Modeling I-V Curves of Photovoltaic Modules at Indoor and Outdoor conditions by using the Lambert function

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Abstract

Accurate and robust modeling of the characteristic I-V curve of a photovoltaic module is essential in many applications focused on forecasting and predicting photovoltaic (PV) performance. The single diode equivalent model has been used extensively for representing the working principles of solar cells. This work presents a simple methodology for solving the single diode equation from the manufacture's datasheet parameters, by combining the Lambert-W function and an iterative procedure on the ideality factor of the diode, which has a fast convergence and robustness. The model has been assessed by comparing with experimental I-V curves measured for different modules at indoor and outdoor conditions with good results. Sensitivity analysis has been also done to indicate the possible impact of the uncertainty of the initial parameters that input the model.

Keywords: PV modeling, I-V curve, indoor and outdoor conditions

1. Introduction

The global installed capacity of photovoltaic systems was over 400 GW at the end of 2017. According to recent IEA PVPS reviews, PV is entering a new era due, in a large extend, to the leadership of Asian countries and thus a growing penetration of PV systems is expected in the next few years (IEA-PVPS, 2018). In this context PV performance and reliability modeling is significantly important since system investment risks depend largely on the prediction of the field. This importance has been recently manifested by the organization of the first PV

Performance Modeling Workshop hosted by Sandia National Lab (Stein and Farnung, 2017). Sandia National Laboratory has been promoting a collaborative framework for improving the accuracy of PV performance models, denoted as PVPMC (PV Performance Modeling Collaborative, https://pvpmc.sandia.gov/). Under this framework workshops and meetings are regularly organized, and tools and resources are freely offered as well. The PV LIB tool is a good example of a collection of functions for modeling PV performance that is gaining visibility and users (Andrews et al., 2014; Holmgren et al., 2015).

The working of a solar cell is completely characterized by the relationship between the current generated and the voltage applied, denoted as the I-V characteristic curve. In modeling the behavior of PV cells, modules or arrays there are generally three main kinds of model approaches: the equivalent circuit diode models, the semi-empirical models and the simple efficiency approach. The equivalent circuit diode models consist of representing the PV generator with a diode equivalent circuit and solving the current-voltage characteristic equation; this is the case of the California Electrical Commission Model (De Soto et al., 2004; Dobos, 2012). The semi-empirical models use empirical correlations to extrapolate the specific points of the I-V curve to other temperature and irradiance conditions. Sandia Array Performance Model (SAPM) is the best known example of semi-empirical model (King et al., 2016, 2004; Peng et al., 2015). PVWatts is the most exponent of the third group of models (Dobos, 2014). Several assessment and comparison works on the performance of the different kind of models can be found elsewhere (Gurupira and Rix, 2017; Stein et al., 2013).

The diode equivalent circuit model, single or double diode versions, has been used extensively in the literature (Celik and Acikgoz, 2007; Ciulla et al., 2014; Khezzar et al., 2014; Mares et al., 2015a; Nassar-Eddine et al., 2016; Rhouma et al., 2017). In this work an iterative method combined with the Lambert W-function is presented for solving the five parameters in the single diode equation method. The Lambert W-function is defined as the function that solves the equation

$$W\,e^{W} = z \tag{1}$$

where z is a complex number. The Lambert W-function has been extensively applied not only in PV modeling but also in other problems in physics and computer science (Valluri et al., 2000; Veberič, 2012). Solving delay differential equations, fracture growth dynamics and Wien's displacement law are a few examples of additional applications of Lambert W-function. Many other examples can be found elsewhere (Kazakova et al., 2010).

The methodology is used for the modeling of the I-V curves of PV modules of different technologies from the basic information provided in the manufacturer's datasheet. Even though the methodology is iterative, the approach presented in this paper is of fast convergence, robust and highly accurate. In addition, the I-V curves are modeled for different temperature and irradiance conditions both indoor and outdoor. The assessment of the methodology with experimental I-V curves at STC (Standard Test Conditions) and different temperature and irradiance conditions has shown good results. However, the sensitivity analysis also presented in this work evidenced that the accuracy of the methodology is partially conditioned by the uncertainty in the input parameters used by the model. Finally, the methodology showed robustness in extrapolating the curves beyond STC. The results demonstrated the equivalence between extrapolating the datasheet parameters to temperature and irradiance to solve afterwards the diode equation, and solving the diode equation at STC and extrapolating afterwards the five parameters to temperature and irradiance different conditions.

2. Methodology for computing the I-V curve

It is widely known that the behavior of a photovoltaic cell can be modeled with an equivalent electrical circuit, frequently referred to as the diode equivalent circuit model (Green, 1981). One of the most recognized approaches for diode equivalent circuits is the five parameter model, which represents the PV cell by a circuit with one diode and two resistances (Fig 1). The single-diode circuit equation for the five parameter model is (De Soto et al., 2006),

$$I = I_L - I_0 \left[exp\left(\frac{V+IR_s}{N_s a\, V_T}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (2)$$

where the aforementioned five parameters are: I_L is the photocurrent, I_0 is the reverse saturation current of the diode, R_s is the series resistance, R_{sh} is the shunt resistance, and a is the ideality factor of the diode. N_s is the number of series-connected cells in the module, and V_T is:

$$V_T = \frac{k\, T_{cell}}{q} \quad (3)$$

being T_{cell} the temperature of the cell, k is the Boltzmann's constant and q is the electron charge.

