Methods for Estimating One-Diode Model Parameters of Photovoltaic Panels and Adjusting to Non-Nominal Conditions

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Abstract—**In this work, we propose a novel method for estimating the one-diode equivalent circuit parameters for photovoltaic (PV) panels in order to obtain accurate current-voltage (I-V) characteristic curves. The performance of the proposed method is compared to those of some works in the literature. We considered as the main comparison parameters the following: root mean square error (RMSE), relative error at the maximum power point and computational processing time. The proposed method provides estimations with low processing time and good precision, the latter being a consequence of a procedure for improving the estimation based on the empirical I-V characteristic curve of the PV panel. Subsequently, we present a new method for adjusting the estimated I-V characteristic curve according to variations in ambient conditions. To this end, we develop a simple representation of the parameter adjustment via an equivalent circuit. The proposed adjustment method accuracy is also compared to those of other methods established in the literature, attaining better performance in terms of RMSE and other error indexes.**

Index Terms—**current-voltage characteristics, equivalent circuits, optimization, parameter estimation, photovoltaic cells.**

I. INTRODUCTION

The uninterruptible growth in the use of alternative energy sources implies the need of using models that support the analysis and design of such sources from the engineering practice viewpoint. In this sense, one of the main resources for modelling solar panels is the photovoltaic cell equivalent circuit. This type of model provides the I-V characteristic curve observed in the cell terminals and, by extension, can be applied to the output terminals of a PV panel, since it can be viewed as a parellel-series associations of individual cells. As in every physical modelling problem, the number of parameters of the equivalent circuit influences the desired precision for a given application. The one-diode model with two resistors is predominantly used in photovoltaic generation studies, which is due to its simplicity and precise reproduction of the I-V characteristic curve [1], [2].

Regarding parameter extraction of PV panel models, the works in the literature usually do not consider possible deviations between the empirical photovoltaic panel data and the nominal datasheet values. In this sense, estimation is usually carried out only in terms of nominal values. In order to mitigate estimation errors caused by this procedure, we propose a novel method for estimating the one-diode model parameters for PV panels. We verify that the proposed method enhances parameter estimation by comparing its error indexes to those of other methods in the literature. We base our method on desirable features for parameter estimation, namely: low processing time and requirement of a small amount of empirical and datasheet input data.

In this paper, we also propose a method for adjusting estimated nominal I-V characteristic curves for non-nominal ambient conditions. Our proposal can be represented by a simple time-varying circuit, which makes it adequate for real time simulations. We also compare the performance of our adjustment approach to those of different methods in the literature, confirming its higher accuracy. The required additional data for adjustment is modest.

This paper is organized as follows. In Section II, we comment on methods recently presented in the literature for estimating one-diode equivalent circuit parameters and adjusting the I-V characteristic curve in terms of ambient conditions. In Section III, we present a novel parameter estimation method that considers discrepancies between nominal and empirical values in order to improve the estimation. We propose, in Section IV, a new algorithm for adjusting the I-V characteristic curve for operation in non-nominal conditions. Our proposal reduces the number of variable parameters and required data, decreasing model complexity as a consequence. In Section V, we compare results obtained via application of the proposed estimation method and other methods in the literature to data concerning the Kyocera KC200GT photovoltaic panel. Similarly, Section VI contains comparisons between results obtained with the application of existing curve adjustment methods and our proposed method. In Section VII, we present final considerations concerning this work and the attained results.

II. RELATED WORKS

The estimation of PV equivalent circuit parameters has been tackled in a variety of recent works, which explore a multidude of different approaches for dealing with the non-linearities, possible approximations and other problems associated to I-V characteristic curve estimation [3-10]. Most works attempt to estimate the one-diode model parameters while restraining the amount of input data to a minimum; this procedure is adequate from a practical standpoint, since methods with few input requirements do not demand many empirical samplings. In fact, the most usual techniques only use the nominal values of notable operation points supplied in panel datasheets, as in [3-7],

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[9]. Methods that use additional data, such as [8], whilst gaining in precision, may require information that is hard to provide. Regarding the estimation procedure itself, a significant fraction of the proposed methods use search-based optimization in order to derive parameter values. This is justified from the fact that nonlinear PV equations permit the isolation of parameters only to a certain point; in this sense, establishing search variables for optimization is reasonable. The main differences between works of this type relate to search dimensionality and adopted variables. In general, one and two-dimensional searches are used. On the other hand, there is great variation in the choice of search variables between estimation works [11-14]. Other works use significantly different estimation techniques. For instance, in [4], [5] the authors propose particle swarm-based procedures in order to conduct parameter optimization, whereas in [9] the authors propose equating the transient response of a first-order linear system to the I-V characteristic curve and estimate the parameters by means of system identification.

Search-based methods are appealing for the present problem due to simple implementation, relatively low computational complexity and their adequacy to problems in which the search space is reasonably well-known [15]. Hence, among the above-mentioned methods present in the literature, we shall focus on comparing [3], [8] to our method, which is similarly search-based.

