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Translation of the Single-Diode PV Model Parameters Identified by Using Explicit Formulas

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***Abstract*—Recent literature proposes some approaches that employ explicit equations for identifying the five parameters of the single diode model describing a photovoltaic panel. These methods avoid the iterative solution of a non-linear system of equations, whose convergence is very sensitive to the guess solution. Therefore, they are particularly suitable to perform parameter identification in real-time and to be implemented on low-cost, low-performance processing platforms. In this paper, the applicability of some explicit methods, previously validated under Standard Test Conditions, is analyzed for a large class of panels under operating conditions that are different from the standard ones. The study considers both a consolidated method for translating the photovoltaic model parameters as well as a novel approach. The analysis allows assessing the most suitable parameter translation equations for each considered explicit identification method, highlighting the effectiveness of such explicit approaches under different operating conditions. An in-depth validation based on experimental data concerning two commercial PV panels corroborates the analysis.**

***Index Terms*-- Photovoltaics, single-diode model, parameter identification, parameter translation.**

I. Introduction

The Single-Diode Model (SDM) is very often adopted for describing the behavior of a PhotoVoltaic (PV) generator. It combines simplicity and accuracy and involves five parameters that are associated with the components appearing in the equivalent circuit that is shown in Fig. 1. The five parameters are $\{I_{ph}, I_{sat}, \eta, R_s, R_p\}$, i.e., the photocurrent, the reverse saturation current, the diode ideality factor, the series resistance and the shunt resistance, respectively [1-4].

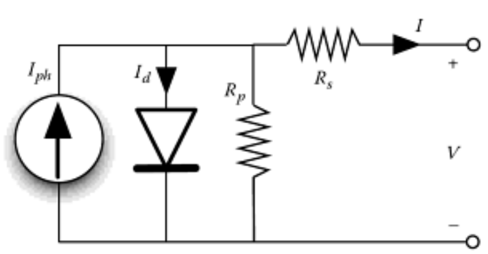

Fig. 1: The single-diode model of a PV generator.

In general, the parameter values can be translated to describe, with the same model, the behavior of a PV generator working in any homogeneous operating condition, thus at any temperature and solar irradiance. As for parameter translation methods, many contributions have been proposed in the technical literature, where analytical or empirical relationships among PV model parameters and environmental conditions are used [5-10]. A short review of such parameter translation methods is presented in [11].

The identification of the parameter values for a given operating condition is usually made through the solution of a non-linear system of equations, which consists of five constraints for the current-voltage I-V characteristic of the PV generator. For example, the curve must be constrained to pass through the Maximum Power Point (MPP), to have a maximum there, and to cross the axes in the open circuit and short circuit points. The solution of such a system is usually accomplished by classical iterative methods, e.g. Newton-Raphson, or by stochastic optimization techniques [4-5], [10], [12-13]. Unfortunately, the performance of both approaches depends on the guess solution provided by the user; moreover, they are not suitable for on-line applications, where limited computational and memory resources are available.

Recently, some methods that allow identifying the SDM parameter values at a given operating condition by using explicit formulas have been presented [14-19]. They use approximated equations, but they do not need any iterative approach for solving the system; therefore, they seem to be attractive for implementation on low-cost, low-performance processing platforms.

The explicit parameter identification method described in [14] returns a five-parameter set by using a new coefficient δ_0, which is defined as the ratio between the diode ideality factor, the open circuit voltage and an auxiliary term w_0. This formulation uses explicitly the temperature coefficients declared by the manufacturer.

The approach presented in [15] is based on simpler equations allowing a straightforward calculation of all the five parameters through direct formulas. Hence, it has the feature of always keeping the fifth-order model. As discussed in [21], this method is not immune from problems when the Fill Factor (FF) of the PV generator is very high.

The method described in [16-17] is based on a figure of merit of the PV generator, i.e. the Series-Parallel-Ratio

(SPR), which can easily be calculated using the tabular parameters of the datasheet. Depending on whether this figure is lower or greater than one, the series or the shunt resistance in the equivalent circuit can be neglected, so that the model is scaled down from five to four parameters. The reduced parameter set can be identified through explicit formulas, as shown in [16-17]. This method will be referred to as 'SPR method' in the following.

The method proposed in [18] also considers a four-parameters model, but it always neglects the shunt resistance. Furthermore, the expressions of parameters R_s and η differ from those in [16-17] for the absence of some terms whose contribution is nevertheless negligible, as it will be shown in Section IV.

As for the method described in [19], it requires the knowledge of the slope of the I-V curve at the open circuit voltage and short circuit conditions, which allow to extract the five parameter set. However, these quantities are obtained by using the identified values of the four parameter SDM and a piecewise curve-fitting method.

In [20], an ideal SDM, which neglects both the shunt and the series resistances, is proposed. In this three-parameters model, the diode ideality factor η exhibits a very high value since it accounts for the effects of the two neglected resistances.

A performance comparison of methods [14] and [18-20] in Standard Test Conditions (STC) is given in [14]; it demonstrates that the best identification results are obtained by explicit methods [14] and [18].

