# Combining Identification and Translation Methods of the Single-Diode Model to Compute the Average Temperature of Photovoltaic Modules From the Open-Circuit Voltage

Caio Felipe Abe, João Batista Dias, Philippe Poggi, and Benjamin Pillot

***Abstract*—A common method of measuring the temperature of a photovoltaic module is by attaching a sensor to its back surface. However, since this method of measurement is punctual, the temperature gradient along the module surface is not considered. In addition to that, the temperature of the sensor is usually considered equal to the temperature of the photovoltaic cells, thus ignoring the temperature drop along the materials in between. This paper focuses on the problem of computing the average cell temperature of photovoltaic modules, based on information available on their respective datasheets and on measurements of the open-circuit voltage and solar irradiance. For that, different methods regarding identification and translation of the single-diode model parameters are used in conjunction, aiming to establish a simple and accurate procedure for computing the average temperature. The best performing combinations are then compared with IEC-60904-5, which presents a procedure for calculating the equivalent cell temperature of a module. Such computing procedures for the average module temperature have been experimentally tested, presenting coherent results.**

***Index Terms*—IEC-60904-5, photovoltaic (PV) cell temperature, single-diode model (SDM) parameters.**

## I. Introduction

THE single-diode model (SDM) of a photovoltaic (PV) cell shows a good balance between complexity and accuracy [1], [2], and different procedures of identification and translation of its parameters have been proposed in the literature, for instance, [3]–[6]. Regardless of the method chosen, cell temperature is a highly significant parameter, which needs to be properly and accurately quantified when considering the modeling of PV arrays under real outdoor operating conditions [7].

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It is known that the temperature distribution along a PV module surface is not uniform. In addition, the temperature measured by a sensor attached to the back surface of a module does not equal the cell temperature. As addressed in [8], this difference in temperature is caused by changes in outdoor ambient conditions, that affect the thermal equilibrium, and by the thermal conductivity of the materials between the back surface of the module and the PV cell. It is reported in [8] that at thermal equilibrium and with the irradiance ($G$) of 1000 W/m², crystalline silicon modules usually present a temperature drop of 2–3 °C from the cell to the back surface. In agreement to that, Krauter and Preiss [7] report an average temperature drop of about 2.8 °C when comparing the actual junction temperature with measurements using Pt-100 sensors attached to the back of a module, under the irradiance level of 1000 W/m². The undesired temperature offset and measurement lag observed under outdoor conditions, due to the poor thermal equilibrium between the module and the temperature sensor, can be avoided by calculating the average temperature of all the cells in the module. This can be achieved based on measurements of its open-circuit voltage $V_{\mathrm{oc}}$ [8]. It is worth noting that the temperature effect on each cell accounts to the overall measurement, since in a module the cells are connected in series and the $V_{\mathrm{oc}}$ of the module is the sum of the $V_{\mathrm{oc}}$ of each cell. Such a method could be applied to accurately measure the average temperature of a PV array before capturing its $I$–$V$ curve at outdoors or to study the thermal influence of wind and installation modes. Using a method based on $V_{\mathrm{oc}}$ to monitor the temperature of an actual PV installation requires the array to be disconnected from the inverter for a short period of time, in order to measure the open-circuit voltage.

The goal of this paper is to compare different methods of identification and translation of the SDM parameters, aiming to determine the most advantageous combination considering complexity and accuracy when computing the average temperature of PV modules from the $V_{\mathrm{oc}}$. This includes considering recent literature [5] regarding the translation of SDM parameters, which proposes a new procedure for computing the $V_{\mathrm{oc}}$ as a function of the irradiance and cell temperature, as long as nominal operating cell temperature (NOCT) and low-intensity condition (LIC) tests data are available. To compute the cell temperature by means of $V_{\mathrm{oc}}$, it is necessary to consider the

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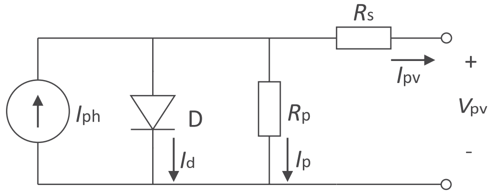


Fig. 1. One-diode PV cell model.