A complementary problem associated to circuit parameter estimation is the adjustment of the I-V characteristic curve as a function of ambient conditions. The estimation methods provide parameter values that are only valid for given irradiance (S) and temperature (T) values. Therefore, a mechanism for compensating the I-V characteristic curve for non-nominal conditions must be used.

References [3], [10], aside from their main estimation algorithms, also propose parameter adjustment methods. We compare these methods with our own proposal. The method in [3] consists in updating a single parameter in terms of (S,T) via repeated iterations of the main estimation algorithm. On the other hand, the authors in [10] present equations for updating each circuit parameter individually.

III. One-Parameter Search Method for Estimating PV Parameters

The one-diode equivalent circuit is shown in Figure 1. The photogenerated current I_{ph} and the anti-parallel diode D (whose modelling parameters are the ideality factor m and reverse saturation current I_o) establish the non-linearity of the I-V characteristic curve. The resistive elements R_{sh} and R_s account for losses due to leakage currents and cell contact resistance, respectively. The resistor R_{sh} lowers cell output current, whereas R_s decreases output voltage [12]. Thus, it can be seen that five parameters must be estimated for characterizing a given PV panel via the one-diode model.

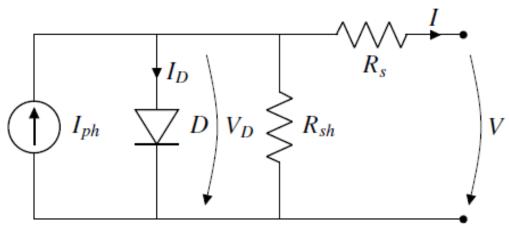

Figure 1. One-diode photovoltaic cell equivalent circuit

By simple manipulations, it is impossible to obtain an explicit analytic solution to the equivalent circuit of the type $I = f(V)$ [16]. This is due to the diode D having a transcendental form $I_D = f(V_D)$ which contains terms in both V and I in its argument. Applying Kirchoff's laws, the following relation of the form $I = f(V, I)$ is obtained:

$$I = I_{ph} - I_o\left[\exp\left(\frac{V + R_s I}{mV_t}\right) - 1\right] - \frac{V + R_s I}{R_{sh}} \qquad (1)$$

The estimation proposed in [3] assumes the only available data are nominal values of voltage and current of open circuit (V_{oc}), short circuit (I_{sc}) and maximum power (V_{mp}, I_{mp}) points. The method is initialized by assuming the approximation $I_{ph} \approx I_{sc}$ and arbitrarily selecting a value for the ideality factor such that $m \in (1, 2)$. Applying $V = V_{oc}$ in (1), the parameter I_o is calculated. Maximum power data is used to express R_{sh} in terms of the remaining parameters. A linear search is then carried out over R_s in order to find the pair (R_s, R_{sh}) that satisfies the maximum power condition. In case the obtained RMSE is not desirable, the authors recommend running the algorithm again with a different assumed m.

The method given in [8] considers that additional information is known, namely one operation point at non-nominal temperature. All data is used in (1) to express all remaining parameters as functions of R_s and m. A two-dimensional search over these parameters is then operated in order to find optimal parameter values.

It can be seen that method [3] has lower complexity and more assumed approximations when compared to [8]. Furthermore, it demands less data for the estimation. We must also observe that these methods only suppose knowledge of nominal values given in the PV datasheet. If a given PV panel has significant mismatch with its nominal data, the estimation error is prone to being increased.

We now proceed to describing our proposed method. In comparison to [3], [8], the required data are nominal datasheet values and a small set of arbitrarily sampled operation points at nominal conditions. Our idea of using both nominal and sampled values is justified due to the following. The use of nominal values is desirable due to their accessibility and representation of an average over all manufactured panels. However, mismatch may occur with individual panels. Hence, we use nominal values in the first step of the estimation and subsequently refine it by considering empirical sampled points.

Let A be the considered set of empirical samples. The only requirement we impose over A is that it must contain empirical open circuit $\left(V_{oc,exp}\right)$ and short circuit points $\left(I_{sc,exp}\right)$, aside from one operating point arbitrarily close to short circuit ($V=\varepsilon$ and $I=I_{\varepsilon}$, ε small).

As an initial estimate, we adopt $I_{ph} \approx I_{sc}$. We then determine the parallel resistance by using the sample points $\left(V=0,\ I=I_{sc,exp}\right)$ and $\left(V=\varepsilon, I=I_{\varepsilon}\right)$ in the following aproximate relation:

$$R_{sh} \approx \frac{\epsilon}{I_{sc,exp}-I_{\epsilon}} \tag{2}$$

We express I_o in terms of the ideality factor and R_{sh}. Introducing the open circuit point $\left(V_{oc}\right)$ in (1), we obtain:

$$I_o = \frac{\dfrac{V_{oc}}{R_{sh}} - I_{ph}}{1-\exp\left(\dfrac{V_{oc}}{mV_t}\right)} \tag{3}$$

