and the simulated *I–V* curve obtained by the estimated parameters. It is clearly observed that the simulated curve passes through all the experimental points. The experimental data together with the absolute error in *I* are reported in Table V. The maximum error is 1.6299×10^{-3} A and the minimum is 2.5938×10^{-5} A. These results indicate that the parameters estimated by the proposed method represent accurate performance of the silicon cell.

3) Comparison With Previous Works: The proposed method is compared with the existing methods [21], [22], [29]–[34] having similar approach and computational complexity. The parameters and RMSE [calculated using (25)] are listed in Table IX. It is observed that the RMSE value obtained by the proposed method for both the cases is the lowest. The poor performance by other methods could be due to

1) some analytical approaches [21], [22] use approximations in the original *I–V* relation given by (1);
2) a few methods [22], [30], [31] approximate the fifth equation as the slope of the *I–V* curve (at the SC point) as $R_{\rm sh}$ and the slope is obtained using few data points near the SC region and polynomial fit;
3) most of the methods [21], [22], [29], [33], [34] consider the slopes at the SC/OC regions of the *I–V* curve in the derivation of the five parameters expressions.

The slopes at the SC/OC regions are not specified in the datasheet and are derived from the approximate polynomial fit using a few data points. Thus, the use of approximate slopes influences the obtained parameters and RMSE. On the contrary, the proposed method considers entire set of the data points along with the key points as the fifth equation in terms of area under the curve. The approach does not use the slope of the curve in the SC/OC regions for the derivation of the expressions. Thus, the proposed method becomes unique in terms of fifth equation and assumptions-free expressions.

Notably, the formulation of the fifth equation is crucial in order to decide the accurate area under the *I–V* curve. For the determination of an accurate area, a large number of data points $(N > 10^6)$ are required (which is not possible by datasheet information and a few experimental data points) which have to be reconstructed from the measured data points using a curve fitting tool. Of course, for on field applications, this algorithm demands for large memory and computational burden, and makes the power control complex. However, this will be very helpful for the cell and module manufacturers at design and fabrication level for the PV device characterizations. Therefore, the applicability of the proposed method is recommended for precise identification of the parameters offline instead of online.

IV. CONCLUSION

In this paper, an efficient and simple approach for single-diode PV model parameters extraction is developed, which considers (*V, I*) data points. The five parameters of the PV model are evaluated by solving the five equations. The salient feature of the method is the formulation of the fifth equation using the area under the *I–V* curve of the PV module which results in precise parameters determination. The method also utilizes a systematic approach to obtain the required initial guess values. This method is validated for the different crystalline silicon and thin-film solar cells. The parameters accuracy is greatly influenced by the number of data points on the *I–V* curve. The method is also employed for experimental *I–V* curve of the silicon cell and module commonly available in the literature. The method provides highly accurate solution and tackles the noise in the measurements. The proposed method outperforms in comparison with other methods.

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