# Modeling and simulation of a grid-connected photovoltaic system

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## Abstract

**The simulation of a Grid Connected Photovoltaic System (GCPVS) is presented, starting from mathematical models, both for the photovoltaic generator (GPV) and the Photovoltaic Inverter (IPV) of grid connection. MATLAB 2015a software was used as a tool for calculating and processing the equations that define the behavior of the system and allowed, from a database of operation of a GCPVS installed in the Solar Energy Research Center (SERC), rated power 7.5 kWp, validate the model by statistical coefficients.**

**Keywords:** photovoltaic system; grid-connected systems; modeling; simulation

## Introduction

The modeling of the GCPVS part of the characterization of the main elements that compose the system: Photovoltaic Generator (GFV) and Photovoltaic inverter (IFV). To this end, three mathematical models were evaluated for the GFV [1- 3] and three models for the IFV [3- 5], of which, from its validation, the best adjustment was selected with respect to the actual data obtained from calibrated instrumentation.

For the GPV, the most accurate model (correlation index 0.981) is the one proposed by **De Soto**, [1], called 5 parameters. Unlike the other models, the complexity of this lies in the solution of the mathematical equations that define the system, unlike the other models, information is required provided by the manufacturers and has been shown to be consistent with Experimental results.

For the IPV, the model with the most adjustment is the one proposed by **Lorenzo**, which, unlike the other models, has a correlation index of 0.9863, which makes it the most robust. Based on the revision of the article by Eduardo Lorenzo [4]: ***Portraits of the Photovoltaic Connection (V): From the AIE to the inverters***, the IFV is modeled using three constants ($\kappa 0$, $\kappa 1$ and $\kappa 2$).

The advantage of this model is that it allows to characterize completely the behavior of the IPV with only three parameters adimensional, $\kappa 0$, $\kappa 1$ and $\kappa 2$, which can be calculated experimentally by measuring the efficiency of the IPV for a few different values of the Input power (actually, this efficiency and, with it, the values of the parameters, is dependent on the operating voltage).

## Description of the 7.5 kWp GCPVS installed in the SERC.

Photovoltaic generator.

The GPV, is composed in its entirety by 30 modules, models HELIENE, formed by three chains of 10 modules PV, each one, with a power of 2.5 kWp, 303 VCD and 8.22 A, which in its totality has a nominal power of 7.5 kWp

**Figure 1. 7.5 kWp photovoltaic generator installed in SERC.**

Power conditioning unit. Photovoltaic Inverter.

Formed by two inverters model FRONIUS 5000k, connected one to two chains of 10 PV modules, and another one to a chain of the same quantity of PV modules. The main features of the 5000k inverter are: maximum power of DC (PDC) 5000 W, DC nominal voltage (VDCnom) 660 V, DC maximum current (IMax) 18 A, working frequency (F) 50 and 60 Hz, maximum AC power (PAC) 5000 W, AC voltage range (VAC) 194 V-242 V and Maximum current ac (IAC) 22.7 A. Internally, the inverters are provided with protections, both in the varistors DC input for the over voltages and the AC outlet with fuses and an earthed socket.

**Development**

To carry out the validation process of the general model that describes the behavior of a GCPVS, it is necessary to have a database of operation of the same. This allows us to relate the results of the model with the actual measurements in order to determine the precision of the model.

The algorithm developed to obtain the Database, aims to have a database containing the variables of relevance that condition the operation of a GCPVS, to, from that information, validate the model.

The first step is executed when we load the measured data. The algorithm is responsible for creating a matrix with 9 columns containing the current and voltage values for both the continuous and alternating parts, the active power, as well as the environmental variables: operating temperature of the PV module, ambient temperature and Irradiation, in addition to the date and time. It then performs a sweep of the matrix to eliminate negative alternating power values, which are unnecessary values, as they refer to null irradiation values and therefore negative yield. The next step is to calculate a new vector, the continuous power, as a product of the voltage and current vectors in the continuous part. If a negative value occurs, the sample is rejected. The end result is an array of ten vectors with the wrong or unnecessary values removed.

The FRONIUS technology has an information management system called FRONIUS Datamanager, which allows monitoring of the installation in real time through a WEB server, providing the user with all the necessary information about the Energy production as well as other system parameters as a whole.

The inverters offer the possibility of cable communication RS 485 through a device Fronius IG SENSOR BOX with a computer, as well as a Software Fronius Solar Access, supplied by the manufacturer, to save and evaluate the main parameters That influence the behavior of the GCPVS, all this allows to have an updated database of operation.

**Simulation of the photovoltaic generator.**

Behavior of the Curve I-V and P-V by variation of irradiation.

