Parameter Extraction of Single-Diode Model From Module Datasheet Information Using Temperature Coefficients

Shigeomi Hara, *Member, IEEE*

***Abstract*—The single-diode model (SDM) is used widely for modeling of photovoltaic cells and modules because of its simplicity and accuracy. The main objective of this article is to propose a new method to estimate the five unknown parameters of the SDM under standard test conditions using the module datasheet information (MDI) alone. The proposed method specifically uses the temperature coefficient (TC) of the maximum power of the module given in the MDI in conjunction with three physical or empirical models of the TCs of the photo-induced current, the diode reverse saturation current, and the diode ideality factor. It is well known that four equations that limit these parameters can be deduced naturally from the MDI, and a new fifth equation was deduced in this research from the MDI and the three TC models above without no simplification or other assumptions. The nonlinear equations for the SDM's parameters were solved using a simple mesh search algorithm. Finally, the proposed method was extended to produce an adaptive model to enable estimation of the SDM parameters at any irradiance and temperature.**

***Index Terms*—Adaptive model, module datasheet, parameter estimation, single-diode model, temperature coefficient.**

I. Introduction

Mathematical models of photovoltaic (PV) cells and modules are important tools for use in the analysis and simulation of solar PV systems and the single-diode model (SDM) is used widely for this purpose because of its simplicity and accuracy [1]. A method that can estimate the five unknown parameters of the SDM for PV modules from only the information in the manufacturer's datasheet is desirable and would be of considerable practical use [2]. The module datasheet information (MDI) gives four equations naturally that restrict these unknown parameters. The main aim of this article is to derive a fifth equation and then propose a method to extract the five unknown parameters from the MDI alone.

Several methods of this type have been proposed previously in the literature. An approximate explicit solution was described in [3] that allowed the five parameters to be extracted under any environmental conditions other than the standard test conditions (STCs) using the temperature coefficients (TCs) of the module's open-circuit voltage V_{oc} and shunt-circuit current I_{sc}. An approximation in which the shunt resistance R_{h} is infinitely large and the photo-induced current I_{ph} is equal to I_{sc} was assumed in that case. In [4], an iterative parameter estimation method was proposed based on the assumption that

$$I_{\mathrm{ph}} = (R_{\mathrm{h}} + R_{\mathrm{s}})I_{\mathrm{sc}}/R_{\mathrm{h}} \tag{1}$$

where R_{s} is the series resistance. In [5] and [6], extraction methods were proposed based on the assumption that $\frac{dI}{dV}|_{V=0} = -\frac{1}{R_{\mathrm{h}}}$. In [7], the fourth equation, which represents the maximum power point (MPP) condition, was considered to be an objective function that was minimized under specific inequality constraints that were determined based on the device's physical limitations. The TC of the open-circuit voltage V_{oc} was used to generate a fifth equation in [8] by assuming that the diode ideality factor η and R_{h} were both independent of the temperature T. A fifth equation was deduced in [9] but unfortunately was not independent of the other four equations. Additional measurement data have also been used together with the datasheet information to estimate the model parameters [10]–[14]. These data included the I-V curve slopes at the short-circuit and open-circuit points, the open-circuit voltage V_{oc} for any irradiance other than 1 kW/m^2, and measured values of R_{h}.

The literature also contains considerable research from another perspective in which the SDM parameters are extracted from full or partial I-V curve data [15], [16]. Although I-V curve data containing more than five points can at least be used to determine the five SDM parameters uniquely in theory, the parameter estimation process remains challenging because of the strong nonlinearity of the problem.

The method proposed in this article to deduce the fifth equation is similar to the method given in [8], but the assumption of constant values of η and R_{h} with respect to T is removed. Using the MDI and the three TC models of the diode reverse saturation current I_0, I_{ph}, and η, a new fifth equation is then calculated without no simplification or other assumptions.

The remainder of this article is organized as follows. Section II describes the method proposed to extract the SDM parameters from the MDI. Section III then evaluates the proposed method using test MDI sets produced from arbitrarily selected SDM parameters. Section IV presents the results of application of the proposed method to real MDI sets. Section V describes extension

Manuscript received September 12, 2020; revised October 23, 2020; accepted October 26, 2020. Date of publication November 18, 2020; date of current version December 21, 2020. *(Corresponding author: Shigeomi Hara.)*

The author is with the Department of Science, and Engineering, Saga University, Saga 8408502, Japan (e-mail: haras@cc.saga-u.ac.jp).

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Digital Object Identifier 10.1109/JPHOTOV.2020.3035116

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of the proposed method to an adaptive model. Conclusions from the study are drawn in the final section.

II. Method

The module datasheet is assumed to give measured values of the following seven variables: $V_{\rm oc}$ (V), $I_{\rm sc}$ (A), $V_{\rm mp}$ (V), $I_{\rm mp}$ (A), $\alpha_{\rm sc}$ (/K), $\beta_{\rm oc}$ (/K), and $\gamma_{\rm mp}$ (/K). Here, $V_{\rm mp}$ and $I_{\rm mp}$ are the voltage and current at the MPP, respectively, and $\alpha_{\rm sc}$, $\beta_{\rm oc}$, and $\gamma_{\rm mp}$ are the TCs of $I_{\rm sc}$, $V_{\rm oc}$, and $I_{\rm mp}V_{\rm mp}$, respectively. In the work up to Section IV, the irradiance is always fixed at 1 kW/m^2, and all variables are considered to be a function of T. Any derivative with respect to T is denoted by $'$, that is, $\frac{dy}{dT} = y'$. The TC of I_0 is calculated in (15) below from