On the other hand, both the identification methods, [15] and [16-17], is validated under STC for different PV panels and returns very satisfactory results [21].

Nevertheless, the effectiveness all the cited explicit identification methods depends on whether they are able to reproduce the PV generator's behavior under operating conditions that are different from STC. It is surely possible to reapply the explicit identification methods in the desired operating conditions. Unfortunately, this would require the knowledge of the $\{I_{sc}, I_{mpp}, V_{mpp}, V_{oc}\}$ values, where the subscripts *sc*, *oc*, and *mpp* stand for short circuit, open circuit, and maximum power point, in the considered operating conditions. A simpler alternative would be the application of literature translation methods to the parameter set obtained through explicit parameter identification in STC.

In this paper, suitable parameter translation equations are tested, and the accuracy of parameter translation is quantitatively assessed for different case studies. In particular, two commercial PV panels, which have characteristics that are typical of most products on the market, have been considered for the analysis.

The paper is organized as follows. Section II is dedicated to a brief recall of the main features of the considered explicit methods. Section III describes the considered parameter translation methods and the case studies. Section IV shows the results obtained using the experimental data provided by the manufacturers of the two chosen PV panels. Finally, conclusions end the paper.

II. Equations Used in the Considered Explicit Identification Methods

The SPR method comes from a simplification of the exact method given in [5]. It introduces a new indicator, the SPR, which allows classifying the PV modules into two complementary groups, thus always reducing the number of parameters from five to four. The SPR is defined as follows:

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

where:

$$\gamma_i = \frac{I_{mpp}}{I_{sc}}, \gamma_v = \frac{V_{mpp}}{V_{oc}}, r = \frac{\gamma_i(1-\gamma_v)}{\gamma_v(1-\gamma_i)} \tag{2a,b,c}$$

If SPR>1, the effect of the series resistance is prevalent and the shunt resistance can be settled to an infinite value, thus neglected in the model. The opposite conclusion holds when SPR<1, so that the series resistance is equal to zero and only the shunt resistance appears in the model. The authors of [16-17] also give some explicit formulas that allow calculating the four parameters of the model straightforwardly, without solving the non-linear five-equation system iteratively. Such expressions have been obtained by analyzing the solution of the system for the extreme values assumed by the two resistances in each case. The non-neglected resistance can be calculated using either of the following equations:

$$R_s = \frac{V_{oc}}{I_{sc}} \frac{\frac{\gamma_v}{\gamma_i}(1-\gamma_i)\ln(1-\gamma_i)+(1-\gamma_v)}{(1-\gamma_i)\ln(1-\gamma_i)+\gamma_i} \quad \text{if } R_p=\infty \tag{3}$$

$$R_p = \frac{V_{oc}}{I_{sc}} \frac{\lambda_2 W(-SPR\cdot\lambda_1 e^{-\lambda_1})+\lambda_1}{W(-SPR\cdot\lambda_1 e^{-\lambda_1})+\lambda_1} \quad \text{if } R_s=0 \tag{4}$$

where λ_1 and λ_2 coefficients are computed starting from γ_i and γ_v, as explained in [17], and W denotes the Lambert-W function. Consequently, the remaining parameters can be computed as follows:

$$\eta = \frac{1}{n_s V_t} \frac{I_{mpp}R_s-(V_{oc}-V_{mpp})}{\ln\frac{(I_{sc}-I_{mpp})(R_s+R_p)-V_{mpp}}{I_{sc}(R_s+R_p)-V_{oc}}} \tag{5}$$

$$I_{ph} = I_{sc} \tag{6}$$

$$I_{sat} = \left(I_{ph} - \frac{V_{oc}}{R_p}\right) e^{-\frac{V_{oc}}{\eta \cdot n_s V_t}} \quad (7)$$

where V_t is the thermal voltage and n_s is the number of PV cells in series within the PV panel. It is worth remarking that, just like the exact method [5] from which it is derived, the SPR method does not need the knowledge of the band gap of the semiconductor; hence, it can also be applied to non-crystalline PV panels [22].

The equations used to extract the four-parameters set according to the method proposed in [18] are not recalled here since they are very similar to those used by the SPR method. Specifically, they differ from those in [16-17] because some terms appearing in equations (3) and (5) are neglected. Anyway, the contribution of such terms being negligible, the methods SPR and [18] return the same SDM four-parameters set. The method proposed in [15] never discards one of the two resistances, but it follows an approach that was initially presented in [23]. As in [23], the shunt resistance is initially neglected to obtain explicit expressions for identifying $\{\eta, I_{ph}, I_{sat}\}$. In particular, I_{ph}, I_{sat} are again calculated using (6) and (7), whereas η is computed according to:

$$\eta = \frac{\alpha_V - \frac{V_{OC}}{T}}{n_s \cdot V_t \cdot \left(\frac{\alpha_I}{I_{ph}} - \frac{3}{T} - \frac{E_{gap}}{k \cdot T^2}\right)} \quad (8)$$

where α_I and α_V are the current and voltage temperature coefficients, respectively, E_g is the semiconductor band gap, and K is the Boltzmann constant.