The simulations were made from the electrical parameters (Datasheets) of a commercial PV module of HELLIENE brand, model 215MA. The main features of this module are shown in Table 1.

**Table 1. Main electrical parameters of the PV module HELLIENE.**

| REFERENCIA | HEE215MA68 |
|---|---|
| CLASES DE POTENCIA | 250 |
| DATOS ELÉCTRICOS STC | |
| Potencia nominal PMPP (W) | 250 |
| Tensión MPP (V) | 30,30 |
| Intensidad MPP (A) | 8,22 |
| Tensión de vacío (V) | 37,40 |
| Corriente de cortocircuito (A) | 8,72 |

In **Figure 2**, there is evidence of the influence of irradiance on the photogenerated current, as the irradiation value increases the short-circuit current grows proportionately and vice versa. An open circuit voltage variation can also be shown for different levels of irradiation.

Because the series resistance is a very small value, it can be despised and assume that the photogenerated current is equal to the short circuit current, therefore, the irradiation also affects mainly the short circuit current.

The behavior of the curve IV is simulated to different irradiance values (200 $\frac{W}{m^2}$ a 1000 $\frac{W}{m^2}$), maintaining the operating temperature at 25 º C.

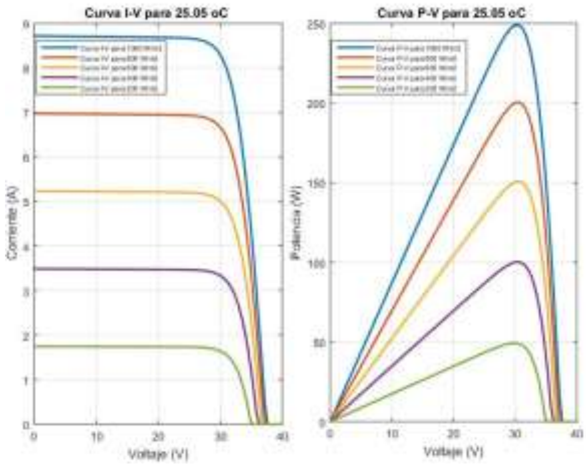



**Figure 2. Simulation of the I-V behavior of the PV module HELLIENE by variation of irradiation.**

Behavior of the Curve I-V and P-V by temperature variation.

In **Figure 3**, it is appreciated that the most dominant effect of the temperature in the I-V curve focuses on open circuit voltage, as the temperature value increases, the open circuit voltage decreases proportionately and vice versa.

It can also be shown that the short circuit current increases slightly for higher temperature values because the band Gap of the material decreases slightly with the temperature as it creates more electron movement.

Similarly, the behavior of the curve IV is appreciated at different operating temperature values (25 º C to 65 º C), maintaining the irradiation in 1000 $\frac{W}{m^2}$.

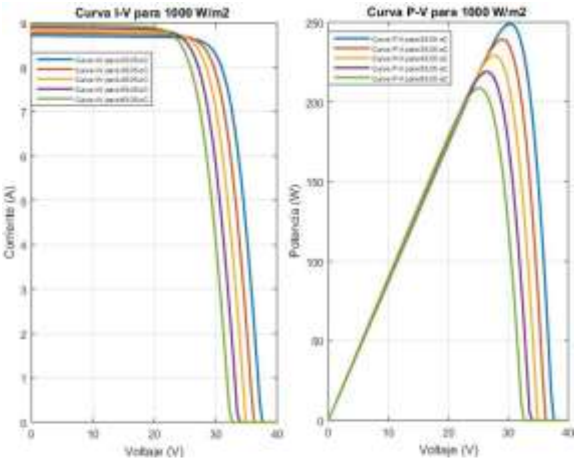



**Figure 3. Simulation of the I-V behavior of the PV module HELLIENE by temperature variation.**

### Simulation of the IFV connected to the grid.

From a three-month operating database (June 2018 – August 2018) of the IPV FRONIUS, the parameters of k0, k1 and k2 were calculated, allowing the efficiency curve to be generated, Figure 4. Table 2, shows the results obtained.