Finally, R_s will be expressed as a function of the remaining parameters. To this end, we use two relations pertaining to maximum power point, namely: $\left(VI\right)_{V=V_{mp}} = P_{mp}$ and $[\partial_V\left(VI\right)]_{V=V_{mp}} = 0$, where ∂_V designates differentiation with respect to terminal voltage. The development of these relations yields, respectively, (4) and (5). The nonlinear system composed by these equations must be solved for R_s.

$$V_{mp}\left(I_{ph}+I_o\right) - V_{mp}I_o\exp\left(\frac{V_{mp}+R_sI_{mp}}{mV_t}\right) = \frac{V_{mp}^2+(R_s+R_{sh})P_{mp}}{R_{sh}} \tag{4}$$

$$I_{ph}+I_o-\left(\frac{V_{mp}}{mV_t}+1\right)I_o\exp\left(\frac{V_{mp}+R_sI_{mp}}{mV_t}\right) = \frac{2V_{mp}+R_sI_{mp}}{R_{sh}} \tag{5}$$

Even though the system is nonlinear, R_s can be obtained explicitly. To do so, it is sufficient to isolate the exponential term in both equations and invoke the identity of this term in both obtained relations. Proceeding in this manner, we arrive at the following equation for R_s:

$$R_s = \left(1-\frac{V_{mp}}{mV_t}\right)\frac{mV_t}{I_{mp}} + R_{sh}\left[\frac{I_{ph}+I_o}{I_{mp}} - \frac{mV_t}{V_{mp}}\left(\frac{V_{mp}}{mV_t}+1\right)\right] \tag{6}$$

It can be seen that (3) and (6) can be used, together with a line search in m, to estimate I_o and R_s. In order to reduce complexity, we take advantage of the known fact that, in general, $m \in \left(1,2\right)$ [11]. The adopted search criterion for m is finding the value for which the estimated maximum power point is closer to the nominal P_{mp}, as in [3]. This first step fits the parameters to the nominal values of the PV panel. We now proceed to the second step, in which we improve the estimation using sample set A.

Let $\mathrm{RMSE_A}$ be the root mean square error of the estimated I-V curve in relation to the points of set A. First, the following ratio factor is computed:

$$f_r = \frac{V_{oc,exp}I_{sc,exp}}{V_{oc}I_{sc}} \tag{7}$$

A line search for minimizing $\mathrm{RMSE_A}$ is carried out over R_s, whose present value is used to update R_{sh} by solving (8), which is a modified version of (4) that takes into account deviation between nominal and empirical maximum power:

$$V_{mp}\left(I_{ph}+I_o\right) - V_{mp}I_o\exp\left(\frac{V_{mp}+R_sI_{mp}}{mV_t}\right) = \frac{V_{mp}^2+(R_s+R_{sh})f_rP_{mp}}{R_{sh}} \tag{8}$$

The f_r parameter is an estimate of the ratio between empirical and nominal maximum power values. This is due to the fill factors c_f of the empirical and nominal I-V characteristic curves being approximately equal, since they are referred to the same ambient conditions [16]. Since $P_{mp} = c_fV_{oc}I_{sc}$, it is easy to derive (7) by defining $f_r = P_{mp,exp}/P_{mp}$. Updating R_{sh} via (8) forces the estimation to converge towards the empirical value $P_{mp,exp}$, since we have $P_{mp,exp} = f_rP_{mp}$. After convergence to a minimum of $\mathrm{RMSE_A}$, the estimate of I_{ph} is improved via the following equation, which takes into account current in R_{sh} [3]:

$$I_{ph} = \left(1+\frac{R_s}{R_{sh}}\right)I_{sc} \tag{9}$$

We now summarize the proposed method. In the first step, all parameters are estimated with the use of nominal values found in the PV panel datasheet. This estimation is made by means of a line search over m, in terms of which all other parameters are calculated. The second step consists of using set A in order to improve the estimation by running a new line search over R_s and updating R_{sh}. In other words, the resistive parameters are tuned in order to reduce mismatch between the empirical I-V characteristic curve and nominal values. The procedure can be represented by the following steps:

i. Adopt $I_{ph} \approx I_{sc}$.
ii. Use (2) to estimate R_{sh}.
iii. Do a line search over m, using (3) and (6) in order to compute I_o and R_s. The search stop criterion is obtaining a minimum for maximum power point error.
iv. Use (7) to compute f_r.
v. Do a line search over R_s, using (8) to update R_{sh}. The search stop criterion is obtained a minimum of $\mathrm{RMSE_A}$.
vi. Update I_{ph} by using (9).

It is worthwhile noting that all input data required are easily measurable with an adequate experimental setup. In effect, the required sample points of set A are either arbitrary or easily measurable (open circuit and short circuit points).