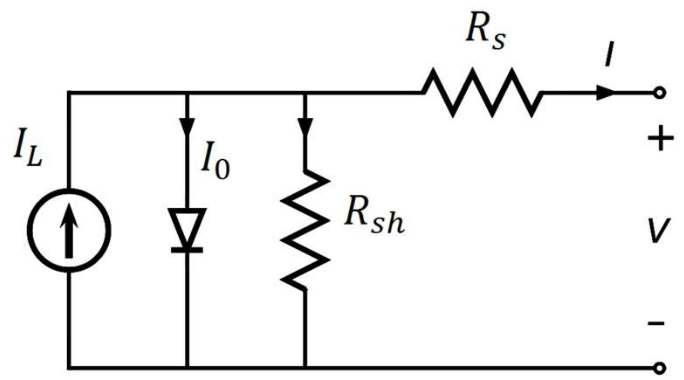

Fig 1. Single-diode equivalent circuit of a solar cell.

Equation (2) is a non-linear function of the current and voltage, and thus the solution is not straightforward and unique either. Different methods and approaches for solving the diode equation can be found elsewhere (Ayodele et al., 2016; Et-Torabi et al., 2017; Ghani et al., 2014; Mares et al., 2015b; Sudhakar Babu et al., 2016). In the case of having a prior estimation of the parameter a, it is possible to determine the other four parameters in a simple and straightforward way using the Lambert W-function by a set of equations recently proposed by Cubas et al. 2014 from the prior knowledge of the module's characteristic parameters (short-circuit current I_{sc} , open-circuit voltage V_{oc} , and maximum power current and voltage I_{mp} and V_{mp}). This method proposes the use of the Lambert W-function to obtain the series resistance first and then computing the remaining three parameters from explicit equations that can be derived from the five parameter model (Cubas et al., 2014). This method presented a good response in modeling the five parameters at Standard Test Conditions (STC) for two multi and mono-crystalline silicon modules (Cubas et al., 2014). However, the methodology is limited by the fact of that it requires a previous knowledge of the ideality factor. In order to overcome this limitation, an interactive method on the ideality factor is proposed here for solving the five parameters of the diode equivalent circuit. The iteration runs on the ideality factor being increased by steps of δ=0.1 as long as the resistances get positive values. The convergence criterion is reached when the series or the shunt resistance values resulting from solving the equations take a negative value, when the iteration stops and the last previous values of both resistances are taken as the best estimate ones. A similar convergence criteria applied only to the shunt resistance was recently proposed for extracting the value of the ideality factor (Rasool et al., 2017). This convergence criterion is very fast and the number of iterations was less than 50 in all the cases explored in this work. Figure 2 shows a flow diagram of the algorithm proposed here.

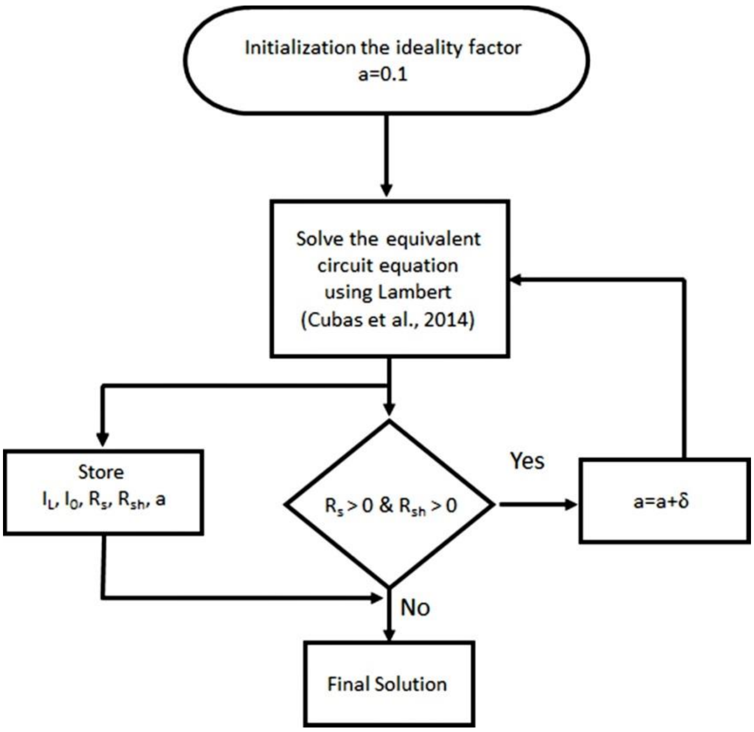

Fig 2. Flow diagram of the algorithm proposed for solving the diode equivalent circuit equation.

Once the five parameters are determined, the I-V curve can be estimated by solving again the diode equation. For instance, the PV LIB tool (open source library of functions for modeling PV systems released by Sandia National Lab) includes a procedure for computing the I-V curve by solving the diode equation using the Lambert W-function (Andrews et al., 2014; Holmgren et al., 2015; Jain, 2004).