The two resistances $\{R_s, R_p\}$ are determined using (9a,b) as functions of the quantity x given in (10), which must be computed using the Lambert-W function. By looking at (9a,b) and (10), it is evident that the two resistances might assume negative values in extreme cases, as discussed in [21].

$$\begin{cases} R_s = \frac{x\eta n_s V_t - V_{mpp}}{I_{mpp}} \\ R_p = \frac{x\eta n_s V_t}{I_{ph} - I_{mpp} - I_{sat} \cdot (e^x - 1)} \end{cases} \quad (9a,b)$$

$$x = W\left[\frac{V_{MPP}(2I_{mpp} - I_{ph} - I_{sat}) e^{\frac{V_{mpp}(V_{mpp} - 2\eta n_s V_t)}{\eta^2 n_s^2 V_t^2}}}{\eta n_s V_t I_{sat}}\right] + 2\frac{V_{mpp}}{\eta n_s V_t} - \frac{V_{mpp}^2}{\eta^2 n_s^2 V_t^2} \quad (10)$$

The method proposed in [14] introduces a new coefficient δ_0 that is computed by using (11a) and an auxiliary term w_0 in (11b) that is computed by using the Lambert-W function.

$$\delta_0 = \frac{a_0}{V_{oc0}} = \frac{1 - 298.15\alpha_{Vpu}}{50.1 - 298.15 a_{Ipu}}, \quad w_0 = W\{e^{1/\delta_0 + 1}\} \quad (11a,b)$$

where $\alpha_{Vpu} = \alpha_V / V_{oc}$ and $\alpha_{Ipu} = \alpha_I / I_{cc}$ are the normalized (p.u.) temperature coefficients. Once these quantities are determined, the SDM five parameter set can be straightforwardly obtained by using the following expressions:

$$a_0 = \eta n_s V_t = \delta_0 V_{oc0} \quad (12)$$

$$R_{s0} = [a_0(w_0 - 1) - V_{mp0}]/I_{mp0} \quad (13)$$

$$R_{p0} = a_0(w_0 - 1)/[I_{sc0}(1 - 1/w_0) - I_{mp0}] \quad (14)$$

$$I_{ph0} = (1 + R_{s0}/R_{p0}) I_{sc0} \quad (15)$$

$$I_{sat0} = I_{ph0} e^{-1/\delta_0} \quad (16)$$

where the subscript ‘0’ indicates the STC.

The evaluation of the Lambert-W function that is required by the considered explicit identification methods can be performed in several ways: 1) using a simple series expansion [24], 2) using iterative methods, such as Newton’s or Halley’s methods [24], 3) using approximate formulas involving a maximum error of a few percent [14] [25]. In particular, the second approach is the commonest choice for the major computational environments, e.g. Matlab® and Mathematica®. On the other hand, a more efficient calculation is possible when series expansions are employed. Instead, the third approach is more suitable for an embedded implementation, as an alternative to the use of a simple lookup table.

III. Description of the translation Procedure

The aim of this work is to evaluate the effectiveness of translating the SDM parameters, which are previously obtained by applying the considered explicit identification methods in STC. The SPR method is applied differently when SPR is above or below the unity threshold. For this reason, the most frequent case, i.e., SPR>1, has been considered in the present work. In fact, the analysis of a recent database of commercial PV panels [26] reveals that most of them, i.e., 83% of the database, are characterized by SPR>1 (see Fig. 2). The case of panels having SPR≤1 deserves further investigations and will be presented in a future paper.

Thus, two PV panels that are currently available on the market and having SPR>1 have been considered. They have been chosen because their manufacturers provide data concerning their behavior both in STC and in different operating conditions, i.e., at Nominal Operating Cell Temperature (NOCT) conditions. This choice allows testing the effective reconstruction of the I-V curve in NOCT conditions that is obtained by translating the parameters values that have been identified in STC. In particular, the values of $\{I_{sc}, I_{mpp}, V_{mpp}, V_{oc}\}$ reported in the datasheet for such a condition are compared with those extracted from the translated curve. NOCT conditions are characterized by a still high irradiance level (800 W/m^2) and by a cell operating temperature that is significantly higher than the 25 °C considered in STC. The same approach can be applied to test the accuracy of the I-V curve reconstruction for PV panels whose manufacturer also gives data at Low Irradiance Conditions (LIC), typically 200 W/m^2 and 25 °C.

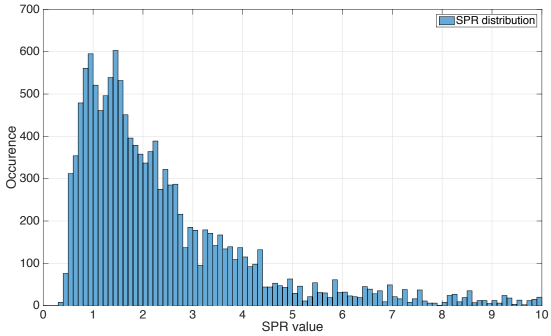

Fig. 2: SPR distribution for commercial PV panels taken from [26].