IV. A Method for I-V Characteristic Curve Adjustment in Non-Nominal Conditions

The nominal parameters provided in PV panel datasheets are usually referred to operation in Standard Test Conditions (STC), which imply an irradiance level of $S_o = 1000\,\mathrm{W/m^2}$ and cell body temperature of $T_o = 25°\mathrm{C}$ [17]. Hence, the nominal characteristic curve has to be adequately adjusted in arbitrary ambient conditions (S,T). Most works employ equations that directly express dependencies of circuit parameters on S and T. However, the nature of such dependencies and their implementation varies.

The adjustment method proposed in [3] consists in adjusting the single parameter I_o as a function of ambient conditions and repeating the estimation method given in the same work with the updated I_o value. The parameter is updated via (3), by taking into account the irradiance and temperature coefficients for I_{sc} and V_{oc}, respectively. The values of these coefficients are usually given in datasheets.

On the other hand, the procedure given in [10] is based on parameter adjustment equations independent from an estimation algorithm. More precisely, the parameters can be estimated only once for STC conditions and subsequently adjusted via equations given for each parameter. This method also requires temperature and irradiance coefficients.

Comparatively, it is clear that the method in [3] is simpler due to its use of a single equation. However, data requirements are equal for both methods and the one given in [10] has the advantage of being independent of a parameter estimation algorithm. Hence, this method is more adequate for online applications in PV simulations.

Similarly to [10], our proposed method is adequate for online use since it is independent of a given estimation algorithm. Moreover, the number of variable parameters is reduced to three (in comparison to all five parameters in [10]) and the only additional data required is a single non-nominal operation point. Our method consists in a modified version of the procedure given in [18], which we now describe.

The first step in the method proposed by [18] is to update I_{ph} in direct proportion to irradiance and linearly with temperature using the short-circuit current temperature coefficient α given in the datasheet:

$$I_{ph} = \frac{S}{S_o}\left[1+\alpha\left(T-T_o\right)\right] I_{ph,STC} \tag{10}$$

Given the updated value of I_{ph}, an auxiliary I-V curve is obtained with all other parameters unchanged. Finally, the desired I-V curve is obtained by transforming all voltages V_{aux} of the auxiliary curve linearly with temperature, by using the datasheet open circuit voltage temperature coefficient β:

$$V = \left[1+\beta\left(T-T_o\right)\right] V_{aux} \tag{11}$$

The original method leads to significant error for greater voltages, since it assumes the temperature coefficient for all voltage values is equal to the open circuit coefficient. Hence, our proposed modification consists in varying the temperature coefficient linearly with voltage. Assuming linearity is reasonable given that the coefficient must vary in a narrow interval, otherwise the I-V characteristic curve would have significant shape changes for different ambient conditions. As it is known, this is not the case for standard PV panel technology and our assumption is justified.

Let $\beta(V_{oc})$ and $\beta(V^*)$ be the temperature coefficients of open circuit voltage and an arbitrary STC curve voltage, respectively. We assume the linear variation of $\beta(V)$ according to the following relation:

$$\beta(V) = \beta(V^*) + \frac{\beta(V_{oc}) - \beta(V^*)}{V_{oc} - V^*}\left(V - V^*\right) \tag{12}$$

Hence, in order to apply our method, $\beta(V^*)$ must be computed. In order to achieve this, information about one non-nominal operation point is required. Suppose that for an arbitrary output current I^*, the voltage is V^* at STC conditions and V_p^* at non-nominal temperature T_p. It is clear that we can estimate $\beta(V^*)$ by means of the following ratio:

$$\beta(V^*) \approx \frac{V^* - V_p}{T_o - T_p} \tag{13}$$

The variable parameters defined so far are I_{ph} and β. In order to further improve our adjustment method, we define R_{sh} as inversely proportional to irradiance. This irradiance dependence is established in [10], in which negligible temperature dependency of R_{sh} is also verified. Hence, our adjustment procedure is given by three parameters that vary in terms of ambient conditions, namely I_{ph}, β and R_{sh}.

We will show that the variable $\beta(V)$ temperature coefficient can be represented by the addition of a controlled voltage source in tandem with the standard one-diode equivalent circuit. This configuration is illustrated in Fig. 2, where the function $g(\beta, V_x)$ that drives the voltage source must be such that $V = V_x\left[1+\beta\Delta T\right]$, where $\Delta T = T - T_o$ is the temperature deviation from 25°C (STC). Calculating the voltage drop over the controlled source, we have:

$$V - V_x = g(\beta, V_x) \tag{14}$$

Furthermore, let us suppose that $g(\beta, V_x) = g_1(\beta)\Delta V_x$. Applying this in (14), we get:

$$V = \left[1 + g_1(\beta)\right] V_x \tag{15}$$

Comparing (15) with the relation $V = V_x\left[1+\beta\Delta T\right]$, it is clear that we must have $g_1(\beta) = \beta\Delta T$. Hence, the driving function of the controlled voltage source is:

$$g(\beta, V_x) = \beta(V_x)\Delta V_x \Delta T \tag{16}$$

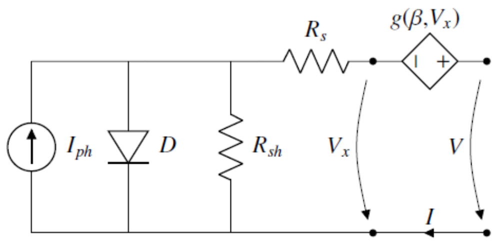

Figure 2. Proposed adjustment method equivalent circuit

Our parameter adjustment method is independent of an estimation algorithm and can be represented by a simple equivalent circuit. These characteristics make it well suited for online use in PV simulations. Furthermore, the number of parameters taken as function of S and T is small and the additional data required for applying the method is modest, being easily obtainable with standard testing equipment.