There are several formulations to describe the variations of the five parameters with irradiance and temperature as a function of the parameters at STC that can be used for extrapolating the I-V curve to outdoor conditions. The De Soto equations used in this work are (De Soto et al., 2006):

$$I_L(G,T_{cell}) = \frac{G}{G_0}\left(I_{Lstc} + \alpha_{I_{SC}}(T_{cell} - T_{stc})\right) \quad (4)$$

$$I_0(G,T_{cell}) = I_{0stc}\left[\frac{T_{cell}}{T_{stc}}\right]^3 exp\left[\frac{1}{k}\left(\frac{E_g(T_{stc})}{T_{stc}} - \frac{E_g(T_{cell})}{T_{cell}}\right)\right] \quad (5)$$

$$E_g(T_{cell}) = E_g(T_{stc})(1 - \delta_{Eg}\,(T_{cell} - T_{stc})) \quad (6)$$

$$R_{sh}(S) = R_{sh\_stc}\left(\frac{G}{G_0}\right) \quad (7)$$

$$a = a_{stc}\,\frac{T_{cell}}{T_{stc}} \quad (8)$$

Where G is the outdoor irradiance, G_0 is the irradiance at STC (1000 W m^{-2}), $\alpha_{I_{SC}}$ is the short-current temperature coefficient, T_{cell} is the cell temperature, T_{stc} is the reference temperature (25 °C), E_g is the energy band gap, δ_{Eg} the temperature dependence of the energy band gap, and the subscript *stc* denotes standard test conditions.

An additional approach to extrapolate the I-V curve to outdoor conditions is to calculate the variation of irradiance and temperature for the manufacturer parameters and use again the method proposed in Fig 2 for solving the diode equation and retrieving the five parameters. Thus, for the short circuit, open voltage and maximum power current and power the corrected parameters can be calculated by (De Soto et al., 2004; Kessaissia et al., 2015; Khezzar et al., 2014):

$$I_{SC}^{corr} = I_{sc}\frac{G}{G_0} + \alpha_{I_{SC}}(T_{cell} - T_{stc}) \quad (9)$$

$$V_{oc}^{corr} = V_{oc} + N_s\, a\, V_T \ln(\frac{G}{G_0}) + \beta_{V_{oc}}(T_{cell} - T_{stc}) \quad (10)$$

$$I_{mp}^{corr} = I_{mp}\frac{G}{G_0} + \alpha_{I_{SC}}(T_{cell} - T_{stc}) \quad (11)$$

$$V_{mp}^{corr} = V_{mp} + N_s\, a\, V_T \ln(\frac{G}{G_0}) + \beta_{V_{oc}}(T_{cell} - T_{stc}) \quad (12)$$

Where N_s is the number of series-connected cells in the module, a is the ideality factor and $\beta_{V_{oc}}$ is the temperature coefficient for the open circuit voltage.

3. Assessment of modeling I-V curves at indoor standard test conditions

The evaluation of the modeling was performed by collecting and using experimental I-V curves for several modules measured at Ciemat PV Lab in previous projects and tests. Thus, indoor measurements of I-V curves of modules of several technologies had been performed at Ciemat in a large-area solar simulator type one-pulse-flash (pulse times of 10 ms) and class AAA (IEC 60 904-9). All measurements were performed at temperature and irradiance values nearly to STC (1000 ± 5 W/m2 and 25 ± 2° C). Temperature and irradiance corrections were negligible because the test values were nearly STC ones. In addition, no spectral corrections were performed. Table 1 shows the manufacturer parameters for six different modules of monocrystalline silicon (m-Si), multicrystalline silicon (mc-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium selenide (CIS), measured in the solar simulator.

Table 1. Manufacturer data for different technology modules.

Module Technology	N_s	Power (W)	I_{mp} (A)	V_{mp} (V)	I_{sc} (A)	V_{oc} (V)
CdTe	154	80	1.58	50.7	1.76	61.7
CIS	56	80	2.29	35.0	2.50	44.0
m-Si Back-Contact	72	238	5.88	40.5	6.25	48.5
a-Si	159	85	0.87	97.7	1.10	136.5
mc-Si Atersa	72	180	5.00	36.1	5.20	44.3
mc-Si Yingly	60	265	8.70	30.5	9.18	37.8

For each module, the procedure detailed in section 2 has been followed to compute the I-V curve at STC from the manufacturer's parameter values. The five parameters estimated by the model are listed in Table 2 for the six PV modules. Figure 1 shows the I-V curve calculated by the model from the manufacturer initial parameters compared to the experimental curve measured at the flash simulator. The results are very accurate in the Si modules and worse in the case of thin film modules. For CdTe and CIS modules the modeled I-V curves were very close to the experimental ones, but their open circuit voltages were underestimated. In the case of the a-Si module, significant differences were found due to large differences in the initial parameters used. It has to be noticed that the measured I-V curve showed in figure 3 is the measurement of the module when delivered, previous to the initial degradation and stabilization of a-Si that is normally taken into account in manufacturer module parameters (Kroposki, 1997; Sanchez et al., 2014). However, in order to ensure that the differences were not attributed to the algorithm it was proven that the model reproduced perfectly the experimental I-V curve of a-Si when measured parameters were used: $I_{mp} = 1.008\ A$, $V_{mp} = 115.79\ V$, $I_{sc} = 1.16\ A$ and $V_{oc} = 145.67\ V$. These parameters have been measured for the a-Si module experimentally with flash simulator and showed important differences to the manufacturer data listed in table 1. In case of using these measured parameters instead of those of table 1 the I-V curve measured is perfectly reproduced by the model. It must be pointed out that this difference cannot be attributed to the manufacturer since the module was measured in Ciemat PV lab before illumination and thus without taking into account the natural light-induced degradation effect (Staebler-Wronski effect) which is usually accounted in the manufacturer data.

Table 2. Five parameters estimated by modeling and solving the single diode equation.