equations that relate these parameters. The equivalent circuit of the SDM of a PV cell is presented in Fig. 1, and its current relations are expressed as

$$I_{\mathrm{pv}} = I_{\mathrm{ph}} - I_d - I_p. \tag{1}$$

Parameter $I_{\mathrm{ph}}$ is the photogenerated current and $I_{\mathrm{pv}}$ is the output current of the PV cell. Substituting the diode current $I_d$ by the Shockley junction equation and $I_p$ by the corresponding mesh equation yields

$$I_{\mathrm{pv}} = I_{\mathrm{ph}} - I_0\left[e^{\left(\frac{q(V_{\mathrm{pv}}+I_{\mathrm{pv}}R_s)}{n_c AkT_c}\right)} - 1\right] - \frac{V_{\mathrm{pv}} + I_{\mathrm{pv}}R_s}{R_p} \tag{2}$$

where $I_0$ is the diode dark saturation current in Aampere, $q$ is the elementary charge, 1.60217662 x$10^{-19}$ C, $A$ is the diode ideality factor, $k$ is the Boltzmann constant, 1.3806505 x$10^{-23}$, $n_c$ is the number of cells connected in series: the PV module cell count. It should be noted that the parameters $V_{\mathrm{oc}}$, $R_s$, and $R_p$ must be scaled according to $n_c$.

Since the dark saturation current $I_0$ is very small compared with the exponential term, it is a common practice to suppress the term "–1" from (2). If the cell output is an open circuit, then $I_{\mathrm{pv}} = 0$ and $V_{\mathrm{pv}} = V_{\mathrm{oc}}$. Thus, (2) becomes

$$0 = I_{\mathrm{ph}} - I_0 e^{\left(\frac{qV_{\mathrm{oc}}}{n_c AkT_c}\right)} - \frac{V_{\mathrm{oc}}}{R_p}. \tag{3}$$

The cell temperature and its open-circuit voltage are related in (3). It is worth mentioning that $V_{\mathrm{oc}}$ refers to the open-circuit voltage of the module, since the exponential term presents the parameter $n_c$ dividing the voltage. However, once the open-circuit voltage has been measured, the temperature cannot be readily derived from (3), since there are other parameters that must be properly identified.

## II. Methods for Identification and Translation of the Single-Diode Model Parameters

In order to describe the PV module electrical behavior, the identification of the parameters $A, I_0, I_{\mathrm{ph}}, R_s$, and $R_p$ of (2) must be carried out. The reference condition for that is the standard test condition (STC), where the irradiance is 1000 W/m² and the cell temperature is 25 °C. The resulting parameters are also with reference to STC, although the subscripts have been suppressed in Section II-A for simplicity. When the operating conditions are different from STC, the translation of the parameters $I_{\mathrm{ph}}$ and $I_0$ is needed, which is presented in Section II-B.

### A. Identification of the Single-Diode Model Parameters

An exact procedure for the identification of the SDM parameters, based uniquely on datasheet information, is presented in [3]. Its derivation starts with (2) rewritten for the three remarkable points of the *I–V* curve, which are the open- and short-circuit points and the maximum power point. The parameter $I_{\mathrm{ph}}$ can be expressed as

$$I_{\mathrm{ph}} = I_0 e^{\left(\frac{qV_{\mathrm{oc}}}{n_c AkT_c}\right)} + \frac{V_{\mathrm{oc}}}{R_p} \tag{4}$$

whereas $I_0$ can be computed by

$$I_0 = \frac{I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}} - I_{\mathrm{sc}}R_s}{R_p}}{e^{\left(\frac{qV_{\mathrm{oc}}}{n_c AkT_c}\right)}}. \tag{5}$$

The remaining three parameters, $R_s$, $R_p$, and $A$, can be calculated iteratively by solving the system of nonlinear equations (6)–(8), whose derivation is explained in detail in [3]

$$\begin{aligned} I_{\mathrm{mpp}} = I_{\mathrm{sc}} &- \frac{V_{\mathrm{mpp}} + I_{\mathrm{mpp}}R_s - I_{\mathrm{sc}}R_s}{R_p} \\ &- \left(I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}} - I_{\mathrm{sc}}R_s}{R_p}\right) e^{\frac{q(V_{\mathrm{mpp}} + I_{\mathrm{mpp}}R_s - V_{\mathrm{oc}})}{n_c AkT_c}} \end{aligned} \tag{6}$$

$$\begin{aligned} \left.\frac{dP}{dV}\right|_{P_{\mathrm{mpp}}} &= I_{\mathrm{mpp}} + V_{\mathrm{mpp}} \\ &\times \frac{-\frac{q(I_{\mathrm{sc}}R_p + I_{\mathrm{sc}}R_s - V_{\mathrm{oc}})}{n_c AkT_c R_p} e^{\frac{q(V_{\mathrm{mpp}} + I_{\mathrm{mpp}}R_s - V_{\mathrm{oc}})}{n_c AkT_c}} - \frac{1}{R_p}}{1 + \frac{q(I_{\mathrm{sc}}R_p + I_{\mathrm{sc}}R_s - V_{\mathrm{oc}})}{n_c AkT_c R_p} e^{\frac{q(V_{\mathrm{mpp}} + I_{\mathrm{mpp}}R_s - V_{\mathrm{oc}})}{n_c AkT_c}} + \frac{R_s}{R_p}} \end{aligned} \tag{7}$$