V. Simulation Results: PV Parameter Estimation

In order to validate the method for estimating one-diode model parameters, we used data pertaining to the KC200GT PV panel [19] for estimation. The results are compared with those obtained via application of the methods in [3] and [8]. We chose this particular PV panel due to its wide consideration in PV parameter estimation works.

The panel datasheet provides the usual nominal data and experimental curves for nominal and some non-nominal conditions. Our procedure consisted in considering the supplied experimental curve as the samplings from which the points of set A are drawn. It is easily seen that mismatch exists between the nominal values and supplied curve [19], which corroborates our estimation approach.

More precisely, we sampled a significant amount of points from the experimental curve in order to compute estimation RMSE. Among such points, a small amount (seven) was chosen to compose set A, as shown in Fig. 3. In Table I, we present the panel datasheet nominal data.

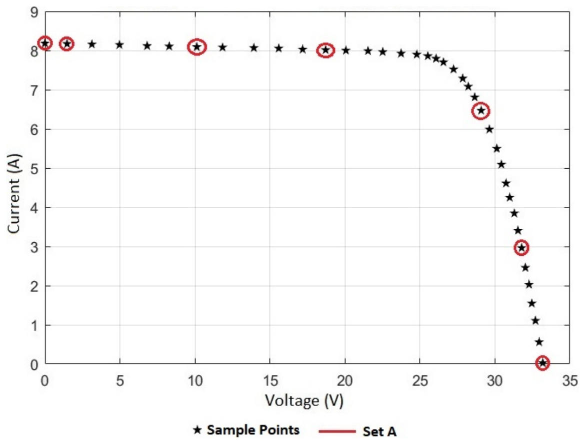

Figure 3. Experimental I-V data for KC200GT panel.

TABLE I. KC200GT PANEL NOMINAL DATA

Parameter	Value
V_{oc}	32.9 V
V_{mp}	26.3 V
I_{sc}	8.21 A
I_{mp}	7.61 A
P_{mp}	200 W

The proposed estimation method was run with line search step sizes for the ideality factor and series resistance equal to, respectively, $\Delta m = 10^{-4}$ and $\Delta R_s = 10^{-3}\Omega$. In Table II, we present the obtained values for the equivalent circuit parameters; also included are parameter values obtained via application of the methods in [3,8].

Aside from RMSE, it is interesting to evaluate the error relative to empirical maximum power point $\Delta P_{mp} / P_{mp,exp}$, where $\Delta P_{mp} = P_{mp} - P_{mp,exp}$, since this is the most important PV panel operation point. Aditionally, we evaluate the normalized root mean square error ξ as defined in [20]:

$$\xi = \frac{\text{RMSE}}{I_{sc}} \tag{17}$$

The obtained error indexes for our estimation and the methods given in [3],[8] are presented in Table III.

TABLE II. ESTIMATED EQUIVALENT CIRCUIT PARAMETERS

Method	m	I_o (nA)	R_s (mΩ)	R_{sh} (Ω)	I_{ph} (A)
Proposed	1.1620	11.03	154.4	175.2	8.2172
[8]	1.2645	56.71	137.4	98.1	8.2215
[3]	1.3000	97.56	230.0	566.9	8.2135

TABLE III. ESTIMATION ERROR INDEXES

Method	RMSE (A)	ξ (%)	$\Delta P_{mp} / P_{mp,exp}$ (%)
Proposed	0.1680	2.05	0.64
[8]	0.1778	2.17	-1.82
[3]	0.3786	4.61	-2.25

The results show that our method provided a more precise estimation of the empirical I-V characteristic curve at nominal conditions. A further comparison can be made in terms of the estimated V_{mp} and I_{mp}. Analogously to ΔP_{mp}, we define estimation errors ΔV_{mp} and ΔI_{mp} and compute their ratio relative to empirical values. The obtained values are given in Table IV.

TABLE IV. ESTIMATION ERRORS AT MAXIMUM POWER POINT

Method	$\Delta V_{mp} / V_{mp,exp}$ (%)	$\Delta I_{mp} / I_{mp,exp}$ (%)
Proposed	0.735	0.532
[8]	1.102	0.798
[3]	3.309	1.330

The values given in Table IV show that our method provided a more precise estimation of the location of the maximum power point in the I-V plane. Precise knowledge of this point is particularly important because it is the ideal operation point for the PV panel.