Module Technology	a	I_L (A)	I_0 (A)	R_s (Ω)	R_{sh} (Ω)
CdTe	1.05	1.76	6.012e-7	0.118	929.5
CIS	2.1	2.50	1.182e-6	0.639	8.644e+3
m-Si Back-Contact	1.3	6.25	1.087e-8	0.192	3.513e+3
a-Si	5.7	1.1	0.003	0.047	3.298e+3
p-Si Atersa	0.65	5.20	5.181e-16	0.831	2.880e+3
p-Si Yingly	0.95	9.18	5.652e-11	0.336	1.605e+3

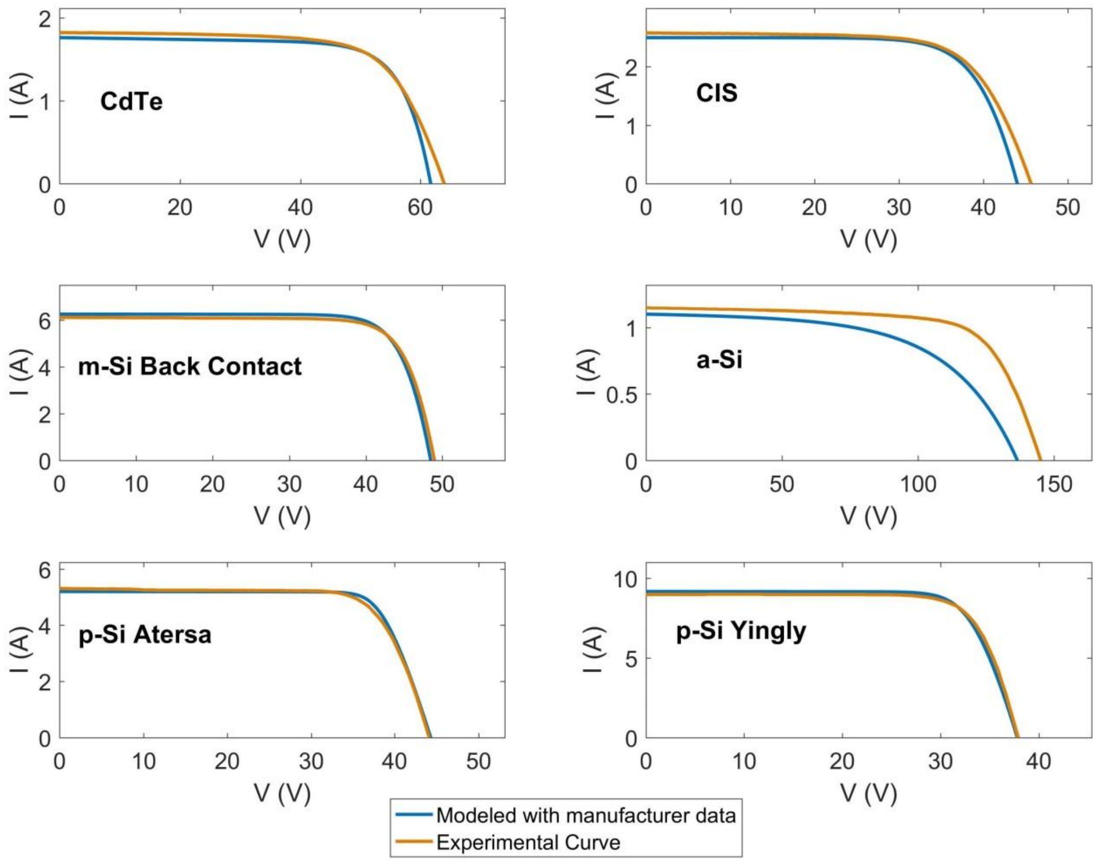

Fig. 3. Comparison of the I-V curves modeled and measured at STC.

In order to compare the methodology for different temperature and irradiance at indoor conditions, several measurements were performed at CIEMAT with the solar simulator for a mc-Si module of Yingly Solar. Module temperature was ranged from 20 °C to 44 °C and solar irradiance from 200 to 950 W m^{-2}. The diode equation was solved using the procedure described in section 2, iterating the ideality diode factor and solving the equation by the Lambert-W function for estimating the five parameters at STC. Then the five parameters were extrapolated to the temperature and irradiance conditions by the equations (4-8), here referred to as first procedure. At each temperature and irradiance condition the I-V curve as well as the maximum power were estimated. Figure 4 shows a scatter plot of the maximum power at different temperatures and solar irradiances with excellent agreement with the maximum power extracted from the experimental I-V curve (the root mean squared error between modeled and experimental maximum power was 0.45 W, representing 0.22%). In addition, in the case of the second procedure for extrapolating to temperature and irradiance conditions beyond STC, equations (9-12) have been used to extrapolate the short circuit current, open circuit voltage and the maximum power according to the temperature and solar irradiance established in the simulator, and for every new situation the single diode model was solved using the procedure described in this work. The resulted new I-V curves were nearly identical to those obtained by correcting the five parameters. The root mean error of the maximum power from the I-V curves using the second approach was 0.46 W, i.e. practically the same than the first approach.