$$-\left.\frac{1}{R_p}\right|_{I_{\mathrm{sc}}} = \frac{-\frac{q(I_{\mathrm{sc}}R_p + I_{\mathrm{sc}}R_s - V_{\mathrm{oc}})}{n_c AkT_c R_p} e^{\frac{q(I_{\mathrm{sc}}R_s - V_{\mathrm{oc}})}{n_c AkT_c}} - \frac{1}{R_p}}{1 + \frac{q(I_{\mathrm{sc}}R_p + I_{\mathrm{sc}}R_s - V_{\mathrm{oc}})}{n_c AkT_c R_p} e^{\frac{q(I_{\mathrm{sc}}R_s - V_{\mathrm{oc}})}{n_c AkT_c}} + \frac{R_s}{R_p}}. \tag{8}$$

The exact method introduced in [3] provides the one-diode PV cell model parameters with the highest accuracy. Therefore, it is usually employed as the reference for other methods, as mentioned in [9]. Noniterative simplified methods have been proposed in the literature, aiming to make the identification of parameters more straightforward, simpler, and faster. For instance, Eicker [10] proposes the assumption of $R_p \to \infty$. That is, the parallel resistance $R_p$ is considered so high that it can be neglected. In addition, another simplification is that since $I_{\mathrm{ph}}$ is much higher than the diode current, $I_{\mathrm{ph}}$ is considered equal to $I_{\mathrm{sc}}$. A recently proposed approach is presented in [4], where the series/parallel ratio (SPR) indicator is introduced as

$$\mathrm{SPR} = \frac{1 - \gamma_i}{e^{-r}} \tag{9}$$

where

$$\gamma_i = \frac{I_{\mathrm{mpp}}}{I_{\mathrm{sc}}}, \quad \gamma_v = \frac{V_{\mathrm{mpp}}}{V_{\mathrm{oc}}}, \quad r = \frac{\gamma_i(1-\gamma_v)}{\gamma_v(1-\gamma_i)}. \tag{10}$$

When SPR $> 1$, $R_p$ can be set as infinite: this is the case for modules presenting high fill factor (FF). Thus, a set of four parameters is to be determined, and this can be achieved by solving the following equations:

$$R_s = \frac{V_{\rm oc}}{I_{\rm sc}} \frac{\frac{\gamma_v}{\gamma_i}(1-\gamma_i)\ln(1-\gamma_i)+(1-\gamma_v)}{(1-\gamma_i)\ln(1-\gamma_i)+\gamma_i}\Bigg|_{R_p=\infty} \tag{11}$$

$$A = \frac{q}{n_c k T_c} \frac{I_{\rm mpp} R_s - V_{\rm oc} + V_{\rm mpp}}{\ln\frac{(I_{\rm sc}-I_{\rm mpp})(R_s+R_p)-V_{\rm mpp}}{I_{\rm sc}(R_s+R_p)-V_{\rm oc}}} \tag{12}$$

$$I_{\rm ph} = I_{\rm sc} \tag{13}$$

$$I_0 = \left(I_{\rm ph} - \frac{V_{\rm oc}}{R_p}\right) e^{-\frac{qV_{\rm oc}}{n_c A k T_c}}. \tag{14}$$

The case with SPR $< 1$ is related to low FF, and it is usually found for modules composed by noncrystalline cells [2]. Such a case is not covered by this paper, since usually SPR $> 1$

### B. Translation of the Single-Diode Model Parameters

For conditions different from STC, the parameters $I_{\rm ph}$ and $I_0$ must be adjusted according to the cell temperature and solar irradiance. The methods presented in this section consider the parameters $A$, $R_s$, and $R_p$ constant. A study concerning noniterative methods for parameter identification, associated with translation methods, is presented in [5]. The authors found that the approximate method presented in [4], as well as other four-parameter methods, does not work properly with the already consolidated translation method introduced in [6], when the temperature of operation differs too much from that taken as reference when computing the parameters of the SDM. The translation method proposed in [6] presents the following:

$$I_0' = I_0 \left(\frac{T_c}{T_{c,\rm STC}}\right)^3 e^{\left(\frac{qE_g}{Ak}\right)\left(\frac{1}{T_{c,\rm STC}} - \frac{1}{T_c}\right)} \tag{15}$$

$$I_{\rm ph}' = I_{\rm ph}\left(\frac{G}{G_{\rm STC}}\right)(1+\alpha(T_c - T_{c,\rm STC})). \tag{16}$$

In (15), $E_g$ is the bandgap energy of the semiconductor, which is 1.12 eV for crystalline silicon and 1.14 eV for multicrystalline silicon [2]. In (16), $\alpha$ is the temperature coefficient of $I_{\rm sc}$, in %/°C. In addition, the reference values $G_{\rm STC}$ and $T_{c,\rm STC}$ refer to the irradiance and cell temperature at STC. Such a method is referred to as translation method A.