In Fig. 4, we present the I-V characteristic curves obtained via application of each method, along with the sample points taken from the empirical curve for RMSE computation. The corresponding graphs of absolute current error as a function of voltage are shown in Fig. 5 for each estimation method.

In terms of computational complexity, all considered methods require negligible time for execution (in the order of milliseconds). In order to compare these methods, we registered their run times in the same standard desktop computer. The obtained values are shown in Table V.

TABLE V. ALGORITHM EXECUTION TIME

Method	Time (ms)
Proposed	46
[8]	122
[3]	7

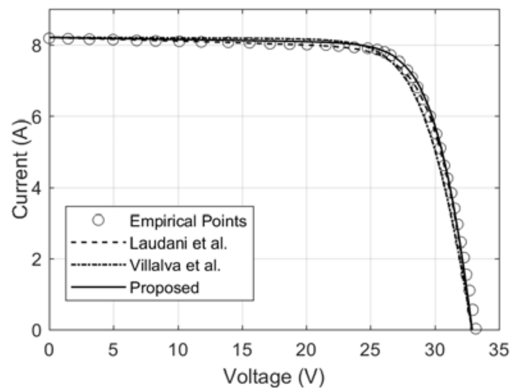

Figure 4. Different estimations for the nominal I-V characteristic curve

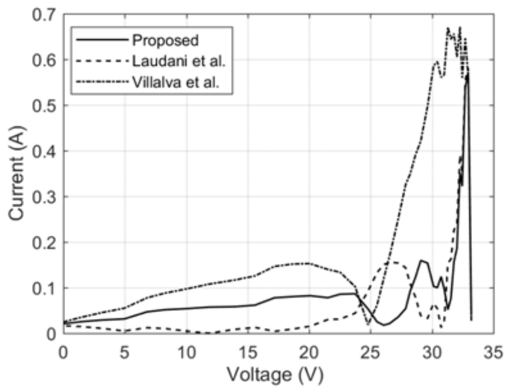

Figure 5. Corresponding error curves for estimations given in Fig. 4

The lower execution time obtained with [3] is expected, since this method consists in a single line search. On the other hand, the greater complexity of [8] is explained by its use of a two-dimensional search for optimizing RMSE. Since our method comprises two consecutive linear searches, its mid-term execution time is a reasonable result.

In regards to the proposed method, it is interesting to note that the first line search in m already places resistive circuit parameters close to their optimal values. Therefore, the domain explored in the second search is not extensive. To illustrate this, we present in Fig. 6 the trajectory verified in the R_s - R_{sh} plane during the estimation process.

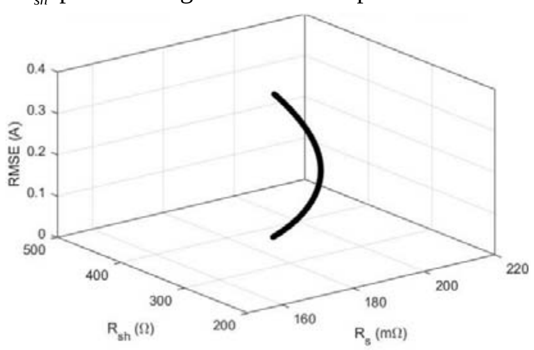

Figure 6. Search trajectory for parameters R_s and R_{sh}

VI. Simulation Results: Parameter Adjustment

In order to validate the adjustment method, we sampled experimental I-V curves supplied in the KC200GT datasheet and used the sample points to compute RMSE of the obtained curves. We applied the proposed adjustment on the PV parameters obtained with our estimation method. The results are compared with those obtained by applying adjustment methods proposed in [3], 10].

The adjustment in [3] is designed to be used in combination with the estimation method proposed in the same work. On the other hand, the adjustment method given in [10] is independent of the considered estimation. For this reason, we opted for applying the method in [10] to the parameters obtained with our proposed estimation method.

The conditions considered were $S \in \{200,600\}\left(\mathrm{W/m^2}\right)$ with nominal temperature and $T \in \{50,75\}\left(°\mathrm{C}\right)$ with nominal irradiance.

In Table VI, we present KC200GT datasheet values for the short-circuit current and open-circuit voltage temperature coefficients, α and β. We estimated the voltage temperature coefficient for $V^* = 28\,\mathrm{V}$ by using (13) and it is also given in Table VI. This value was used to implement (12).

TABLE VI. KC200GT PANEL TEMPERATURE COEFFICIENTS

Coefficient	Value (%)
α	0.0387
β	-0.3739
$\beta\left(V^*\right)$	-0.5714

By applying our method, we obtained the I-V characteristic curves presented in Figs. 7 and 8, in which sample points from the empirical curves are also shown in order to illustrate method accuracy. For the sake of completeness, we also include estimated curves and samples for nominal conditions.

