



## Validation of the procedure: Quantification of the degradation index of Photovoltaic Grid Connection Systems

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### Abstract

The results obtained from the validation of the procedure "Quantification of the degradation index of Photovoltaic Grid Connection Systems" are presented, using statistical parameters, which corroborate its accuracy, achieving a coefficient of determination of 0.9896, a percentage of the root of the mean square of the error RMSPE = 1.498% and a percentage of the mean absolute error MAPE = 1.15%, evidencing the precision of the procedure.

## Introduction

Validation is a fundamental phase of any simulation model (Ablan 2011). Although there is some controversy between different authors about the semantics of the term (Barlas, 1996; Martis, 2006), validation can be defined quite broadly as the examination of the quality of the model with respect to the stated objectives.

The most common way to validate a model is to graphically examine the fit of the model results to the corresponding data for the same period. This process is done iteratively and is repeated for different versions of the same model obtained by a change in the set of parameters used or by changes in the structure of the model. Many times, it is not easy to decide, based only on visual evaluation, which version of the model is the best. If the comparison is made between the same data set and several alternative models, this process can be even more complicated and subject to errors. It is for this reason that objective statistical methods and criteria are required that allow the results obtained by a model and the data to be compared, and even more so, that allow evaluating alternative models for the same data set.

## Developing

The mean square error (MSE) consists of the differences between the observed values and the model predictions, respectively (Tedeschi, 2006). When each data pair is mutually independent and the model is independent, the MSE estimate is a reliable measure of the model's accuracy. If the model parameters were adjusted to the observed data, the MSE will underestimate the true value of the measure because the model will tend to reproduce the real data (Tedeschi, 2006). The root mean square of the error (RMSE), shown in Eq. (1), is often used, which provides a measure of the error in the same units as the variable under consideration.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - Y_i)^2} \quad (1)$$

One of the most frequently used adjustment measures is the coefficient of determination R<sup>2</sup>, reflected by Eq. (2) (Sterman, 2000).

$$R^2 = r^2 = \frac{cov(x,y)^2}{\frac{s_x^2 s_y^2}{x y}} \quad (2)$$

The coefficient of determination measures the fraction of the variance in the data that is explained by the model. If the model exactly replicates the current series, R<sup>2</sup> = 1 if the output of the model is constant, without in any way reflecting the variance of the observations, R<sup>2</sup> = 0 (Sterman, 2000; Wainwright & Mulligan, 2004).

For the validation of the procedure, field measurements were performed with the I-V Curve Tracer commercial instrument. 8 photovoltaic (PV) modules were evaluated and the chain formed by these PV modules, which are part of the 7.5 kWp PV Microsystem installed in the Solar Energy Research Center (SERC), Figure 1, which have an operating time of 9 years.



*Figure 1. PV Microsystem 7.5 kWp*

## Methods

### Design of experiment for field measurements

First, the I-V 400 curve tracer was parameterized to evaluate PV modules manufactured by HELLIENE model 215 MA, based on the information provided by the manufacturer's Datasheet. The instrument was connected to the PV module and measurements were obtained every 15 minutes for two days, enough to sweep the greatest number of operating conditions, taking as a premise what is referred to in the standard IEC 60891. The chain formed by the eight PV modules, previously used, was then evaluated for three days. The curve tracer provides several results as part of the I-V curve analysis, including; (1) I-V curve in real operating conditions; (2) Extrapolation of the I-V curve for Standard Measurement Conditions (STC); (3) Deviation of real maximum power with respect to that declared by the manufacturer.

## Results and Discussion

### Field measurements with the I-V 400 curve tracer

The I-V curve measurements were carried out in compliance with the standards of the IEC 60891 standard that establishes the following; (1) Measurements should be made only when the total irradiance does not fluctuate by more than  $\pm 1\%$  during the measurement; (2) The irradiance must be at least  $700 \text{ W/m}^2$ ; (3) For the measurement of incident irradiance and cell temperature, reference modules must be used, the same as those that make up the photovoltaic module or generator (PVG).