On the other hand, the authors in [5] propose a new translation method for $I_0$, through the application of (17)–(22). The method relies on results of tests under NOCT (800 W/m² at $T_{c,\rm NOCT}$) and LIC (200 W/m² at 25 °C). NOCT data are usually provided by module manufacturers on the datasheets, whereas LIC data are sometimes informed. Such a method is reported in [5] to produce reliable results when associated with both exact and approximate parameter identification methods, and the authors refer to this novel method as translation method B. Thus, [5] provides

$$I_0' = \frac{I_{\rm ph}}{e^{\left(\frac{qV_{\rm oc}}{n_c A k T_c}\right)} - 1} \tag{17}$$

with $I_{\rm ph}$ given by (16) as in translation method A, and

$$V_{\rm oc} = V_{\rm oc,STC}(1+\beta(T_c - T_{\rm STC}))\left(1+\delta(T_c)\ln\frac{G}{G_{\rm STC}}\right). \tag{18}$$

In (18), $\beta$ is the temperature coefficient of $V_{\rm oc}$ in %/°C and $\delta(T_c)$ is given by

$$\delta(T_c) = MT_c + N \tag{19}$$

where the coefficients are

$$M = \frac{\delta_{\rm NOCT} - \delta_{\rm LIC}}{T_{c,\rm NOCT} - T_{c,\rm LIC}} \quad \text{and} \quad N = \delta_{\rm NOCT} - MT_{c,\rm NOCT}. \tag{20}$$

The factors $\delta_{\rm NOCT}$ and $\delta_{\rm LIC}$ are given as

$$\delta_{\rm NOCT} = \frac{1}{\ln\left(\frac{G_{\rm NOCT}}{G_{\rm STC}}\right)} \times \left(\frac{V_{\rm oc,NOCT}}{V_{\rm oc,STC}(1+\beta(T_{c,\rm NOCT} - T_{c,\rm STC}))} - 1\right) \tag{21}$$

$$\delta_{\rm LIC} = \frac{1}{\ln\left(\frac{G_{\rm LIC}}{G_{\rm STC}}\right)}\left(\frac{V_{\rm oc,LIC}}{V_{\rm oc,STC}(1+\beta(T_{c,\rm LIC} - T_{c,\rm STC}))} - 1\right). \tag{22}$$

In cases where the module manufacturer provides only STC and NOCT data, $M = 0$ and $N = \delta_{\rm NOCT}$ in (19).

## III. Computing the Average Temperature of Modules From $V_{\rm oc}$

The problem of determining the equivalent cell temperature of PV cells is within the scope of IEC-60904-5 [11]. It presents (23) and (24), which calculate the cell temperature as a function of parameters of the module and the values of $V_{\rm oc}$ and $G$. The two pairs of irradiance and open-circuit voltage in (24) must be at the same temperature. Thus, it can be computed using STC and LIC data, since $T_c$ is 25 °C in both conditions. The IEC-60904-5 method has been reported in [12] and [13] to provide reliable and accurate results; therefore, its application has been included in this paper

$$T_c = 25 + \beta^{-1}\left(V_{\rm oc} - V_{\rm oc,STC} + U_T n_c \ln\left(\frac{1000}{G}\right)\right) \tag{23}$$

$$U_T = \frac{1}{n_c}\frac{V_{\rm oc4} - V_{\rm oc3}}{\ln\left(\frac{G_4}{G_3}\right)}. \tag{24}$$

It is worth mentioning that under the same irradiance level, $T_c$ and $V_{\rm oc}$ can be related using the parameter $\beta$. Multiplying such a parameter by $V_{\rm oc,STC}$ equals the rate $\partial V_{\rm oc} / \partial T_c$, which can be written as

$$V_{\rm oc2} = V_{\rm oc1} + V_{\rm oc,STC}\beta(T_{c_2} - T_{c_1}). \tag{25}$$

TABLE I
DATASHEET INFORMATION FOR DIFFERENT CONDITIONS

| Parameter | STC | | NOCT (44 °C) | | LIC | |
|---|---|---|---|---|---|---|
| | N245 | N325 | N245 | N325 | N245 | N325 |
| $I_{sc}$ (A) | 5.86 | 6.03 | 4.74 | 4.86 | 1.17 | 1.21 |
| $V_{oc}$ (V) | 53 | 69.6 | 50.2 | 65.7 | 49.6 | 65.3 |
| $I_{mpp}$ (A) | 5.54 | 5.65 | 4.46 | 4.5 | 1.1 | 1.1 |
| $V_{mpp}$ (V) | 44.3 | 57.6 | 42.7 | 55.9 | 42.7 | 56.4 |
| $P_{mpp}$ (W) | 245 | 325 | 187.3 | 247.8 | 46.8 | 62.3 |