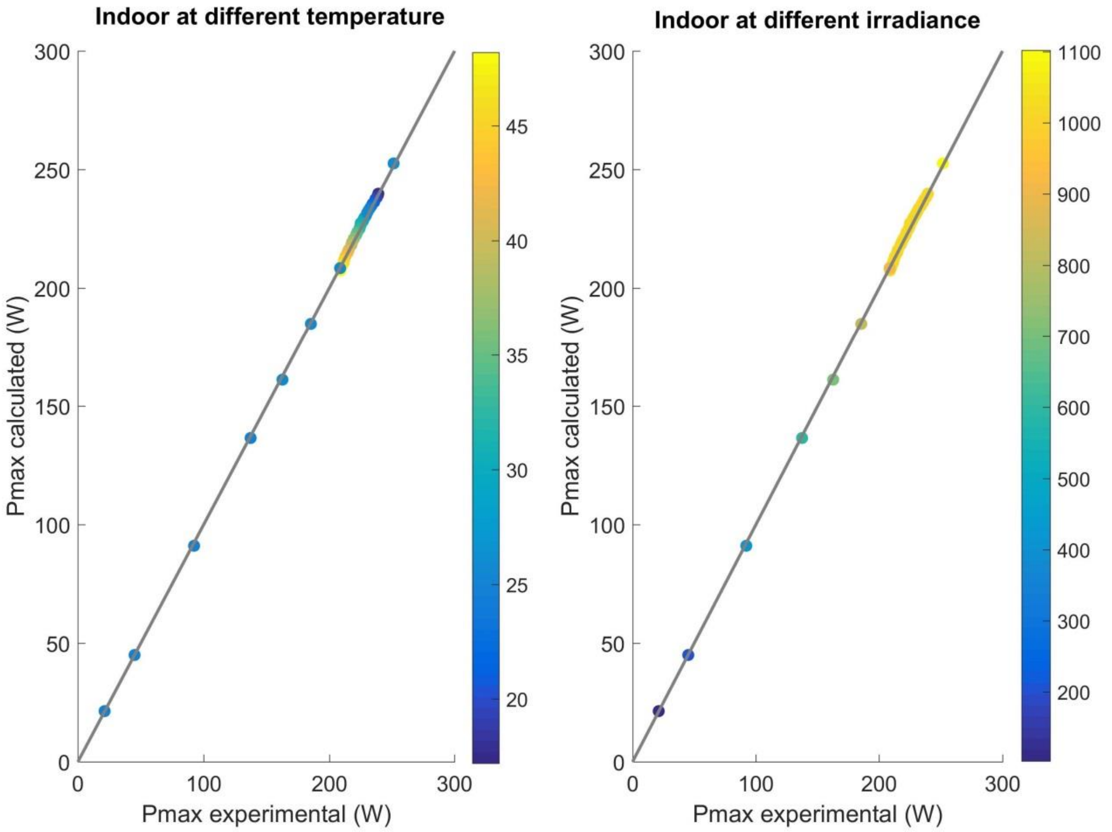

Fig. 4. Scatter plots of maximum power at different indoor temperature and irradiance conditions for a p-Si module (Yingly 230-P).

4. I-V curve at outdoor conditions

In order to explore the approach for modeling the IV curve in outdoor conditions three modules have been monitored during one day (3rd September 2018). The modules tested were all of m-Si technology south oriented and with a tilt angle of 30°. The experimental IV curve is measured around every 8 minutes using I-V-curve measuring device PVPM2540C manufactured by PVE Photovoltaik Engineering. For monitoring the I-V curves and other parameters in a continuous manner, a specific commutation system was mounted for driving the signal sequentially to the every module after each measurement. Irradiance at the plane of the array was measured with a calibrated solar cell, and the temperature of each module was measured with a thermocouple on the back side. Manufacturer data for each module are listed in table 3. Figure 5 illustrates the plane of array (POA) irradiance and the module temperature measured for the Photowatt module during a whole day.

Table 3. Manufacturer data for three monitored m-Si modules, with the same number of cells in series.

Module	N_s	Power (W)	I_{mp} (A)	V_{mp} (V)	I_{sc} (A)	V_{oc} (V)
Panasonic HIT	72	225	5.21	43.2	5.54	52.4
Photowatt PW1650	72	165	4.80	34.3	5.10	43.2
EGNG EGM180	72	180	5.12	35.1	5.54	44.3

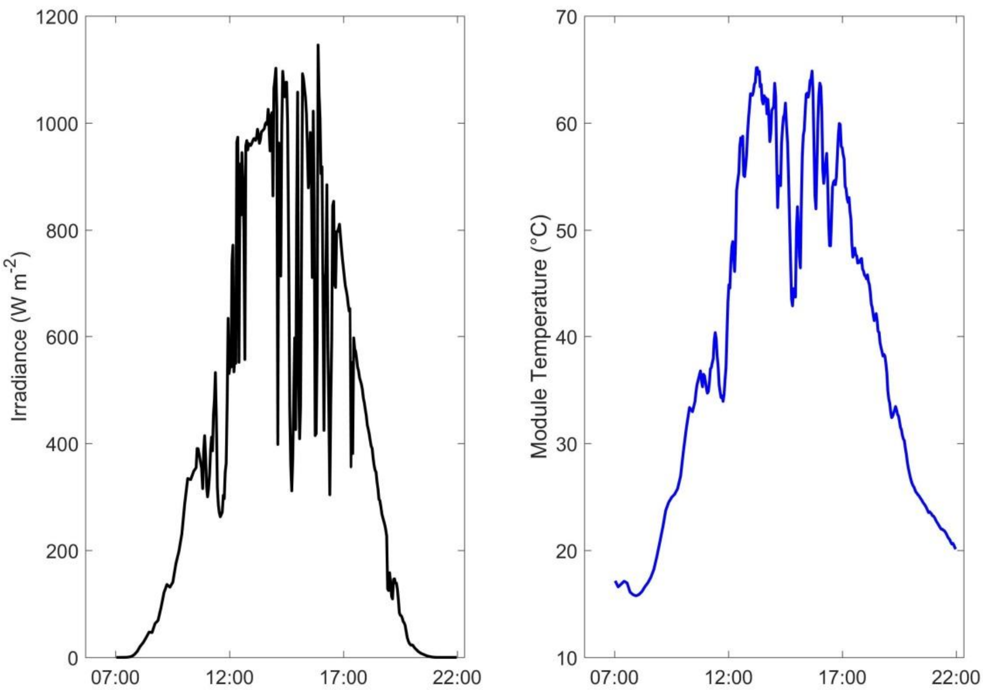

Fig. 5. POA irradiance and module temperature recorded for a Photowatt module on 3th September 2018.