Measurements were made with an I-V Curve tracer, HT brand, I-V 400 model manufactured by HT Instruments, Figure 2, which allows directly obtaining the I-V curve and the characteristics of the main electrical parameters of the PV modules. This Curve Plotter allows you to measure up to a maximum of  $1000 \text{ V}$  and  $10 \text{ A}$ , with an accuracy of  $\pm 2\%$ .

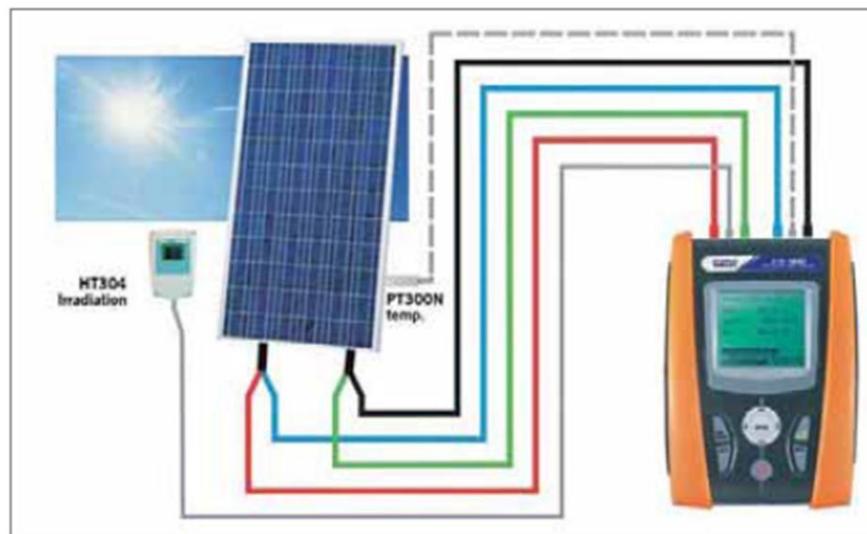


Figure 2. I-V 400 Curve Tracer

The incident irradiance measurement was performed with a reference cell model HT 304, of the same technology and material as the PV module, placed coplanar to the PV module and the temperature of the cell, using a Thermoresistance; model PT300N, placed in the center of rear of PV module. Both auxiliary devices are part of the I-V 400 Curve Tracer.

It must be specified that, to select the area where the resistance thermometer was placed, an inspection was previously carried out with a Thermography Camera (FLUKE) to avoid false measurements from hot spots, these candidates being discarded.

Table 1, collects the main electrical parameters resulting from 10 of the I-V curve measurements carried out on the PV modules, with the environmental variables in the range: Irradiance [ $565 \text{ W/m}^2$ ;  $1146 \text{ W/m}^2$ ] and operating temperature [ $41.3 \text{ }^\circ\text{C}$ ;  $59.7 \text{ }^\circ\text{C}$ ]. The measurements went through a filtering process before being used for the validation of the procedure, based on what is referred to in the IEC 60891 standard.

Table 1. Real measurements with the I-V curve tracer

<i>Number of Measurements</i>	<b>Pmax (W)</b>	<b>Voc (V)</b>	<b>Vmpp (V)</b>	<b>Impp (A)</b>	<b>Isc (A)</b>	<b>Irradiance W — m<sup>2</sup></b>	<b>Operating Temperature (°C)</b>
1	155.01	34.43	26.79	5.79	6.38	792	45.2
2	155.36	34.36	26.79	5.8	6.42	793	45.5