Table I collects the most meaningful data concerning the PV panels that have been chosen for the analysis: the number of cells, the thermal coefficients, the NOCT and the SPR.

TABLE I

DETAILS OF THE TWO CONSIDERED PV PANELS

PV panel model	n_S	α_I	α_V	NOCT	SPR
LDK 240D-20	60	0.06%/°C	-0.34%/°C	45 °C	2.98
Sanyo HIT-H250	60	0.03%/°C	-0.25%/°C	46 °C	1.47

Two parameter translation techniques have been used. The first set of formulas (17)-(18), which is proposed in [27], will be referred to as 'translation method A' in the following.

$$I_{ph} = I_{ph\_STC}\left(\frac{G}{G_{STC}}\right)\left(1+\alpha_I(T-T_{STC})\right) \qquad (17)$$

$$I_{sat} = I_{sat\_STC}\left(\frac{T}{T_{STC}}\right)^3 e^{\left(\frac{Eg}{\eta K}\right)\left(\frac{1}{T_{STC}}-\frac{1}{T}\right)} \qquad (18)$$

The other approach will be referred to as 'translation method B'. Compared to the one in [27], this approach replaces (18) with the following equation:

$$I_{sat} = I_{ph}/(e^{V_{oc}/(\eta n_s V_t)}-1) \qquad (19)$$

where I_{ph} is obtained by (17) and:

$$V_{oc} = V_{oc_{STC}}\cdot\left(1+\alpha_V(T-T_{STC})\right)\cdot\left(1+\delta(T)log(G/G_{STC})\right) \qquad (20)$$

As far as the equations (19) and (20) are concerned, the first one is taken from [6]; the second one is an extension of the equation for V_{oc} proposed in [6] and it allows to take into account the dependence on solar irradiance, as it is suggested in [28].

Differently from [28], the translating method B does not perform a bilinear interpolation, thus it does not require the knowledge of four reference I-V curves. This is a clear advantage of the proposed translation method because the PV panel manufacturers usually give only the remarkable points of two or three I-V curves (i.e., in STC, NOCT and LIC). As for equation (20), the term $\delta(T)$ is expressed as:

$$\delta(T) = M\cdot T + N \qquad (21)$$

Values of M and N can be determined by interpolating data related to different operating conditions. In particular, if the datasheet reports tabular data for both LIC and NOCT conditions, the two coefficients can be computed as follows:

$$M = \frac{\delta_{NOCT}-\delta_{LIC}}{T_{NOCT}-T_{LIC}},\quad N = \delta_{NOCT} - M\cdot T_{NOCT} \qquad (22)$$

with:

$$\delta_{NOCT} = \frac{1}{log\left(\frac{G_{NOCT}}{1000}\right)}\left(\frac{V_{OC,NOCT}}{V_{OC,STC}(1+\alpha_V(T_{NOCT}-T_{STC}))}-1\right) \qquad (23)$$

$$\delta_{LIC} = \frac{1}{log\left(\frac{G_{LIC}}{1000}\right)}\left(\frac{V_{OC,LIC}}{V_{OC,STC}(1+\alpha_V(T_{LIC}-T_{STC}))}-1\right) \qquad (24)$$

On the other hand, if the manufacturer only provides tabular data for NOCT conditions, it must be assumed that $M = 0$ and $N = \delta_{NOCT}$.

Finally, with both translation approaches, parameters $\{\eta,\ R_s,\ R_p\}$ are assumed constant when the operating conditions change.

For each case study and for each explicit identification method, once the parameter set (in STC, NOCT conditions or LIC) has been computed, the reconstructed I-V curve is plot by using (25). Alternatively, it is possible to plot the I-V curve by using the explicit version of (25), which is given in [11] in the form *I=f(V)*.

$$I = I_{ph} - I_{sat}\cdot\left(e^{\frac{V+I\cdot R_S}{\eta\cdot n_S V_t}}-1\right)-\frac{V+I\cdot R_S}{R_p} \qquad (25)$$

Of course, the SPR method neglects one of the two resistances, i.e., the series or the parallel one. In the former case, the R_s is zeroed in (25), whereas the last term of (25) is neglected in the latter case.

IV. RESULTS AND DISCUSSION

This Section describes how the procedure shown in Section III is applied to each case study. Furthermore, the obtained results are presented and commented.

A. Case study 1: LDK 240D-20

The manufacturer of this PV panel declares the performance in STC and NOCT conditions, which is expressed by the values reported in Table II.

TABLE II
DATASHEET VALUES OF THE FIRST ANALYZED PV PANEL

	@STC (1000 W/m^2, 25 °C)	@NOCT (800 W/m^2, 46 °C)
V_{oc} [V]	37.3	34.5
I_{sc} [A]	8.88	7.19
V_{mpp} [V]	29.1	26.3
I_{mpp} [A]	8.26	6.61

The application of the four considered explicit methods in STC returns the SDM parameters values given in Table III.