TABLE II
DATASHEET COMPLEMENTARY INFORMATION

| Parameter | N245 | N325 |
|---|---|---|
| Number of cells | 72 | 96 |
| α (%/°C) | 0.055 | 0.03 |
| β (%/°C) | -0.24 | -0.25 |

TABLE III
VALUES FOR THE FOUR-PARAMETER SET

| Parameters | Four-parameter set [4] | | Five-parameter set [3] | |
|---|---|---|---|---|
| | N245 | N325 | N245 | N325 |
| $I_0$ (A) | 2.85 x$10^{-9}$ | 5.71 x$10^{-8}$ | 2.80 x$10^{-10}$ | 9.60 x$10^{-9}$ |
| $I_{ph}$ (A) | 5.86 | 6.03 | 5.86 | 6.03 |
| $A$ | 1.335975 | 1.527401 | 1.205545 | 1.393026 |
| $R_s$ (Ω) | 0.273 | 0.281 | 0.398 | 0.433 |
| $R_p$ (Ω) | inf | inf | 33402.46 | 8512.82 |

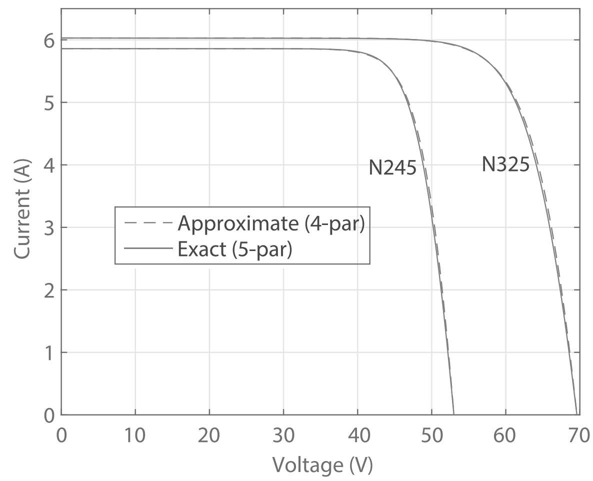


Fig. 2. *I–V* curves of the two modules in STC, employing methods [3], [4] of SDM parameter identification.

TABLE IV
ERRORS ON $T_c$ AT NOCT

| NOCT condition | Error on $T_c$ (%) | |
|---|---|---|
| $G$ = 800 W/m², $T_c$ = 44 °C | N245 | N325 |
| Method: 4-par, A | -0.12 | -1.65 |
| Method: 5-par, A | 1.84 | 0.23 |
| Method: 4-par, B | 0.02 | 0.06 |
| Method: 5-par, B | 0.01 | -0.01 |
| Method: IEC-60904-5 | -0.84 | 0.03 |

## *A. Computing the Single-Diode Model Parameters*

The task of calculating the PV cell model parameters, according to the methods presented in the previous section, is accomplished by a code developed in MATLAB. The program has been designed in such a way that the first step is computing the set of four parameters, by applying the straightforward noniterative method proposed in [4]. Then, these values are used as initial guesses in an iterative loop, which employs the *fzero* function and calculates the values of the set of five parameters, by means of the exact method presented in [3]. It is worth mentioning that since $R_p$ is considered infinite in [4], a proper initial value has to be calculated prior to the application of the exact method [3]. This is accomplished by solving (8) for $R_p$, while using the results from the simplified method.

Two crystalline PV modules are considered in this section. No tuning of any parameter of the MATLAB code is needed when the module specifications are changed. Key data related to each PV module are presented in Table I. These values come from the datasheet of each module and refer to tests under STC, NOCT, and LIC conditions. The complete part numbers of the modules are Panasonic VBHN245SJ25 and Panasonic VBHN325SJ47, referred to as N245 and N325 for simplicity. Complementary data are presented in Table II.

Since both modules present SPR $> 1$, the parallel resistance is considered infinite according to [4]. In fact, values of SPR are 1.63 and 1.39 for N245 and N325 modules, respectively. The parameters computed by the MATLAB code, according to [3] and [4], are presented in Table III.

For each module, the *I–V* curves in STC have been reconstructed in a process that considers the solution of (2) and the values from Table III. They are illustrated in Fig. 2, and their remarkable points present negligible error when compared with STC data from Table I, regardless of using the exact or approximate identification method.