$$I_0 = CT^{\frac{3}{\eta}} \exp\left\{-E_{\rm g}/(\eta kT)\right\} \tag{2}$$

following the manner of [17]. Here, C is a constant, k is the Boltzmann constant, η is the diode ideality factor, and $E_{\rm g}$ is the material band gap, which is given by $E_{\rm g} = E_{\rm g,0} - aT^2/(T+b)$, where $E_{\rm g,0} = 1.852 \times 10^{-19}$ J, $a = 1.125 \times 10^{-22}$ J/K, and $b = 1108$ K for the semiconductor material Si [18]. A model of $I_{\rm ph}$ from (1) is used in this article only for its TC, as shown in (17) below. The TC of η under the STCs is given in [19]

$$\eta' = -5.7 \times 10^{-4} \text{ (/K)}. \tag{3}$$

The MDI and the three TC models have now been specified, and the proposed method to extract the five unknown parameters of the SDM is deduced in the following without no simplification or other assumptions. The voltage V and the current I of the SDM are related by

$$I = I_{\rm ph} - I_0\left\{\exp\left(\frac{V+R_{\rm s}I}{\eta V_{\rm t}}\right) - 1\right\} - \frac{V+R_{\rm s}I}{R_{\rm h}} \tag{4}$$

where $V_{\rm t} = N_{\rm s}kT/q$. Here, $N_{\rm s}$ represents the number of series-connected cells contained in the module, and q is the electron charge. The derivative of $V_{\rm t}$ with respect to T is given by $V_{\rm t}' = N_{\rm s}k/q$. For brevity, the variables X, Y, and Z are introduced here as follows:

$$X = e^{V_{\rm oc}/(\eta V_{\rm t})},\ Y = e^{R_{\rm s}I_{\rm sc}/(\eta V_{\rm t})},\ Z = e^{(V_{\rm mp}+R_{\rm s}I_{\rm mp})/(\eta V_{\rm t})}. \tag{5}$$

The pair $(V,\ I) = (V_{\rm oc},\ 0)$ satisfies (4), which yields the first equation

$$I_{\rm ph} - I_0(X-1) - V_{\rm oc}/R_{\rm h} = 0. \tag{6}$$

The second equation is then given by (4) for the pair $(0,\ I_{\rm sc})$

$$I_{\rm ph} - I_0(Y-1) - R_{\rm s}I_{\rm sc}/R_{\rm h} - I_{\rm sc} = 0. \tag{7}$$

Substitution of $(V_{\rm mp},\ I_{\rm mp})$ into (4) gives the third equation

$$I_{\rm mp} = I_{\rm ph} - I_0(Z-1) - (V_{\rm mp} + R_{\rm s}I_{\rm mp})/R_{\rm h}. \tag{8}$$

The derivative of the power with respect to the voltage at the MPP is zero, that is

$$\left.\frac{d(VI)}{dV}\right|_{V=V_{\rm mp},I=I_{\rm mp}} = I_{\rm mp} + V_{\rm mp}\left.\frac{dI}{dV}\right|_{V=V_{\rm mp},I=I_{\rm mp}} = 0. \tag{9}$$

This equation is combined with (4) to give

$$1 + \frac{R_{\rm s}I_0}{\eta V_{\rm t}}Z + \frac{R_{\rm s}}{R_{\rm h}} = \left(I_0 Z\frac{1}{\eta V_{\rm t}} + \frac{1}{R_{\rm h}}\right)\frac{V_{\rm mp}}{I_{\rm mp}} \tag{10}$$

which can then be arranged as shown to give the fourth equation

$$A \equiv \frac{R_{\rm s}I_{\rm mp} - V_{\rm mp}}{\eta V_{\rm t}}I_0 Z + \left(\frac{R_{\rm s}}{R_{\rm h}} + 1\right)I_{\rm mp} - \frac{V_{\rm mp}}{R_{\rm h}} = 0. \tag{11}$$

Next, to obtain the fifth equation, the derivatives of (6), (7), and (8) with respect to T are taken, given that all variables are dependent on T

$$\frac{V_{\rm oc}}{R_{\rm h}^2}R_{\rm h}' + I_0 X\frac{V_{\rm oc}}{\eta^2 V_{\rm t}}\eta' + I_{\rm ph}' - (X-1)I_0'$$
$$-\left(I_0 X\frac{1}{\eta V_{\rm t}} + \frac{1}{R_{\rm h}}\right)V_{\rm oc}' + I_0 X\frac{V_{\rm oc}V_{\rm t}'}{\eta V_{\rm t}^2} = 0 \tag{12}$$

$$\left(-I_0 Y\frac{1}{\eta V_{\rm t}} - \frac{1}{R_{\rm h}}\right)I_{\rm sc}R_{\rm s}' + \frac{R_{\rm s}I_{\rm sc}}{R_{\rm h}^2}R_{\rm h}' + I_0 Y\frac{R_{\rm s}I_{\rm sc}}{\eta^2 V_{\rm t}}\eta' + I_{\rm ph}'$$
$$-(Y-1)I_0' - \left(1 + I_0 Y\frac{R_{\rm s}}{\eta V_{\rm t}} + \frac{R_{\rm s}}{R_{\rm h}}\right)I_{\rm sc}' + I_0 Y\frac{R_{\rm s}I_{\rm sc}V_{\rm t}'}{\eta V_{\rm t}^2}$$
$$= 0, \tag{13}$$

$$\left(-I_0 Z\frac{1}{\eta V_{\rm t}} - \frac{1}{R_{\rm h}}\right)I_{\rm mp}R_{\rm s}' + \frac{V_{\rm mp}+R_{\rm s}I_{\rm mp}}{R_{\rm h}^2}R_{\rm h}'$$
$$+ I_0 Z\frac{V_{\rm mp}+R_{\rm s}I_{\rm mp}}{\eta^2 V_{\rm t}}\eta' + I_{\rm ph}' - (Z-1)I_0'$$
$$-\left(I_0 Z\frac{1}{\eta V_{\rm t}} + \frac{1}{R_{\rm h}}\right)V_{\rm mp}' - \left(1 + I_0 Z\frac{R_{\rm s}}{\eta V_{\rm t}} + \frac{R_{\rm s}}{R_{\rm h}}\right)I_{\rm mp}'$$
$$+ I_0 Z\frac{(V_{\rm mp}+R_{\rm s}I_{\rm mp})V_{\rm t}'}{\eta V_{\rm t}^2} = 0. \tag{14}$$