TABLE III
SETS OF PV PARAMETERS OBTAINED USING THE TWO EXPLICIT METHODS FOR CASE STUDY 1

methods @ STC	I_{ph} [A]	I_{sat} [nA]	η	R_s [Ω]	R_p [Ω]
[16-17]	8.88	48.5	1.27	0.361	∞
[15]	8.88	0.796	1.05	0.408	186
[14]	8.91	0.153	0.977	0.424	143
[18]	8.88	48.5	1.27	0.361	∞

A significant difference appears in the value of all the parameters, except for the photocurrent. However, all the parameter sets, although quite different, give a very good reproduction of the panel I-V curve in STC, as it is evident from Fig. 3.

Once achieved this very satisfying result in STC, it must be evaluated whether translation methods A and B allow reproducing the I-V curve correctly also in NOCT conditions.

Table IV gives several sets of PV parameters. The first six rows are obtained starting from Table III and applying translation methods A and B. Parameters values of {η, R_s, R_p} (in bold in Table IV) are kept unchanged. The last three rows of Table IV show the parameter sets obtained by repeating the identification procedure in NOCT conditions starting from the last column of Table II and by using the considered explicit identification approaches. The I-V curve has been reconstructed by using all the parameter sets of Table IV. Fig. 3 reveals that, by excluding the first one (methods [16-18] @ STC + translation method A), all the remaining parameter sets give a fully satisfactory curve reconstruction. In particular, these sets, although greatly different, give almost the same I-V curve, with a correct reproduction of the short circuit current, the open circuit voltage, and the MPP coordinates. The error on each quantity is shown in Table V.

TABLE IV
SETS OF PV PARAMETERS IN NOCT CONDITIONS OBTAINED FOR CASE STUDY 1

n. of parameters	Parameter identification method and operating conditions	Translation method	I_{ph} [A]	I_{sat} [nA]	η	R_s [Ω]	R_p [Ω]
4	methods [16-17] & [18] @ STC	A	7.19	723	**1.27**	**0.361**	∞
4	methods [16-17] & [18] @ STC	B	7.19	495	**1.27**	**0.361**	∞
5	method [15] @ STC	A	7.19	15.2	**1.05**	**0.408**	**186**
5	method [15] @ STC	B	7.19	13.7	**1.05**	**0.408**	**186**
5	method [14] @ STC	A	7.21	2.9	**0.977**	**0.424**	**143**
5	method [14] @ STC	B	7.21	3.25	**0.977**	**0.424**	**143**
4	methods [16-17] & [18] @ NOCT	none	7.19	321	1.24	0.464	∞
5	method [15] @ NOCT	none	7.19	12.4	1.04	0.503	180
5	method [14] @ NOCT	none	7.21	7.94	1.02	0.5	151

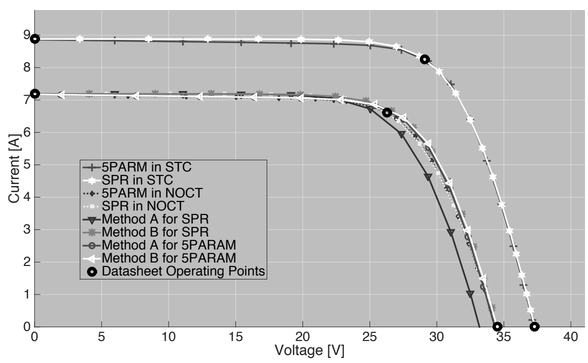

Fig. 3: Various reconstructions of the I-V curve in STC and NOCT conditions for case study 1.

The translation method A, which works in a proper way when applied to the identification method [15], is not able to reproduce the I-V curve change due to the temperature accurately when applied to four-parameter methods [16-18]. The discrepancy on V_{oc} is significant and the same holds for the MPP location.

TABLE V
ERROR METRICS FOR TRANSLATION PARAMETERS OF CASE STUDY 1

	% Error on				
	V_{oc}	I_{sc}	V_{mpp}	I_{mpp}	P_{mpp}
methods [16-17] & [18] @ STC + translation method A	-3.77	-0.01	-2.67	-0.22	-2.88
methods [16-17] & [18] @ STC+ translation method B	-0.003	-0.01	1.92	0.15	2.07
method [15] @ STC+ translation method A	-0.494	-0.23	2.42	-0.53	1.87
method [15] @ STC+ translation method B	-0.003	-0.23	3.06	-0.53	2.52
method [14] @ STC+ translation method A	0.489	-0.01	4.07	-0.44	3.61
method [14] @ STC+ translation method B	-0.003	-0.01	3.42	-0.45	2.95

B. *Case study 2: Sanyo HIT-H250*

Besides providing the performance in STC and NOCT conditions, the manufacturer of the second PV panel also gives tabular data for LIC, namely for an irradiance value of 200 W/m^2 and a cell temperature of 25 °C. This information allows performing a further parameter translation test. The performance in the three mentioned conditions, as declared by the manufacturer, is expressed by the values reported in Table VI.