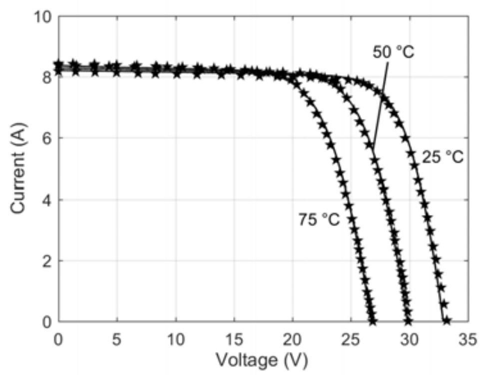

Figure 7. Obtained I-V characteristic curves for non-nominal temperatures

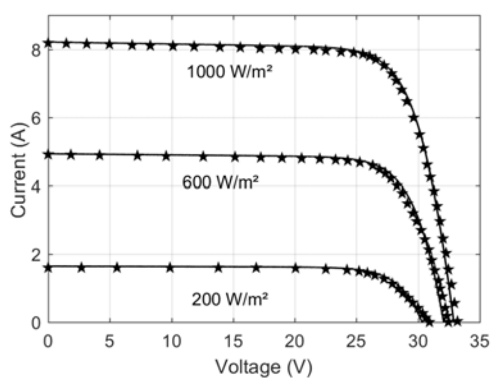

Figure 8. Obtained I-V characteristic curves for non-nominal irradiances

In order to compare our proposal with methods [3,10], we present in Figures 9 to 16, for each considered non-nominal condition, the I-V characteristic curves and error curves obtained via application of each method. The corresponding error indexes are given in Tables VII to X.