Here, η' is given by (3), and for I_0', the derivative of (2) with respect to T is taken to be

$$I_0' = 3CT^{\frac{3}{\eta}}\left(\frac{1}{T\eta} - \frac{\eta'}{\eta^2}\ln T\right)\exp\left(-\frac{E_{\rm g}}{\eta kT}\right)$$
$$+ CT^{\frac{3}{\eta}}\exp\left(-\frac{E_{\rm g}}{\eta kT}\right)\left(-\frac{1}{k}\right)\frac{E_{\rm g}'\eta T - E_{\rm g}(\eta' T + \eta)}{(\eta T)^2}$$

which is then arranged appropriately to give

$$I_0' = \left\{\left(\frac{3}{T} - \frac{E_{\rm g}'}{kT} + \frac{E_{\rm g}}{kT^2}\right)\frac{1}{\eta} + \left(\frac{E_{\rm g}}{kT} - 3\ln T\right)\frac{\eta'}{\eta^2}\right\}I_0. \tag{15}$$

Using the TCs $\alpha_{\rm sc}$ and $\beta_{\rm oc}$, $I_{\rm sc}'$, and $V_{\rm oc}'$ are then given by

$$I_{\rm sc}' = \alpha_{\rm sc}I_{\rm sc}, \qquad V_{\rm oc}' = \beta_{\rm oc}V_{\rm oc}. \tag{16}$$

The model of $I_{\rm ph}$ from (1) gives

$$I_{\rm ph}' = \frac{I_{\rm sc}}{R_{\rm h}}R_{\rm s}' - \frac{R_{\rm s}I_{\rm sc}}{R_{\rm h}^2}R_{\rm h}' + \frac{R_{\rm h}+R_{\rm s}}{R_{\rm h}}I_{\rm sc}'. \tag{17}$$

Substitution of this equation into (13) causes $R_{\rm h}'$ to disappear, and the following expression is then obtained for $R_{\rm s}'$:

$$R_{\rm s}' = \frac{R_{\rm s}}{\eta}\eta' + \frac{\eta V_{\rm t}}{I_0 I_{\rm sc}}\left(\frac{1}{Y} - 1\right)I_0' - \frac{R_{\rm s}}{I_{\rm sc}}I_{\rm sc}' + \frac{R_{\rm s}}{V_{\rm t}}V_{\rm t}'. \tag{18}$$

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Substitution of (17) into (12) gives an expression for R_{h}' as follows:

$$R_{\mathrm{h}}' = \frac{R_{\mathrm{h}}^2}{R_{\mathrm{s}}I_{\mathrm{sc}} - V_{\mathrm{oc}}}\left\{\frac{I_{\mathrm{sc}}}{R_{\mathrm{s}}}R_{\mathrm{s}}' + \frac{R_{\mathrm{s}}+R_{\mathrm{h}}}{R_{\mathrm{h}}}I_{\mathrm{sc}}' + I_0 X\frac{V_{\mathrm{oc}}}{\eta^2 V_{\mathrm{t}}}\eta' \right.$$
$$\left. +(1-X)I_0' - \left(I_0 X\frac{1}{\eta V_{\mathrm{t}}} + \frac{1}{R_{\mathrm{h}}}\right)V_{\mathrm{oc}}' + I_0 X\frac{V_{\mathrm{oc}}V_{\mathrm{t}}'}{\eta V_{\mathrm{t}}^2}\right\}. \tag{19}$$

By definition, the TC γ_{mp} satisfies $(V_{\mathrm{mp}}I_{\mathrm{mp}})' = \gamma_{\mathrm{mp}}V_{\mathrm{mp}}I_{\mathrm{mp}}$, which can be rewritten to give

$$V_{\mathrm{mp}}' + I_{\mathrm{mp}}'V_{\mathrm{mp}}/I_{\mathrm{mp}} = \gamma_{\mathrm{mp}}V_{\mathrm{mp}}. \tag{20}$$

The substitution of (10) into the coefficient of I_{mp}' in (14) and the substitution of (20) into (14) then cause V_{mp}' and I_{mp}' to disappear, and the following fifth equation is thus obtained:

$$B \equiv \left(-I_0 Z\frac{1}{\eta V_{\mathrm{t}}} - \frac{1}{R_{\mathrm{h}}}\right)I_{\mathrm{mp}}R_{\mathrm{s}}' + \frac{V_{\mathrm{mp}}+R_{\mathrm{s}}I_{\mathrm{mp}}}{R_{\mathrm{h}}^2}R_{\mathrm{h}}' + I_{\mathrm{ph}}'$$
$$+ I_0 Z\frac{V_{\mathrm{mp}}+R_{\mathrm{s}}I_{\mathrm{mp}}}{\eta^2 V_{\mathrm{t}}}\eta' - (Z-1)I_0' - \left(I_0 Z\frac{1}{\eta V_{\mathrm{t}}} + \frac{1}{R_{\mathrm{h}}}\right)\gamma_{\mathrm{mp}}V_{\mathrm{mp}}$$
$$+ I_0 Z\frac{(V_{\mathrm{mp}}+R_{\mathrm{s}}I_{\mathrm{mp}})V_{\mathrm{t}}'}{\eta V_{\mathrm{t}}^2} = 0. \tag{21}$$

This equation in combination with (18), (19), (17), (3), and (15) can be considered to give a nonlinear equation for $R_{\mathrm{s}},\ R_{\mathrm{h}},\ \eta$, and I_0.