The application of the explicit methods for identifying the SDM parameters in STC returns the values given in Table VII. Again, Fig. 4 confirms that a very good reproduction of the panel I-V curve in STC is obtained.

TABLE VI
DATASHEET VALUES OF THE SECOND ANALYZED PV PANEL

	@STC (1000 W/m^2, 25 °C)	**@NOCT (800 W/m^2, 46 °C)**	**@LIC (200 W/m^2, 25 °C)**
V_{oc} [V]	43.1	40.5	40.1
I_{sc} [A]	7.74	6.23	1.55
V_{mpp} [V]	34.9	32.8	34.1
I_{mpp} [A]	7.18	5.76	1.43

Table VIII gives several sets of PV parameters obtained in NOCT conditions, with the same combination of parameter identification and translation methods given in Table IV. Then, the I-V curve has been reconstructed using all the parameter sets. The results are shown in Fig. 4. Once again, excluding the first one (methods [16-18] @ STC + translation method A), all the remaining parameter sets give a fully satisfactory curve reconstruction. Table X lists the errors on the short circuit current, the open circuit voltage, and the MPP coordinates.

TABLE VII
SETS OF PV PARAMETERS OBTAINED USING THE TWO EXPLICIT METHODS FOR CASE STUDY 2

methods @ STC	**I_{ph} [A]**	**I_{sat} [nA]**	**η**	**R_s [Ω]**	**R_p [Ω]**
[16-17]	7.74	551	1.70	0.184	∞
[15]	7.74	0.019	1.05	0.426	158
[14]	7.76	0.003	0.977	0.456	143
[18]	7.74	551	1.70	0.184	∞

TABLE VIII
SETS OF PV PARAMETERS IN NOCT CONDITIONS OBTAINED FOR CASE STUDY 2

n. of parameters	**Parameter identification method and operating conditions**	**Translation method**	**I_{ph} [A]**	**I_{sat} [nA]**	**η**	**R_s [Ω]**	**R_p [Ω]**
4	methods [16-17] & [18] @ STC	A	6.23	12100	**1.70**	**0.184**	∞
4	methods [16-17] & [18] @ STC	B	6.23	2940	**1.70**	**0.184**	∞
5	method [15] @ STC	A	6.23	0.422	**1.05**	**0.426**	**158**
5	method [15] @ STC	B	6.23	0.322	**1.05**	**0.426**	**158**
5	method [14] @ STC	A	6.25	0.063	**0.977**	**0.456**	**143**
5	method [14] @ STC	B	6.25	0.073	**0.977**	**0.456**	**143**
4	methods [16-17] & [18] @ NOCT	none	6.23	1040	1.57	0.172	∞
5	method [15] @ NOCT	none	6.23	0.336	1.04	0.425	196
5	method [14] @ NOCT	none	6.24	0.151	1.00	0.443	185

TABLE IX
SETS OF PV PARAMETERS IN LIC OBTAINED FOR CASE STUDY 2

n. of parameters	**Parameter identification method and operating conditions**	**Translation method**	**I_{ph} [A]**	**I_{sat} [nA]**	**η**	**R_s [Ω]**	**R_p [Ω]**
4	methods [16-17] & [18] @ STC	A	1.55	551	**1.70**	**0.184**	∞
4	methods [16-17] & [18] @ STC	B	1.55	347	**1.70**	**0.184**	∞
5	method [15] @ STC	A	1.55	0.019	**1.05**	**0.426**	**158**
5	method [15] @ STC	B	1.55	0.021	**1.05**	**0.426**	**158**
5	method [14] @ STC	A	1.55	0.002	**0.977**	**0.456**	**143**
5	method [14] @ STC	B	1.55	0.003	**0.977**	**0.456**	**143**
4	methods [16-17] & [18] @ LIC	none	1.55	7.03	1.36	0	990
5	method [15] @ LIC	none	1.55	0.011	1.01	0.695	613
5	method [14] @ LIC	none	1.55	0.012	1.02	0.742	652

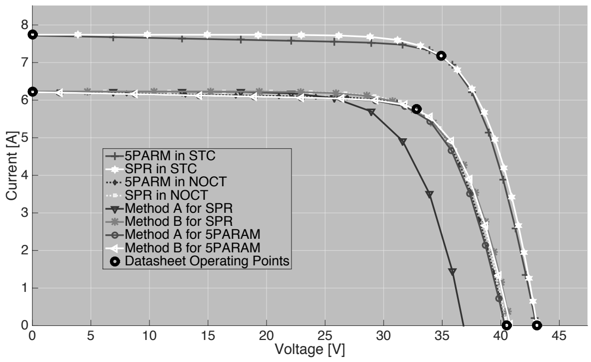

Fig. 4: Various reconstructions of the I-V curve in STC and NOCT conditions for case study 2.