For each module and timestamp the POA irradiance and the module temperature have been used to derive the corresponding I-V curve at outdoor conditions using the two procedures described in this paper: modeling the five parameters from the simplified diode equation at STC from the manufacturer data and extrapolating the parameters to outdoor conditions, and extrapolating the manufacturer data to outdoor conditions and solving the simplified diode equation for the new extrapolated initial parameters. Instead of comparing the experimental and calculated I-V curves each other the maximum power has been obtained from the I-V experimental and modeled curves for the comparison. Figure 6 and 7 shows the scatter plots of the maximum power obtained by the first and the second procedure, respectively.

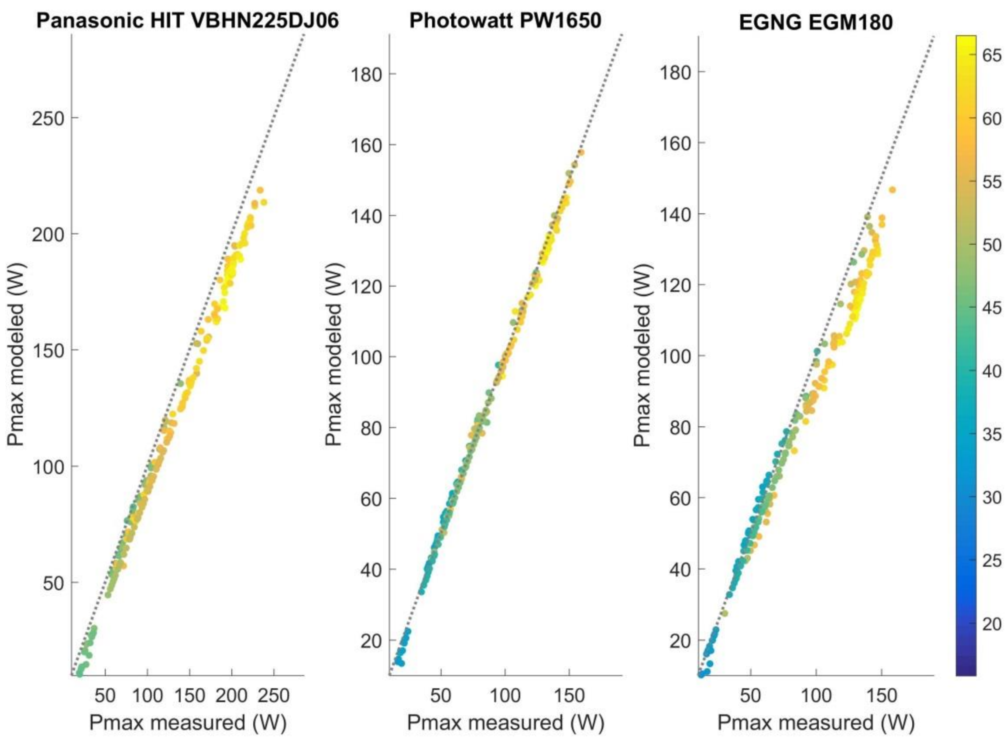

Fig. 6. Scatter plots of maximum power points taken from the I-V curves of three m-Si modules modeled by the first procedure.