Following the method of [7] and using (6) and (7), the unknown variables I_{ph} and I_0 can be expressed as functions of R_{s}, R_{h}, and η

$$I_{\mathrm{ph}} = \left(I_{\mathrm{sc}} + \frac{I_{\mathrm{sc}}R_{\mathrm{s}} - V_{\mathrm{oc}}}{R_{\mathrm{h}}}\right)\frac{X-1}{X-Y} + \frac{V_{\mathrm{oc}}}{R_{\mathrm{h}}}, \tag{22}$$

$$I_0 = \left\{\left(1+\frac{R_{\mathrm{s}}}{R_{\mathrm{h}}}\right)I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}}}{R_{\mathrm{h}}}\right\}/(X-Y). \tag{23}$$

Then, using (8), (22), and (23) and following the approach of [7], the unknown variable R_{h} can be expressed as a function of R_{s} and η

$$R_{\mathrm{h}} = \frac{(R_{\mathrm{s}}I_{\mathrm{sc}} - V_{\mathrm{oc}})Q + V_{\mathrm{oc}} - V_{\mathrm{mp}} - R_{\mathrm{s}}I_{\mathrm{mp}}}{I_{\mathrm{mp}} - I_{\mathrm{sc}}Q} \tag{24}$$

where $Q = (X-Z)/(X-Y)$. Equations (6), (7), and (8) have now been consumed and the two remaining unknown variables are R_{s} and η. Therefore, equations (11) and (21) are considered as the two nonlinear equations for the two unknown variables R_{s} and η. In this work, the values of $R_{\mathrm{s}},\ \eta$ that make $A,\ B$ equal to zero are sought using a mesh search algorithm. The mesh points used for η are 5000 terms of the arithmetic series from 0.5 to 2.5, while those used for R_{s} are 10 000 terms of the geometric series from 0.01 to 10. For every pair of $(R_{\mathrm{s}},\ \eta)$, the value of $E = \frac{|A|}{|A_0|} + \frac{|B|}{|B_0|}$ is calculated and the $(R_{\mathrm{s}},\ \eta)$ pair that minimizes E is then selected as the estimation result. Here, $A_0,\ B_0$ are the values of $A,\ B$ for the standard values $R_{\mathrm{s}} = 0,\ \eta = 1.0$. The comprehensive procedure for the proposed method is summarized as follows.

(Algorithm 1)

1) Let the MDI be given, that is, I_{sc}, V_{oc}, V_{mp}, I_{mp}, α_{sc}, β_{oc}, γ_{mp}. Calculate I_{sc}', V_{oc}' using (16).
2) Set $R_{\mathrm{s}} = 0,\ \eta = 1$.
3) Calculate $R_{\mathrm{h}},\ I_0,\ A$ using (24), (23), and (11). (C in (2) is determined using I_0.)
4) Using η' from (3), calculate I_0', R_{s}', R_{h}', I_{ph}', and B using (15), (18), (19), (17), and (21), respectively.
5) Set $A_0 = A$, $B_0 = B$.
6) Set $E_{\mathrm{min}} = +\infty$. For each $R_{\mathrm{s}} = 0.01,\ 0.01\times k,\ 0.01\times k^2, \ldots,\ 10$ and $\eta = 0.5,\ 0.5+d,\ 0.5+2\,d, \ldots,\ 2.5$, perform the subsequent steps 7), 8), and 9). Here $k = \exp\{\ln(\frac{10}{0.01})/10000\}$ and $d = (2.5-0.5)/5000$.
7) Compute R_{h}, I_0, A, B using the same procedures as 3) and 4).
8) Calculate I_{ph} using (22).
9) If $E = \frac{|A|}{|A_0|} + \frac{|B|}{|B_0|} < E_{\mathrm{min}}$ and R_{h}, I_0, $I_{\mathrm{ph}} \geq 0$, then set $E_{\mathrm{min}} = E$, $R_{\mathrm{s,min}} = R_{\mathrm{s}}$, $R_{\mathrm{h,min}} = R_{\mathrm{h}}$, $\eta_{\mathrm{min}} = \eta$, $I_{\mathrm{ph,min}} = I_{\mathrm{ph}}$, and $I_{0,\mathrm{min}} = I_0$.
10) Output $R_{\mathrm{s,min}}$, $R_{\mathrm{h,min}}$, η_{min}, $I_{\mathrm{ph,min}}$, and $I_{0,\mathrm{min}}$ as the estimation results.

III. Evaluation of Method

A. How to Produce Test Data

To evaluate the method proposed in the previous section, test data from the module datasheets are produced in the following manner. Because each module datasheet gives values for seven parameters, the values of the seven parameters can be selected arbitrarily when the test data are composed. Therefore, the values of $R_{\mathrm{s}},\ R_{\mathrm{h}},\ \eta,\ I_{\mathrm{ph}},\ I_0$, and $\alpha_{\mathrm{sc}},\ \beta_{\mathrm{oc}}$ are selected arbitrarily, and the other datasheet parameters are determined using the equations derived in the previous section. The specific procedure used to produce the test data is summarized as follows.

1) Select R_{s}, R_{h}, η, I_{ph}, I_0, α_{sc}, and β_{oc} arbitrarily.
2) Compute V_{oc}, I_{sc}, V_{mp}, and I_{mp} using (6), (7), (8), and (11).
3) Using η' from (3), compute I_{sc}', V_{oc}', R_{s}', and I_{ph}' using (16), (18), and (17).
4) Compute γ_{mp} with (21).