TABLE X
ERROR METRICS FOR TRANSLATION PARAMETERS OF CASE STUDY 2 IN NOCT

	Error on				
	V_{oc}	I_{sc}	V_{mpp}	I_{mpp}	P_{mpp}
methods [16-17] & [18] @ STC + translation method A	-8.93	0.015	-11.2	-1.68	-12.7
methods [16-17] & [18] @ STC+ translation method B	-0.013	0.015	-1.13	-0.68	-1.80
method [15] @ STC+ translation method A	-0.33	-0.254	0.13	-1.13	-1.00
method [15] @ STC+ translation method B	-0.013	-0.254	0.53	-1.13	-0.603
method [14] @ STC+ translation method A	0.56	0.014	1.4	-0.84	0.539
method [14] @ STC+ translation method B	-0.013	0.014	0.66	-0.82	-0.163

Finally, the whole procedure has been repeated for the second case study in LIC. The results are shown in Fig. 5 and in Tables IX and XI. In this condition the best results are obtained with the methods [16-18] @ STC + translation method B.

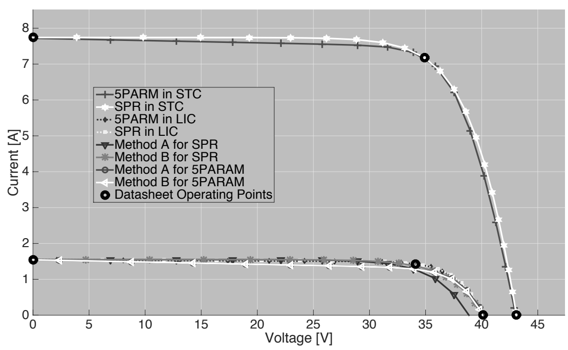

Fig. 5: Various reconstructions of the I-V curve in LIC for case study 2.

By looking at Table XI it is evident from the last four rows that the corresponding methods exhibit a high percentage deviation in the I_{mpp} estimation because, in LIC conditions, its low value appears in the denominator of the relative error calculation.

TABLE XI
ERROR METRICS FOR TRANSLATION PARAMETERS OF CASE STUDY 2 IN LIC

	Percentage Error on				
	V_{oc}	I_{sc}	V_{mpp}	I_{mpp}	P_{mpp}
methods [16-17] & [18] @ STC + translation method A	-3.03	-0.129	-6.49	-0.018	-6.51
methods [16-17] &[18] @ STC+ translation method B	0.007	-0.129	-3.17	0.238	-2.94
method [15] @ STC+ translation method A	0.279	-0.398	0.977	-10.8	-9.89
method [15] @ STC+ translation method B	0.007	-0.398	0.657	-10.7	-10.1
method [14] @ STC+ translation method A	0.71	-0.13	2.00	-11.8	-10.0
method [14] @ STC+ translation method B	0.007	-0.13	1.17	-11.7	-10.6

V. CONCLUSIONS

The most advantageous methods for identifying the five/four SDM parameters through explicit formulas have been considered in this paper. In particular, the effectiveness of classical and novel SDM parameter translating formulas applied to the achieved sets of parameters has been evaluated. The analysis has been based on experimental data provided by manufacturers in their panels' datasheets in STC, NOCT conditions and LIC.

The tests, which have been performed on panels having a high shunt resistance, reveal that the two considered translating formulas work properly with the parameter sets provided by the five-parameter methods. On the other hand, translation method A is not able to correct the parameter sets provided by the four-parameter methods when the operating conditions highly differ in terms of temperature from those at which the set was identified. The discrepancy affects the voltage values, so that a correct reproduction is obtained only for the part of the I-V curve that is close to the short circuit operating point. Instead, the four-parameter methods ensure reliable results when they are used in conjunction with the translation method B.

The results achieved in this paper open the field to further research activities on translation formulas for parameter sets provided by the considered methods for

PV panels with SPR≤1 and by considering translating effects also on the R_s and R_p parameters.

References

[1] Castañer L., Silvestre S. (2002) Modelling photovoltaic systems using Pspice. Wiley, Chicester.

[2] Luque, A. (Editor), Hegedus, S. (Editor), (2003), Handbook of Photovoltaic Science and Engineering, Wiley, Hoboken, NJ.

[3] Chan, S. H., Phang, J. C. H., (1987), Analytical Methods for the Extraction of Solar-Cell Single-and Double-Diode Model Parameters from I-V Characteristics, IEEE Trans. On Electron. Devices, vol. ED-34, n. 2: 286-293

[4] Gradella Villalva, M., Gazoli, J. R., Filho, E. R. (2009) Comprehensive approach to modeling and simulation of photovoltaic array, IEEE Trans. Power Electron., vol. 24, n.5: 1198-1208.

[5] Sera, D., Teodorescu, R., Rodriguez, P., (2007), PV panel model based on datasheet values, in Proc. IEEE Intern. Symp. on Industr. Electron.: 2392-2396.

[6] Xiao, W., Dunford, W.G., Capel, A., (2004), A novel modeling method for Photovoltaic cells, in Proc. IEEE 35th Annual Power Electron. Spec. Conf.: 1950 – 1956.