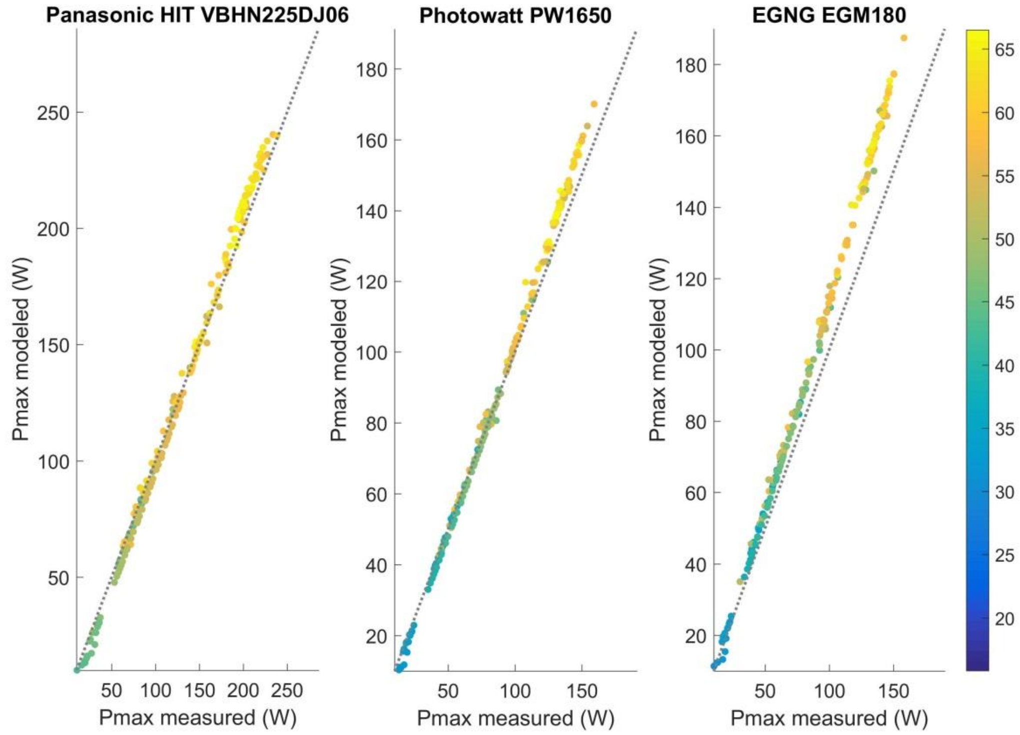

Fig. 7. Scatter plots of maximum power points taken from the I-V curves of three m-Si modules modeled by the second procedure.

The results for outdoor conditions are good in general terms; however they show some differences among the different modules. The highest accuracy was found for the case of Photowatt module. Additional differences were also found in the results of extrapolating to outdoor conditions with first and second procedure described in the methodology section. Since the methodology has proven to be very accurate at indoor conditions, where module temperature and solar irradiance were accurately controlled, the differences observed in the outdoor conditions tests could be attributed to the impact of the uncertainty in the input parameters on the modeled I-V curve. In outdoor conditions the uncertainty of the input parameters can be divided in two groups: the uncertainty in the manufacturer datasheet parameters and the uncertainty in the environment measurements (particularly the module temperature and the solar irradiance at outdoor conditions). In addition, other sources of uncertainty can arise in the outdoor conditions such as soiling, angular and spectral effects, whose impact is difficult to be determined when input and boundary parameters have an unknown level of uncertainty.

In order to investigate the impact of the uncertainty in the manufacturer datasheet parameters in the methodology for modeling the I-V curve, sensitivity analysis were performed using the proposed model with the datasheet parameters of the Photowatt module. Assuming that the manufacturer data in table 3 for the Photowatt module are perfectly accurate the sensitivity analysis of the model was performed by perturbing artificially all the input parameters at different levels of uncertainty. For a range of 0-20% of uncertainty (i.e. from 20% underestimation to 20% overestimation in all the input parameters) the methodology was followed to compute I-V curve at STC conditions. Figure 8 shows the uncertainty (in terms of relative absolute deviation) in the maximum power of the modeled I-V curve as a function of the uncertainty in the input parameters, in other words it shows the sensitivity of the model to the uncertainty of the input. The results show that the errors have a linear propagation in the model for computing the I-V curve. However error in the maximum power increases slightly for larger errors in the input parameters. Thus, a 20% of overestimation in the input parameters resulted in near a 45% of overestimation in the maximum power, and conversely an underestimation of 20% in the input parameters resulted in underestimations of around 35% of the maximum power.

The extrapolation of the uncertainty due to inaccurate values of the manufacturer datasheet parameters to different temperature and irradiance conditions is complex because the different sources of uncertainty cannot be easily separated, at least in the experimental conditions available to the outdoor tests in this work. Therefore, a new sensitivity analysis was done for the case of very well controlled temperature and irradiance conditions. This new study consisted on using the flash I-V curves measured at different and controlled temperature and irradiance values for the Yingly 230-P module. Since the results of modeling I-V curve at different temperature and irradiance for this module were very accurate (Figure 4), it was assumed that the manufacturer data were perfectly accurate and the I-V curves were modeled again increasing and decreasing the input parameters by a 10%. Figure 9 shows the scatter plots for the maximum power obtained from the computed I-V curves.