V_{oc} in (6) and I_{sc} in (7) can be acquired using the Lambert W-function [20]. I_{mp} in (8) can be expressed as a function of V_{mp} using the Lambert W-function. This expression is then substituted for I_{mp} in (11), and (11) is solved with respect to V_{mp} using, for example, the bisection search algorithm. V_{mp} and I_{mp} are thus obtained using (8) and (11). The equation (21) can be solved explicitly with respect to γ_{mp}.

B. Parameter Estimation for Test Data

For example, let the following module parameter values be selected arbitrarily: $R_{\mathrm{s}} = 0.5,\ R_{\mathrm{h}} = 400,\ \eta = 1.1,\ I_{\mathrm{ph}} = 8.5,\ I_0 = 5.0\times 10^{-10},\ \alpha_{\mathrm{sc}} = 0.0003,\ \beta_{\mathrm{oc}} = -0.0035$, and $N_{\mathrm{s}} = 60$. The virtual datasheet values that were calculated using the procedure described in the previous subsection then become: $V_{\mathrm{oc}} = 47.73,\ I_{\mathrm{sc}} = 8.489,\ V_{\mathrm{mp}} = 38.52,\ I_{\mathrm{mp}} = 8.005,\ \gamma_{\mathrm{mp}} = -0.006713,\ \alpha_{\mathrm{sc}}$, and β_{oc}. Using this MDI, the method described in the previous section can be used to estimate the five SDM parameters as follows: $R_{\mathrm{s}} = 0.4996,\ R_{\mathrm{h}} = 400.2,\ \eta =$

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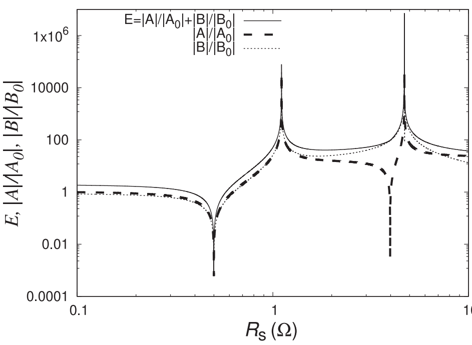

Fig. 1. Plots of E, $\frac{|A|}{|A_0|}$, and $\frac{|B|}{|B_0|}$ versus R_s. η is fixed at the estimated value of 1.101.

$1.101,\ I_{\mathrm{ph}} = 8.500,\ I_0 = 5.086 \times 10^{-10}$ with $E = 7.078 \times 10^{-4}$. These estimated results are very close to the arbitrarily selected input values given above. To investigate the uniqueness of the above estimation, a graph of E, $\frac{|A|}{|A_0|}$, $\frac{|B|}{|B_0|}$ versus R_s is plotted as shown in Fig. 1. This graph strongly suggests the uniqueness of $(R_s,\ \eta)$ in minimizing E.

C. Evaluation With Test Data Set

Next, 100 MDI test datasets are generated using the procedure described in Section III-A. Seven arbitrary parameter values are selected randomly. The ranges of these random parameters are set as follows: $0.5 \leq R_s \leq 5.0,\ 100 \leq R_h \leq 500,\ 1.0 \leq \eta \leq 1.5,\ 8.0 \leq I_{\mathrm{ph}} \leq 10.0,\ 1.0 \times 10^{-11} \leq I_0 \leq 1.0 \times 10^{-9},\ 0.0002 \leq \alpha_{\mathrm{sc}} \leq 0.0004,\ -0.004 \leq \beta_{\mathrm{oc}} \leq -0.002$, and $60 \leq N_s \leq 80$. The estimation result for R_s is evaluated based on the mean absolute error ratio (MAER), that is, the average of $|R_{\mathrm{s,estimated}} - R_{\mathrm{s,\ randomly\ chosen}}|/R_{\mathrm{s,\ randomly\ chosen}}$. The MAERs of $R_h,\ \eta,\ I_{\mathrm{ph}},\ I_0$, and the average of E are also calculated and the results are as follows: $R_s : 0.019\%,\ R_h : 29.6\%,\ \eta : 0.169\%,\ I_{\mathrm{ph}} : 0.518\%,\ I_0 : 3.08\%,\ E : 3.19 \times 10^{-3}$. These error indices also strongly suggest the uniqueness of the results of the proposed estimation method.

IV. Application

The proposed SDM parameter extraction method is applied to real module datasheets in this section. The MDI is obtained from the Sandia module database (SMDB) [21]. Six modules of four technologies comprising "monocrystalline Si (c-Si)," "multicrystalline Si (mc-Si)," "amorphous Si (3-a-Si)," and "Si-Film" are selected. The datasheet values from these modules are collected in Table I. The proposed parameter estimation method is then applied to these six sets of module datasheet values. For module no. 5, the search range for η has been changed to [2.25, 11.25]. The estimation results obtained using the proposed method are summarized in Table II. The minimal error $E_{\min}$ values of the mesh search algorithms are listed in the table. The SMDB gives the values of I_x and I_{xx}, which are the module currents at the module voltages of $V_{\mathrm{oc}}/2$ and $(V_{\mathrm{oc}} + V_{\mathrm{mp}})/2$, respectively. For each of the six modules, the values of $V_{\mathrm{oc}},\ I_{\mathrm{sc}},\ V_{\mathrm{mp}},\ I_{\mathrm{mp}},\ I_x$, and I_{xx} are calculated using SDMs with the five estimated parameters in Table II. The