## *B. Combining Parameter Identification and Translation Methods to Compute $T_c$*

In this section, the parameter identification and translation methods presented in Section II are combined, to determine the average module temperature $T_c$ from $V_{oc}$ and $G$. Results from IEC-60904-5 are also provided, for reference.

*1) Nominal operating cell temperature case:* The average NOCT of the N245 and N325 modules has been computed from their respective open-circuit voltage, while employing four combinations between parameter identification and translation methods. The exact five-parameter [3] identification method is referred to as 5-Par, whereas the approximate method [4] is referred to as 4-Par. Therefore, 5-Par, A and 4-Par, A concern the application of such parameter identification methods in conjunction with translation method A [6], and 5-Par, B and 4-Par, B refer to the exact and approximate identification approaches associated with translation method B [5]. Taking the reported NOCT of the modules as reference and the $T_c$ computed from each combination of methods, Table IV presents the percent errors for each module and each combination of identification and translation methods. It shows that the results provided by translation method B along with parameter sets given by [3] or

TABLE V
ERRORS ON $T_c$ AT LIC

| LIC condition | Error on $T_c$ (%) | |
|---|---|---|
| $G$ = 200 W/m², $T_c$ = 25 °C | N245 | N325 |
| Method: 4-par, A | -17.80 | -37.90 |
| Method: 5-par, A | -6.14 | -27.47 |
| Method: 4-par, B | -0.13 | 0.20 |
| Method: 5-par, B | -0.24 | -0.30 |
| Method: IEC-60904-5 | -0.11 | 0.20 |

[4] present significantly smaller error compared with the cases employing translation method A. An advantage of translation method A is that it does not require NOCT or LIC datasets.

*2) Low-intensity condition case:* The percent errors on $T_c$ for the LIC case are organized in Table V.

Considering that the combination 5-Par, B requires the solution of a system of three nonlinear equations, in this paper, the 4-Par, B approach provides smaller absolute error with smaller computing effort.

Translation method A provides the worst results in the present analysis. An important source of error is the parameter $E_g$, which is not precisely known for each module. IEC-60904-5 provides good results under LIC; however, it produced relatively high error at NOCT, considering the N245 module.

It should be noted that using (3) together with the four-parameter set causes the elimination of the last term to the right, since $R_p$ is considered infinite. Thus, using the four-parameter set in (3) along with translation method B allows simplification of the resulting equation. This way, $T_c$ can be computed from $V_{\text{oc}}$ using (18), without the need of parameter identification.

### *C. Discussion*

Regarding the two modules studied and the cell temperature calculated at NOCT and LIC, three methods present coherent results, with error below 1%: 4-Par, B, 5-Par, B, and IEC-60904-5 with $U_T$ computed from (24). To obtain a better view of the behavior of these three methods concerning the calculation of $T_c$, four other modules have been analyzed. They are Sanyo HIT-H250E01 and HIT-N230SE10, and Panasonic VBHN225DJ06 and VBHN294SJ45. For simplicity, these modules are referred to as H250, N230, D225, and N294, respectively. The errors on $T_c$ at NOCT and LIC are illustrated in Figs. 3 and 4, per module and per method.

From Fig. 3, it is clear that the method presenting higher errors under LIC is 5-Par, B, whereas in Fig. 4, the method presenting higher errors under NOCT is IEC-60904-5. Concerning the performance of 4-Par, B under both conditions, the small errors on $T_c$ come at the cost of informing more data: whereas IEC-60904-5 with (24) requires $V_{\text{oc}}$ and $G$ under STC and LIC, translation method B requires these parameters at STC, NOCT, and LIC. The combination 5-Par, B requires the solution of the nonlinear system of equations to determine the SDM parameters. In addition to that, the iterative procedure of solving (3) in conjunction with (15) and (16) for $T_c$ is remarkably more complex than solving (18) or (23). It is worth mentioning that although the SDM is known to present inaccuracies under LIC

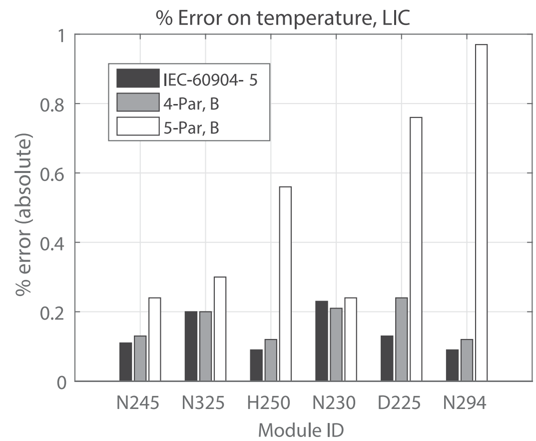


Fig. 3. Errors on $T_c$ at LIC.