[7] Veissid, N., De Andrade, A. M., (1991), The I-V silicon solar cell characteristic parameters temperature dependence, an experimental study using the standard deviation method, in Proc. European Photovoltaic Solar Energy Conf.:43-47.

[8] Eikelboom, J.A., Reinders, A.H.M.E., (1997). Determination of the irradiation dependent efficiency of multicrystalline Si PV modules on basis of IV curve fitting and its influence on the annual performance, in Proc. European PV Solar Energy Conf.: 293–296.

[9] Bätzner, D.L., Romeo, A., Zogg, H., Tiwari, A.N., (2001), CdTe/CdS solar cell performance under low irradiance, in Proc. European PV Solar Energy Conf.: paper VB1.40.

[10] Gow, J. A., Manning, C. D., (1999), Development of a photovoltaic array model for use in power-electronics simulation studies, IEE Proc. Elect. Power Appl., vol. 146, n. 21:193–200.

[11] Di Piazza, M. C., Vitale, G., (2013), Photovoltaic Sources Modeling and Emulation. Springer Verlag, London.

[12] Da Costa, W. T. Fardin, J. F. Simonetti, D. S. L. Neto, L. de V.B.M., (2010), Identification of photovoltaic model parameters by Differential Evolution, in Proc. Intern. Conf. on Ind. Technology: 931 – 936.

[13] Petcut, F.-M., Dragomir, T.-L., (2010), Solar cell parameter identification using genetic algorithms, CEAI, vol.12, n. 1:30-37.

[14] E. I. Batzelis and S. A. Papathanassiou, “A method for the analytical extraction of the single-diode PV model parameters,” IEEE Trans. Sustain. Energy, vol. 7, no. 2, pp. 504–512, Apr. 2016.

[15] Accarino, J., Petrone, G., Ramos-Paja, C. A., Spagnuolo, G., Symbolic algebra for the calculation of the series and parallel resistances in PV module model. International Conference on Clean Electrical Power (ICCEP), 11-13 June, 2013, pp. 62-66.

[16] Cannizzaro, S., Di Piazza, M. C., Luna, M., Vitale, G., Generalized classification of PV modules by simplified single-diode models. Proc. IEEE International Symposium on Industrial Electronics (ISIE’14), June 1-4, 2014, pp. 2262-2269.

[17] Cannizzaro, S., Di Piazza, M. C., Luna, M., Vitale, G., PVID: an interactive Matlab application for parameter identification of complete and simplified single-diode PV models”, IEEE Workshop on Control and Modeling for Power Electronics (COMPEL), 22-25 June, 2014, pp.1-7.

[18] R. Khezzar, M. Zereg, and A. Khezzar, “Modeling improvement of the four parameter model for photovoltaic modules,” Sol. Energy, vol. 110, pp. 452–462, Dec. 2014.

[19] J. Bai, S. Liu, Y. Hao, Z. Zhang, M. Jiang, and Y. Zhang, “Development of a new compound method to extract the five parameters of PV modules,” Energy Convers. Manag., vol. 79, pp. 294–303, Mar. 2014.

[20] E. Saloux, A. Teyssedou, and M. Sorin, “Explicit model of photovoltaic panels to determine voltages and currents at the maximum power point,” Sol. Energy, vol. 85, no. 5, pp. 713–722, May 2011.

[21] Di Piazza, M.C., Luna, M., Petrone, G., Spagnuolo, G., About the identification of the single-diode model parameters of high-fill-factor photovoltaic modules, 2015 International Conference on Clean Electrical Power (ICCEP), Taormina, Italy 16-18 June 2015, pp. 85 – 91.

[22] Cannizzaro, S., Di Piazza, M. C., Luna, M., Vitale, G., Calogero, G., Citro, I. Parameter Identification and Real-Time J-V Curve Reconstruction of Polymer PV and Dye-Sensitized Cells Using Non-Iterative Algorithm, EUPVSEC 2014, 22-26 September, 2014, pp. 1548-1553.

[23] U. Eicker, Solar Technologies for Buildings. John Wiley & Sons, Inc., Hoboken, New Jersey, 2003.

[24] R.M. Corless, G.H. Gonnet, D.E.G. Hare, D.J. Jeffrey, D.E. Knuth, “On the Lambert W Function”, Advances in Computational Mathematics, vol. 5, 1996, pp. 329–359.

[25] D.A. Barry, J.-Y. Parlange, G.C. Sander, M. Sivaplan, “A class of exact solution for Richards’ equation”, Journal of Hydrology, vol. 142, no. 1-4, 1993, pp. 29-46.

[26] https://sam.nrel.gov/libraries.

[27] S.Lineykin, M.Averbukh, A.Kuperman, An improved approach to extract the single-diode equivalent circuit parameters of a photovoltaic cell/panel, Renewable and Sustainable Energy Reviews, Volume 30, February 2014, Pages 282-289.

[28] Marion, B., Rummel, S. and Anderberg, A. (2004), Current–voltage curve translation by bilinear interpolation. Prog. Photovolt: Res. Appl., 12: 593–607.