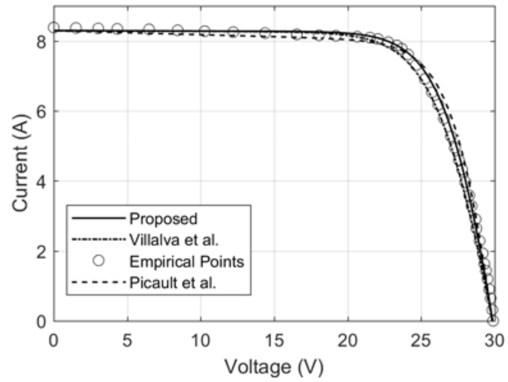

Figure 9. Obtained I-V characteristic curves for $T = 50°\text{C}$

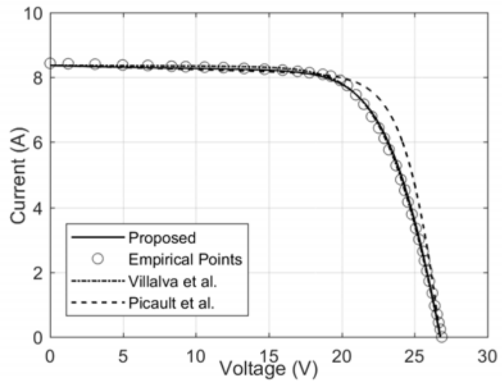

Figure 10. Obtained I-V characteristic curves for $T = 75°\text{C}$

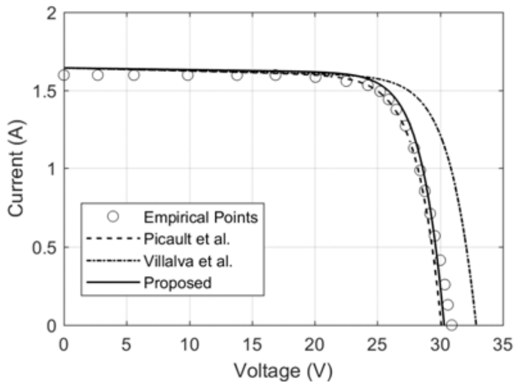

Figure 11. Obtained I-V characteristic curves for $S = 200W / m^2$

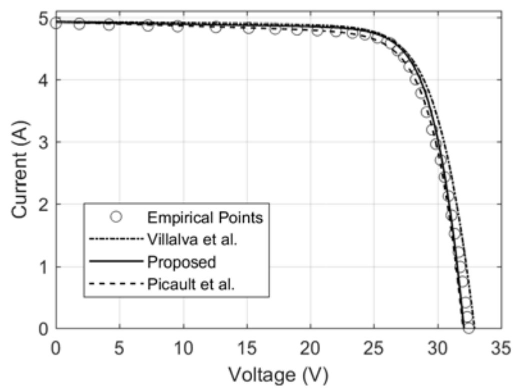

Figure 12. Obtained I-V characteristic curves for $S = 600W / m^2$

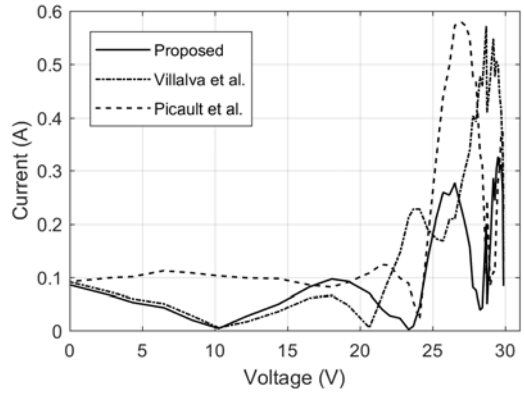

Figure 13. Obtained error curves for $T = 50°\text{C}$

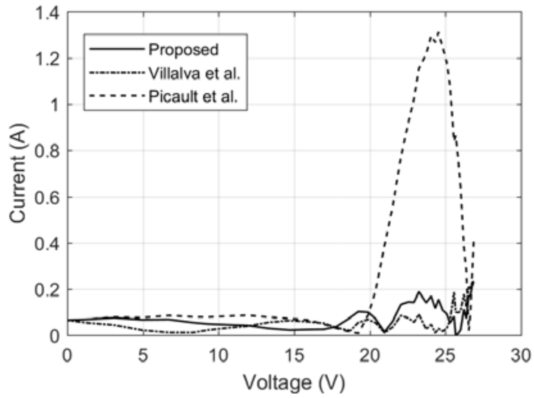

Figure 14. Obtained error curves for $T = 75°\text{C}$

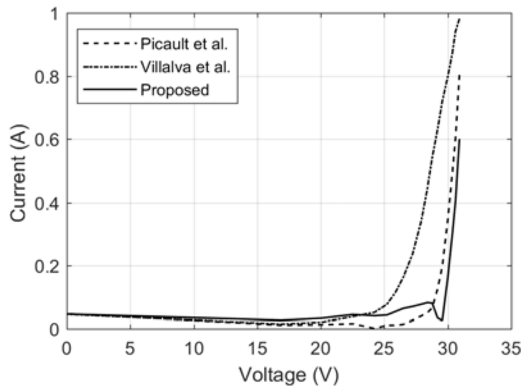

Figure 15. Obtained error curves for $S = 200W / m^2$

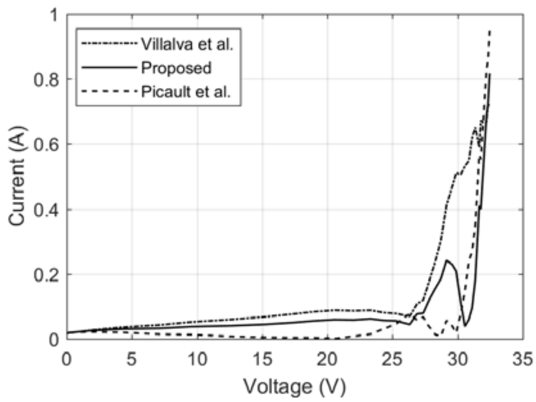

Figure 16. Obtained error curves for $S = 600W / m^2$

TABLE VII. ESTIMATION ERROR INDEXES FOR $T = 50℃$

Method	RMSE (A)	ξ (%)	$\Delta P_{mp} / P_{mp,exp}$ (%)
Proposed	0.1687	2.01	0.61
[10]	0.2891	3.44	0.02
[3]	0.2964	3.53	2.88

TABLE VIII. ESTIMATION ERROR INDEXES FOR $T = 75℃$

Method	RMSE (A)	ξ (%)	$\Delta P_{mp} / P_{mp,exp}$ (%)
Proposed	0.0997	1.37	0.13
[10]	0.6612	7.87	5.60
[3]	0.0955	1.13	-0.61

TABLE IX. ESTIMATION ERROR INDEXES FOR $S = 200\text{W}/\text{m}^2$

Method	RMSE (A)	ξ (%)	$\Delta P_{mp} / P_{mp,exp}$ (%)
Proposed	0.1769	11.52	0.96
[10]	0.2564	15.08	0.70
[3]	0.4715	27.73	9.29

TABLE X. ESTIMATION ERROR INDEXES FOR $S = 600\text{W}/\text{m}^2$

Method	RMSE (A)	ξ (%)	$\Delta P_{mp} / P_{mp,exp}$ (%)
Proposed	0.2764	5.46	1.21
[10]	0.3302	6.74	1.65
[3]	0.3964	8.09	1.89

The obtained results show that, in general, our proposed adjustment method yielded either lower or approximately equal error indexes in relation to the other methods.

A further advantage of the proposed method suggested by the results is greater estimation consistency, since our proposal presented the least variation of error indexes among different ambient conditions when compared to the other evaluated methods. This result, combined with the simple nature of the method and the fact that it does not impose strict input data requirements, lead us to believe it can be an useful alternative for running dynamic PV simulations after the parameters for STC conditions are determined with our proposed estimation method.

VII. CONCLUSION

In this work, we presented a new method for estimating equivalent circuit parameters for the one-diode PV model. Furthermore, we proposed a new procedure for adjusting the estimated STC current-voltage characteristic curve for arbitrary ambient conditions. The proposed methods have shown to be advantageous in terms of precision, ability of fitting to empirical values and simple data input. We have compared the performance of our method with those of recent works via simulation aided by data pertaining to the Solarex KC200GT solar panel. All methods were compared in terms of their estimation error indexes for various ambient conditions. In general, our proposed methods provided higher precision and estimation consistency.

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