TABLE I
MODULE DATASHEET INFORMATION

	N_s / I_{mp} (A)	V_{oc} (V) / α_{sc} (/K)	I_{sc} (A) / β_{oc} (/K)	V_{mp} (V) / γ_{mp} (/K)
No.1, BP Solar	120	73.97	4.246	59.87
BP3232G (c-Si)	3.961	4.87E-4	-3.15E-3	-4.10E-3
No.2, SunPower	96	65.31	5.92	54.43
SPR-305-WHT (c-Si)	5.59	4.00E-4	-2.96E-3	-4.04E-3
No.3, BP Solar	72	43.71	5.10	35.3
BP3180N (mc-Si)	4.747	4.85E-4	-3.25E-3	-4.17E-3
No.4, SolarFun	60	37.05	8.482	29.17
SF220-30-P220 (mc-Si)	7.942	4.95E-4	-3.16E-3	-4.49E-3
No.5, Uni-Solar	11	21.52	2.616	15.16
US-32 (3-a-Si)	2.122	8.20E-4	-4.53E-3	-2.21E-3
No.6, AstroPower	30	16.44	10.36	12.23
APX-110-SL (Si-Film)	8.84	8.73E-4	-4.93E-3	-6.00E-3

TABLE II
PARAMETER ESTIMATION RESULTS

	R_s (Ω) / $E_{\min}$	R_h (Ω) / MAER	η / AERx	I_{ph} (A) / AERxx	I_0 (A)
No.1	0.0106	4.68E7	1.69	4.25	2.85E-6
	0.978	6.72E-3	3.98E-3	5.99E-2	
No.2	0.0921	2.03E6	1.46	5.92	7.45E-8
	0.242	3.44E-3	8.51E-3	4.13E-2	
No.3	0.0103	1.23E7	1.69	5.10	4.35E-6
	0.966	6.48E-3	2.77E-2	7.20E-2	
No.4	0.0102	2.78E6	1.84	8.48	1.76E-5
	1.25	1.35E-2	7.10E-3	9.75E-2	
No.5	0.441	481.2	11.23	2.62	2.94E-3
	0.118	6.95E-8	1.86E-2	4.78E-2	
No.6	0.158	19.9	1.56	10.4	1.07E-5
	0.104	2.35E-8	5.65E-3	7.08E-3	

results are then compared with the values obtained from the SMDB, which are denoted by the superscript "SMDB," using the following indexes:

$$\mathrm{MAER} = \frac{1}{4}\Big(|V_{\mathrm{oc}} - V_{\mathrm{oc}}^{\mathrm{SMDB}}|/V_{\mathrm{oc}}^{\mathrm{SMDB}} + |I_{\mathrm{sc}} - I_{\mathrm{sc}}^{\mathrm{SMDB}}|/I_{\mathrm{sc}}^{\mathrm{SMDB}} + |V_{\mathrm{mp}} - V_{\mathrm{mp}}^{\mathrm{SMDB}}|/V_{\mathrm{mp}}^{\mathrm{SMDB}} + |I_{\mathrm{mp}} - I_{\mathrm{mp}}^{\mathrm{SMDB}}|/I_{\mathrm{mp}}^{\mathrm{SMDB}}\Big) \tag{25}$$

$$\mathrm{AERx} = \frac{|I_x - I_x^{\mathrm{SMDB}}|}{I_x^{\mathrm{SMDB}}},\ \mathrm{AERxx} = \frac{|I_{xx} - I_{xx}^{\mathrm{SMDB}}|}{I_{xx}^{\mathrm{SMDB}}} \tag{26}$$

for which results are also given in Table II. All the MAERs, AERx values and AERxx values for the six modules are very small, which illustrates the good coincidence of SDMs using the estimated parameters with the six real modules from four different technologies.

The method proposed in this article is also compared with Jadli's method [22], Moshksar's method [7], and Jordehi's method [16]. The input data used for both Jadli's method and Moshksar's method are taken from the MDI in the same manner as the proposed method. The input data used for Jordehi's method are five points on the module I-V curve, that is, the points at which the currents are I_{sc}, I_x, I_{mp}, I_{xx}, and 0. The averages of the six AERx values and AERxx values for modules 1–6 are taken as the performance criteria and are listed in

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TABLE III
COMPARISON OF THE PARAMETER ESTIMATION METHODS

	Jadli	Moshksar	Jordehi	Proposed
Average AERx	6.88E-2	3.36E-1	6.93E-3	1.19E-2
Average AERxx	1.66E-1	4.32E-1	2.50E-2	5.43E-2

Table III. Because Jordehi's method performs the fitting to five points on the I-V curve, it produces the best estimates of I_x and I_{xx}. The proposed method shows a performance that is comparable to Jordehi's method.

V. EXTENSION TO ADAPTIVE MODEL

In this section, a method to estimate the SDM's five parameters under the arbitrary environmental conditions $G,\ T$ is considered. The subscript "*n*" indicates that the variable is evaluated under the STCs. The method uses the MDI under the STCs and the values of $V_{\text{oc},1},\ P_{\text{max},1}$ of $V_{\text{oc}},\ P_{\text{max}}(=V_{\text{mp}}I_{\text{mp}})$ at $G_1(\neq G_{\text{n}}),\ T_1$. An irradiance-dependent model of I_0 is assumed here [17], [23]

$$I_0 = CT^{\frac{3}{\eta}}\left(\frac{G_{\text{n}}}{G}\right)^m \exp\left(\frac{-E_{\text{g}}}{\eta kT}\right) \tag{27}$$

where $m = 0.278$ for crystalline Si. Because there are nine variables, that is, $R_{\text{s}},\ R_{\text{h}},\ \eta,\ I_{\text{ph}},\ I_0,\ V_{\text{oc}},\ I_{\text{sc}},\ V_{\text{mp}},\ I_{\text{mp}}$, that appear in the SDM's four restricting equations, that is, (6), (7), (8), (11), and the model (27), then if the values of the four variables at $G,\ T$ are given, the values of the other five variables will be determined automatically. The following four translational equations are then adopted [6], [24]:

$$I_{\text{sc}} = I_{\text{sc,n}}\frac{G}{G_{\text{n}}}\left(1+\alpha_{\text{sc}}\left(T-T_{\text{n}}\right)\right) \tag{28}$$

$$V_{\text{oc}} = V_{\text{oc,n}}\frac{1}{1-\delta_{\text{oc}}\ln\frac{G}{G_{\text{n}}}}\left(1+\beta_{\text{oc}}\left(T-T_{\text{n}}\right)\right) \tag{29}$$

$$V_{\text{mp}} = V_{\text{mp,n}}\left(\frac{1}{1-\delta_{\text{oc}}\ln\frac{G}{G_{\text{n}}}}+\beta_{\text{oc}}\left(T-T_{\text{n}}\right)\right) \tag{30}$$

$$P_{\text{max}} = P_{\text{max,n}}\frac{\frac{G}{G_{\text{n}}}}{1-\delta_{\text{mp}}\ln\frac{G}{G_{\text{n}}}}\left(1+\gamma_{\text{mp}}\left(T-T_{\text{n}}\right)\right) \tag{31}$$

where δ_{oc} and δ_{mp} are constants that can be determined using the values of $V_{\text{oc,n}},\ P_{\text{max,n}},\ V_{\text{oc},1},\ P_{\text{max},1}$. From (6), it holds that

$$I_{\text{ph}} = I_0\left(X-1\right)+V_{\text{oc}}/R_{\text{h}}. \tag{32}$$

Substitution of this equation into (7) and (8) gives

$$R_{\text{h}} = \left(R_{\text{s}}I_{\text{sc}}-V_{\text{oc}}\right)/\{I_0(X-Y)-I_{\text{sc}}\} \tag{33}$$

$$F \equiv I_0(X-Z)+\frac{V_{\text{oc}}}{R_{\text{h}}}-\frac{V_{\text{mp}}+R_{\text{s}}I_{\text{mp}}}{R_{\text{h}}}-I_{\text{mp}}=0. \tag{34}$$

The algorithm for the proposed estimation method is written as follows.

(Algorithm 2)

1) Given the MDI, calculate $R_{\text{s,n}},\ R_{\text{h,n}},\ \eta_{\text{n}},\ I_{\text{0,n}}$ using the estimation method described in Section II. Determine the constant C in (27) using $I_{\text{0,n}}$.

TABLE IV
ESTIMATED VALUES OF FIVE SDM PARAMETERS FOR MODULE NO. 1 IN TABLE I

G (W/m^2)	T (°C)	R_{s} (Ω)	R_{h} (Ω)	η	I_{ph} (A)	I_0 (A)
300	0	1.57	2.66E5	1.48	1.26	2.15E-8
600	15	0.454	2.86E5	1.56	2.74	2.97E-7
800	50	8.80E-2	507	1.37	3.44	1.33E-6
1100	10	5.64E-2	1.14E5	1.85	4.64	2.74E-6
1200	70	2.31E-4	52.5	1.20	5.21	1.19E-6

2) Given $V_{\text{oc},1},\ P_{\text{max},1}$, determine the constants $\delta_{\text{oc}},\ \delta_{\text{mp}}$ in (29), (31), respectively.
3) Let any $G,\ T$ be given.
4) Compute $I_{\text{sc}},\ V_{\text{oc}},\ V_{\text{mp}},\ I_{\text{mp}}$ using (28), (29), (30), (31), and the relation $P_{\text{max}} = V_{\text{mp}}I_{\text{mp}}$.
5) Set $R_{\text{s}} = 0$ and $\eta = 1$. Calculate $I_0,\ R_{\text{h}},\ A,\ F$ using (27), (33), (11), and (34), respectively. Set $A_0 = A, F_0 = F$.
6) Set $E_{\text{min}} = +\infty$. For each $R_{\text{s}} = 0.01,\ 0.01\times k,\ 0.01\times k^2,\ldots,\ 10$ and $\eta = 0.5,\ 0.5+d,\ 0.5+2\,d,\ldots,\ 2.5$, perform the subsequent steps 7) and 8). Here $k = \exp\{\ln(\frac{10}{0.01})/10000\}$ and $d = (2.5-0.5)/5000$.
7) Calculate $I_0,\ R_{\text{h}},\ A,\ F,\ I_{\text{ph}}$ using (27), (33), (11), (34), and (32), respectively.
8) If $E = \frac{|A|}{|A_0|}+\frac{|F|}{|F_0|} < E_{\text{min}}$ and $R_{\text{h}},\ I_{\text{ph}} \geq 0$, then set $E_{\text{min}} = E$, $R_{\text{s,min}} = R_{\text{s}}$, $R_{\text{h,min}} = R_{\text{h}}$, $\eta_{\text{min}} = \eta$, $I_{\text{ph,min}} = I_{\text{ph}}$, and $I_{\text{0,min}} = I_0$.
9) Output $R_{\text{s,min}},\ R_{\text{h,min}},\ \eta_{\text{min}},\ I_{\text{ph,min}}$, and $I_{\text{0,min}}$ as the estimation results.

The adaptive model described above is applied to modules 1–4, which comprise crystalline Si, as listed in Table I. Here, G_1 and T_1 are set at 800 W/m^2 and 47 °C, respectively. The estimation results for module no. 1 are presented in Table IV. The R_{s} search range for $G = 1200$ and $T = 70$ has been changed to $[1.1\times 10^{-5},\ 1.1\times 10^{-2}]$. The estimation results are evaluated using AERx and AERxx, as defined in Section IV. The average values of both AERx and AERxx for five $G,\ T$ pairs listed in Table IV for each of modules 1–4, that is, 20 AERx values and 20 AERxx values in total, are taken. The mean AERx and mean AERxx values become 0.046 and 0.074, respectively.