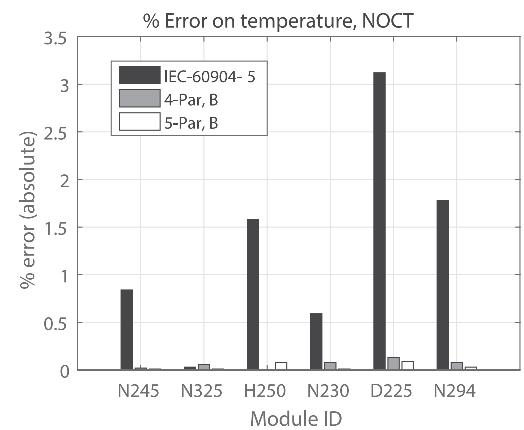


Fig. 4. Errors on $T_c$ at NOCT.

[2], especially regarding the $V_{\text{oc}}$, the errors presented in Fig. 3 remain below 1%. Such an error magnitude would not justify the adoption of a more exact—and more complex—model for the PV cell. Moreover, the errors on $T_c$ computed from 5-Par, B and 4-Par, B under NOCT presented error smaller than 0.25%.

## IV. EXPERIMENTAL VERIFICATION

Practical procedures have been carried out to experimentally verify the performance of 4-Par, B, 5-Par, B, and IEC-60904-5 to compute $T_c$ from measurements of $V_{\text{oc}}$. First, reference *I–V* curves of a PV module have been traced using a solar simulator, to provide values of $V_{\text{oc}}$ under known conditions of irradiance and temperature. Then, values of $V_{\text{oc}}$ and $G$ at outdoors have been recorded, and the $T_c$ has been computed for each case.

### *A. Photovoltaic Module Parameters*

The module tested is a 20-W Komaes KM(P)20 with 36 multicrystalline cells. *I–V* curves of this module have been plotted using a Pasan solar simulator, under irradiances of 200, 700, and 1000 W/m² at 25 °C. Parameters of the module at STC, which have been used to compute the parameters of the SDM, are presented in Table VI. These data have been experimentally

TABLE VI
KOMAES KM(P)20 MODULE DATA AT STC

| Parameters at STC | KM(P)20 36 cells |
|---|---|
| $V_{oc}$ (V) | 22.266 |
| $I_{sc}$ (A) | 1.309 |
| $V_{mpp}$ (V) | 18.311 |
| $I_{mpp}$ (A) | 1.191 |
| $P_{mpp}$ (W) | 21.802 |

obtained from the solar simulator. In addition to that, the $V_{\mathrm{oc}}$ at 700 and 200 W/m² are 21.816 and 20.098 V, respectively.

The thermal coefficient $\beta$ for $V_{\mathrm{oc,STC}}$ is informed on the datasheet of the module as $-0.34\%/°\mathrm{C}$. In addition, the NOCT is reported as 47 °C. For the application of translation method B, the open-circuit voltage referring to the NOCT condition is needed. Instead of conducting practical outdoor measurements, which would require questionable temperature measurements via sensors attached to the module or thermal camera analysis, the $V_{\mathrm{oc,NOCT}}$ has been computed. For that, (16) has been employed to translate $I_{\mathrm{ph}}$ to 800 W/m² and (3) has been used to calculate the $V_{\mathrm{oc}}$, resulting in 21.973 V. It should be noted that although this process may seem simple, it requires the calculation of the five-parameter set according to [3]. Following, the thermal coefficient $\beta$ has been used to translate the $V_{\mathrm{oc}}$ to 47 °C, resulting in 20.307 V from (25). This way, the $V_{\mathrm{oc}}$ at the NOCT condition has been computed relying only on $\beta$ and the parameters of the SDM at STC, without interference of $E_g$ or any datasets under different conditions. It is worth noting that employing (3) and (16) to reproduce the $V_{\mathrm{oc}}$ at 700 W/m² and 25 °C, the error of -0.09% is found, relative to the $V_{\mathrm{oc}}$ measured by the solar simulator at the same condition of irradiance and temperature. In addition, the use of the same procedure to determine the $V_{\mathrm{oc,STC}}$ presents negligible error compared with the solar simulator result.

## *B. Outdoor Measurements*

Practical outdoor tests have been performed in different days to record values of open-circuit voltages and irradiance. The $V_{\mathrm{oc}}$ has been measured in 30-s intervals, using an Agilent 34970A data logger, whereas the irradiance has been measured using a Vantage Pro2 weather station, with resolution of 1 min and with its sensor at the same inclination as that of the Komaes module. The resulting data have been filtered as to eliminate steep variations of irradiance. Particularly, around 200 W/m², variations of irradiance up to 4%/min have been observed, making it difficult to obtain reliable data points for reference, since the weather station presents 1-min average values. For irradiances above 700 W/m², the maximum irradiance change rate is 0.4%/min. The open-circuit voltage at 25 °C under 700 W/m² has been measured during the tests with the solar simulator; therefore, from (25), using the open-circuit voltages measured outdoors, the reference temperature of the module at this irradiance level can be computed for each case. This allows assessing the performance of 4-Par, B, 5-Par, B, and IEC-60904-5 methods to compute $T_c$ from $V_{\mathrm{oc}}$ and $G$ without relying on measurements via temperature sensors attached to the module.