3	155.43	34.25	26.72	5.82	6.47	797	46.1
4	160.26	34.06	26.65	6.01	6.73	828	47.6
5	160.9	34.15	26.65	6.04	6.75	832	47.5
6	161.14	34.07	26.65	6.05	6.75	834	47.2
7	160.34	34.06	26.65	6.02	6.73	829	47.5
8	166.45	34.22	26.36	6.31	6.95	857	46.3
9	166.08	34.22	26.29	6.32	6.98	860	46.9
10	168.92	34.15	26.79	6.31	7.11	874	48.5

### Validation of the procedure

It should be noted that the fundamental objective of the procedure, for the quantification of the degradation index of the Photovoltaic Grid Connection Systems, is to calculate, in the photovoltaic generator (GFV), the deviation of the real power with respect to that declared by the manufacturer, during its useful life, therefore, the most relevant statistical indices are those focused on this indicator. The statistical parameters used for the validation of the procedure were; (1) Coefficient of determination of the line (R2) is nothing more than the percentage of variation of the response that is explained by the model, that is, how well the result of the procedure adjusts to the real measurements, this parameter varies from 0% to 100%. The higher the value of the coefficient, the better the method fits the data; (2) Root of the mean square of the error (RMSE) which provides a measure of the error in the same units as the variable under consideration; (3) The percentage of the root mean square of the error (RMSPE), where the error is normalized using the average of the measurements; (4) Mean absolute error (MAE) which gives us a measure of the error linearly; (5) The percentage of the mean absolute error (MAPE) gives a weighted measure of the previous parameter with respect to the real measurements.

For the validation, the deviation resulting from the procedure and that produced by the Curve I-V 400 tracer were related, as shown in Figure 3.

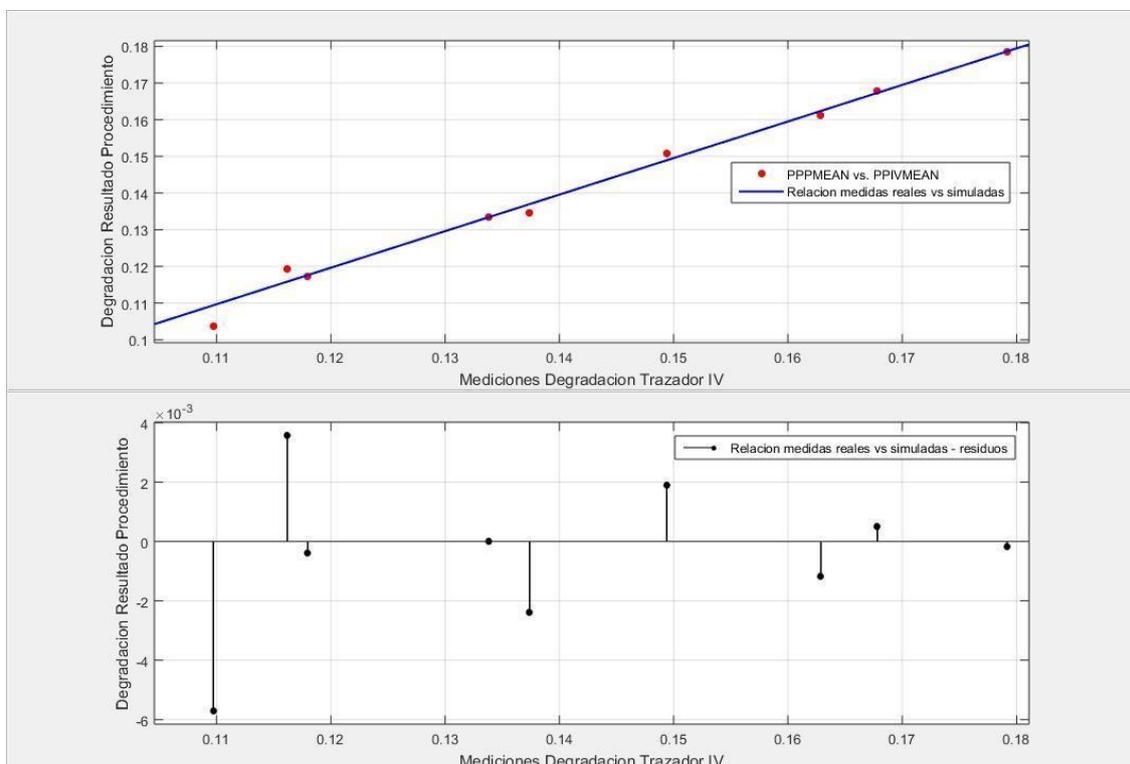


Figure 3. Relationship between the degradation resulting from the procedure and Tracer I-V 400.