For comparison with the figures derived from the adaptive model, direct parameter estimations using given G and T values are performed as follows. The parameter extraction method under the STCs explained in Section II can be applied directly for any values of G and T. This means that if seven values of $V_{\text{oc}},\ I_{\text{sc}},\ V_{\text{mp}},\ I_{\text{mp}},\ \alpha_{\text{sc}},\ \beta_{\text{oc}}$, and γ_{mp} at G and T are available, five SDM parameters can then be estimated at the same G and T using the method described in Section II. Additionally, because the SMDB gives values for both V'_{mp} and I'_{mp} in addition to γ_{mp}, the assumption made in (3) for η' becomes unnecessary, as described in Appendix A. Therefore, the mean AERx and mean AERxx have become 0.012 and 0.020, which are smaller than the corresponding results of 0.046 and 0.074 given above, respectively. However, because the adaptive model basically uses only the MDI under the STCs, the adaptive model's performance can be said to be comparable to that of direct parameter estimation at $G,\ T$.

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VI. Conclusion

A new fifth equation for the SDM's parameters has been derived in this article using the three TCs of I_{sc}, V_{oc}, and $P_{\max}$, values of which are supplied in most module datasheets. Three physical or empirical TC models of the diode reverse saturation current I_0, the photocurrent I_{ph}, and the diode ideality factor η are assumed for the derivation of the equation. It is also shown that the assumption of the TC of η becomes unnecessary when the TCs of both V_{mp} and I_{mp} are available in addition to that of $P_{\max}$. Using a total of five equations, the five parameters of the SDM under the STCs are sought by minimizing an error function with respect to two parameters of the SDM. The minimization problem is solved using a simple mesh search algorithm. Analyses performed with artificially produced test MDI strongly suggested that the five equations obtained determine the five SDM parameters uniquely. The proposed method was applied to real MDI and the results were comparable to those obtained by application of an optimization algorithm using I-V curve data. Finally, the proposed method is extended to an adaptive model that estimates the five parameters of the SDM at any G and T. The adaptive model showed a performance that was comparable to that of the parameter estimation from the given MDI at G, T. The methods proposed in this article provide new procedures to accurately determine the five parameters of the SDM from the MDI.

Appendix A
Parameter Estimation Using Values of V'_{MP} and I'_{MP}

Only step 4) from Algorithm 1 is changed, as follows. Equation (15) is a linear equation of η' and thus can be written as $I'_0 = L_0\eta' + M_0$. Substitution of this equation into (18) allows (18) to be written as $R'_{\mathrm{s}} = L_1\eta' + M_1$. The substitution of this expression for R'_{s} into (19) then yields $R'_{\mathrm{h}} = L_2\eta' + M_2$. In addition, the substitution of this expression for R'_{h} and the above expression for R'_{s} into (17) yields $I'_{\mathrm{ph}} = L_3\eta' + M_3$. Finally, substitution of the four equations given above into (21) allows (21) to be written as $L_4\eta' + M_4 = 0$, and thus the value of η' is obtained using the formula $\eta' = -M_4/L_4$. The values of I'_0, R'_{s}, R'_{h}, and I'_{ph} can then be obtained using the expressions for these derivatives that were obtained above in this Appendix. Next, to derive a new minimization quantity B rather than (21), equation (11) is multiplied by $\eta V_{\mathrm{t}} R_{\mathrm{h}}$ and its derivative with respect to T is given as follows:

$$\begin{aligned} B \equiv & \left\{ \left(R'_{\mathrm{s}} I_{\mathrm{mp}} + R_{\mathrm{s}} I'_{\mathrm{mp}} - V'_{\mathrm{mp}}\right) R_{\mathrm{h}}\, I_0 \right. \\ & \left. + \left(R_{\mathrm{s}} I_{\mathrm{mp}} - V_{\mathrm{mp}}\right)\left(R'_{\mathrm{h}} I_0 + R_{\mathrm{h}} I'_0\right)\right\} Z + \left(R_{\mathrm{s}} I_{\mathrm{mp}} - V_{\mathrm{mp}}\right) R_{\mathrm{h}} I_0 Z \\ & \times \left\{ \frac{V'_{\mathrm{mp}} + R'_{\mathrm{s}} I_{\mathrm{mp}} + R_{\mathrm{s}} I'_{\mathrm{mp}}}{\eta V_{\mathrm{t}}} - \frac{\left(V_{\mathrm{mp}} + R_{\mathrm{s}} I_{\mathrm{mp}}\right)\left(\eta' V_{\mathrm{t}} + \eta V'_{\mathrm{t}}\right)}{\left(\eta V_{\mathrm{t}}\right)^2} \right\} \\ & + \left(R'_{\mathrm{s}} + R'_{\mathrm{h}}\right) \eta V_{\mathrm{t}} I_{\mathrm{mp}} + \left(R_{\mathrm{s}} + R_{\mathrm{h}}\right)\left(\eta' V_{\mathrm{t}} I_{\mathrm{mp}} + \eta V'_{\mathrm{t}} I_{\mathrm{mp}} + \eta V_{\mathrm{t}} I'_{\mathrm{mp}}\right) \\ & - \left(\eta' V_{\mathrm{t}} V_{\mathrm{mp}} + \eta V'_{\mathrm{t}} V_{\mathrm{mp}} + \eta V_{\mathrm{t}} V'_{\mathrm{mp}}\right) = 0. \end{aligned} \tag{35}$$

Using the given values of V'_{mp} and I'_{mp}, the new minimization quantity B can then be computed using this expression.

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