TABLE VII
AVERAGE MODULE TEMPERATURES COMPUTED FROM $V_{\mathrm{oc}}$ BY EACH METHOD

| $V_{oc}$ | $T_{c,ref}$ | $T_c$ (4-Par, B) | $T_c$ (5-Par, B) | $T_c$ (IEC-60904-5) |
|---|---|---|---|---|
| 20.573 | 41.42 | 41.12 | 40.98 | 41.02 |
| 20.084 | 47.88 | 47.62 | 47.46 | 47.48 |
| 19.558 | 54.83 | 54.63 | 54.50 | 54.42 |
| 18.921 | 63.24 | 63.12 | 62.98 | 62.84 |

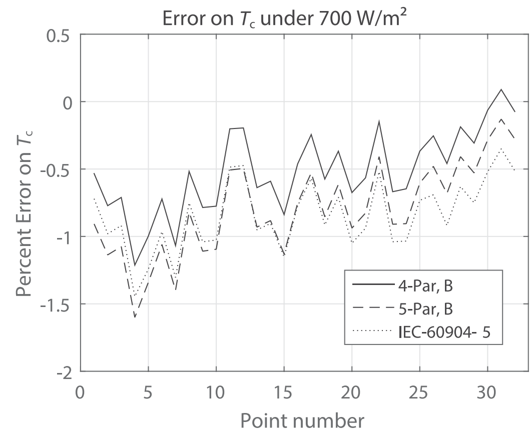


Fig. 5. Errors under 700 W/m² and different temperatures for IEC-60904-5 and 4-Par, B methods.

TABLE VIII
AVERAGE ABSOLUTE ERRORS ON $T_c$ UNDER 700 W/M², PER METHOD

| Method | 4-Par, B | 4-Par, B (no LIC data) | 5-Par, B | 5-Par, B (no LIC data) | IEC-60904-5 |
|---|---|---|---|---|---|
| Average error (%) | 0.52 | 0.56 | 0.80 | 0.79 | 0.84 |

During the experiment, 32 points under 700 W/m² ($\pm1\%$ tolerance) have been measured. Open-circuit voltages, reference, and computed temperatures of four measurement points under exact 700 W/m² are organized in Table VII.

The errors on the computed values of $T_c$ have been calculated for each of the 32 points, ordered from lower to higher temperature, and are illustrated in Fig. 5. In all cases, the temperature values provided by the combination 4-Par, B present errors with smaller magnitude than 5-Par, B or IEC-60904-5.

The error introduced when using 4-Par, B or 5-Par, B to compute $T_c$ in the absence of LIC data has also been assessed. In this case, $\delta(T) = \delta_{\mathrm{NOCT}}$ in (19). The average absolute errors for each method, considering the 32 measurement points, are presented in Table VIII. In this paper, 4-Par, B performs better than 5-Par, B and IEC-60904-5, even if LIC data were not available.

## V. CONCLUSION

Different modeling methods of the SDM have been employed in this paper, aiming to calculate the average temperature of PV modules from the open-circuit voltage, to avoid the use of temperature sensors. From the reported conditions in STC, the parameters of the SDM have been computed using exact and approximate methods. Then, two translation methods for $I_0$ have been considered, one relying on $E_g$ and another on tests at NOCT and LIC. In Section III, different combinations between these methods have been employed to compute the average temperature of six modules based on their $V_{\rm oc}$ and $G$. The results have been compared with the temperatures computed by means of IEC-60904-5, and the method that presented best performance is the four-parameter [4] along with translation method B [5]. Such a combination can be simplified so that the method introduced in [5] with (18)–(22) is capable of computing $T_c$ from $V_{\rm oc}$. Experimental outdoor measurements have been conducted to compare the $T_c$ provided by the methods employing (18) and (23), using a module whose parameters have been measured using a solar simulator. The results provided by 4-Par, B, which in practice means solving (18) for $T_c$, presented smaller error than 5-Par, B and IEC-60904-5, considering different cases under 700 W/m².

The authors are working toward a method for computing both $T_c$ and $G$ from $V_{\rm mpp}$ and $I_{\rm mpp}$ measurements of an actual PV system, without the need of disconnecting the array from the inverter.

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