In figure 3, it is possible to appreciate the relationship between the analyzed variables, a polynomial adjustment of the type  $ax + b$  was carried out, which resulted in  $a = 0.996$  and  $b = 0.001$ , direct proportionality and of equal magnitude. Table 2, shows the values obtained, results of the analysis and data processing.

Table 2. Results of the statistical indices for the validation of the procedure

Statistical indices	Procedure validation result
$R^2$	0.9896
RMSE	0.0021
RMSPE	1.4975 %
MAE	0.0017
MAPE	1.1498 %

The results obtained from the validation of the procedure corroborate its accuracy, achieving a coefficient of determination of 0.9896, which tells us that approximately 99% of the data can be explained by the fit line between these variables. Another indicator of the precision of the procedure is denoted by the calculated errors,  $RMSPE = 1.498\%$  and  $MAPE = 1.15\%$ . Due to the above we can affirm that the procedure has a good performance when calculating the deviation of the maximum power with respect to that declared by the manufacturer.

From the simulation of the photovoltaic module, it was possible to build the maximum power plane as a function of irradiance and temperature. As an example, Figure 4 shows the behavior of the evaluated PV module 2, observing the existing deviation between the declared and real power for some of the cases analyzed. The points, in red color, below the theoretical generation plane denote degradation of the PV module.

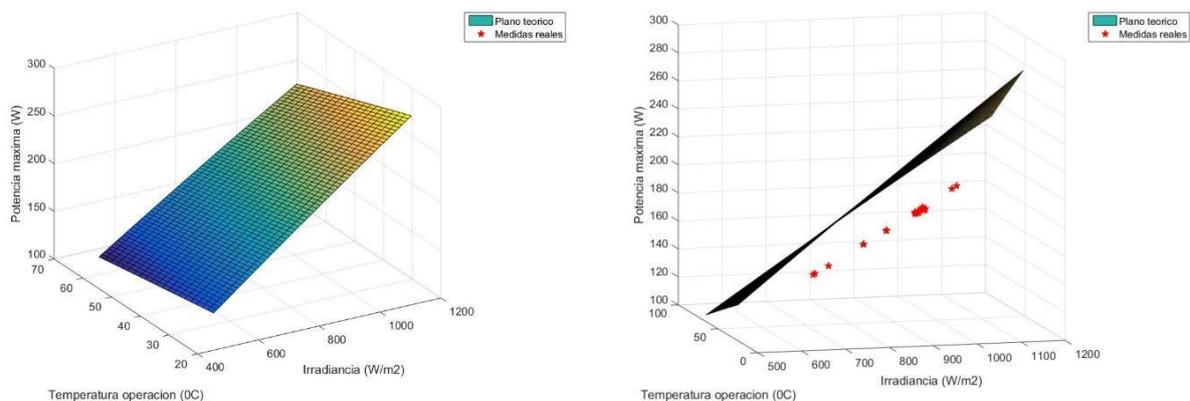


Figure 4. Theoretical behavior of the PV module 2 compared to the measurements carried out

## Conclusion

The validation of the procedure through statistical parameters corroborates its accuracy, achieving a coefficient of determination of 0.9896, as well as,  $RMSPE = 1.498\%$  and  $MAPE = 1.15\%$ , evidencing the precision of the procedure for the calculation of the deviation of the maximum power with respect to the declared by the manufacturer.

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