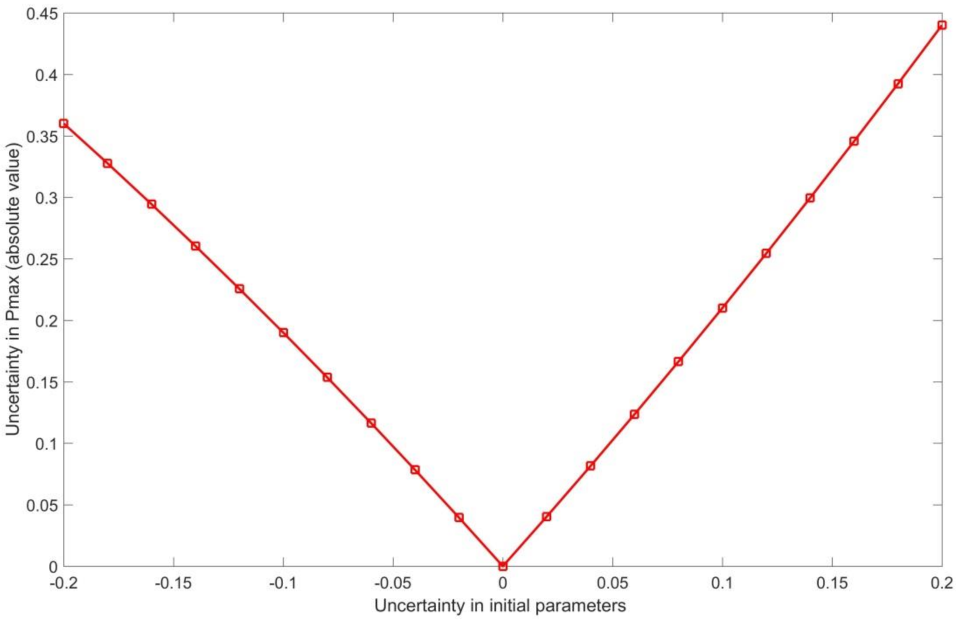

Fig. 8. Propagation of the uncertainty in the input parameters

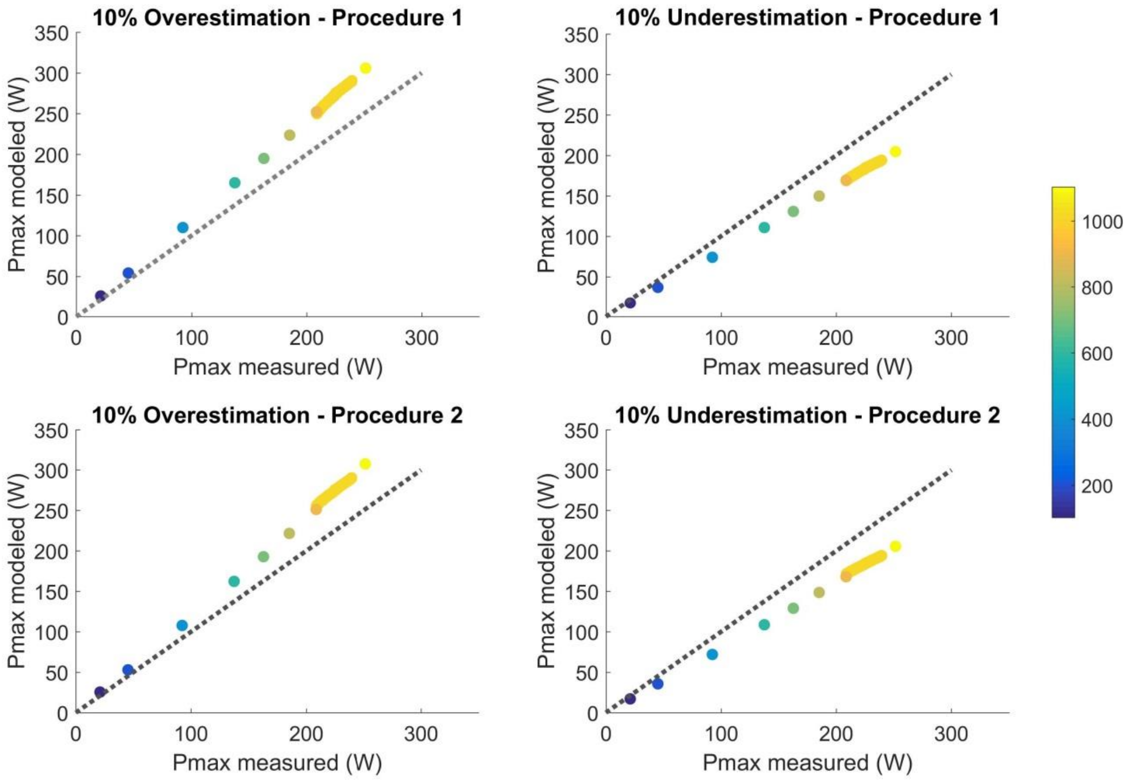

Fig. 9. Sensitivity in the modeled maximum power to irradiance and temperature for a 10% of uncertainty in the input parameters for Photowatt module.

As expected the overestimation in the input parameters of the model resulted in overestimation of the maximum power and, conversely, underestimation in the input resulted in underestimating the maximum power. Moreover, the error in the estimated maximum power or in the estimated I-V curves increases with the irradiance and with the module temperature. It should be also emphasize that the differences between using the first or second procedure for extrapolating the I-V curves to temperatures and irradiances beyond STC were practically negligible.

5. Conclusions

Modeling accurately the I-V curve of a photovoltaic module from the basic parameters appearing in the manufacturer's datasheet can be of high interest in many applications. In this work a fast and straight method is presented for solving the single diode equivalent circuit equation to deriving the five parameters. The methodology is based on a previous proposal in the literature where the Lambert-W function was used to obtain four parameters under the prior knowledge of the ideality factor of the diode. In this work an iterative procedure is proposed in combination with the aforementioned simple method to obtain the five parameters fast, accurately and in a straight way.

The methodology presented here has been assessed with experimental data available from previous projects and tests performed with different modules at Ciemat's PV Lab. The comparison with measurements made with a flash solar simulator showed rather accurate results. In addition, for very well controlled conditions of module temperature and solar irradiance at indoor measurements the methodology was very accurate in computing the I-V characteristic curve at STC and at different temperature and irradiance conditions. The evaluation of indoor conditions has proven the robustness and accuracy of the methodology proposed. Differences became slightly larger for outdoor tests, particularly for higher temperatures and irradiance. In this regard a sensitivity analysis has been performed to investigate the sources and propagation of the uncertainties. In particular, it might be of high interest to know the sensitivity to the uncertainty in the input parameters The results have shown the impact of the uncertainty in the manufacturer's datasheet, which might be important, particularly in conditions of high module temperature or irradiance.

In conclusion, the methodology presented in this work allows the accurate computation of the I-V curve of a photovoltaic module from manufacturer's datasheet at STC and other conditions of temperature and irradiance. The model presented is fast and very easy to be implemented in any tool for modeling requiring only a few equations and small number of iterations. Nevertheless, the accuracy is conditioned by the uncertainty of the input parameters used.

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