**Table 2. Parameters of the mathematical model of the IFV.**

| Mathematical model of IPV. | Parameters. Result of processing the operation data |
|---|---|
| Eduardo Lorenzo | $k_0 = 0.001496$<br>$k_1 = 0.005431$<br>$k_2 = 0.04028$ |

In Figure 4, you can appreciate the performance of the efficiency of a IPV network connection, FRONIUS Technology, American manufacturing, model PRIMO 5000k for the mathematical model proposed:

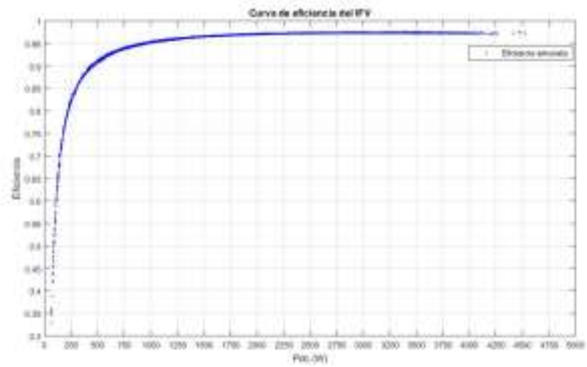


**Figure 4. Simulation of the efficiency of a IFV.**

### Results and discussion

The general mathematical model describing the behavior of a GCPVS is validated from the operating data of a real plant, under climatic conditions characteristic of the area where the ***Solar Energy Research Center*** is located Santiago de Cuba, located at the following geographical coordinates: Latitude 20 00 14N and Longitude: 75 46 10 O, approximately about 90 m above sea level.

The validation process of the general model is part of two fundamental stages: a first generation of the system operating database and the second calculation of the statistical coefficients from the model simulations and the actual data obtained of Data Acquisition System (DAS) FRONIUS.

Figure 5 shows the structure of the general model, as well as the relation of parameters influencing the models.

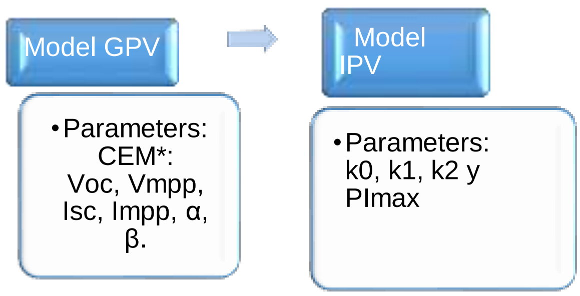



**Figure 5. Structure of the general model of a GCPVS.**

STC* Standard conditions of measures:

1000W/m$^2$, 25$^0$C y 1,5 AM.

**Model validation.**

Based on the programming of the proposed models, the following statistical indexes were established, as a characteristic of their evaluation:

1. Pearson's correlation coefficient, which measures the linear relationship between two quantitative variables X and Y, and is calculated as:

   $\rho_{(x,y)} = \frac{Cov(X,Y)}{\sigma_X * \sigma_Y}$ (2)

   Being:
   $Cov(X, Y)$ covariance of $(X, Y)$.
   $\sigma_i$ is the typical deviation of $i$.

   If the index is worth 1, there is a perfect positive correlation. This indicates a total dependence between the two variables called direct relation: when one of them increases, the other also does in the same proportion.

2. The value of the square root of the mean quadratic error, which is defined in the following way:

   $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)^2}$ (3)

   $X_i$ value $i$ of the measures.
   $Y_i$ value $i$ of the simulation.

These indexes are used in other works of a similar nature [6], and their combined use ensures adequate validation of the results obtained.

**Evaluation of the general model.**

After processing the information provided by the DAS of the FRONIUS, a database was developed in order to store the variables of interest that influence the behavior of the GCPVS.

Table 3, presents as an example, the structure of the database, as well as some measures obtained from the Data Acquisition System, with the environmental variables in this range: irradiation $[561\frac{W}{m^2}; 709\frac{W}{m^2}]$ and operating temperature [49 ºC; 55 ºC].

**Table 3. Measures obtained from the SAD FRONIUS.**

| Fecha V. Ambientales | Irrad. $[\frac{W}{m^2}]$ | Tem. Oper ºC | Tem Amb ºC | Pac (W) | Uac L1 [V] | Iac L1 [A] | Udc MPP T1 [V] | Idc MPP T1 [A] | Udc MPP T2 [V] | Idc MPP T2 [A] | Vdc MPPT TOTAL | Idc MPPT TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2017-12-15 06:15 | 561 | 49 | 27 | 2631,3663 | 236,1 | 11,12 | 271,30 | 5,00 | 270,80 | 5,03 | 271,05 | 10,03 |
| 2017-12-15 06:20 | 576 | 50 | 28 | 2688,7416 | 236,0 | 11,36 | 271,10 | 5,11 | 270,60 | 5,14 | 270,85 | 10,25 |
| 2017-12-15 06:25 | 596 | 50 | 28 | 2756,1779 | 236,1 | 11,64 | 269,70 | 5,26 | 269,20 | 5,30 | 269,45 | 10,56 |
| 2017-12-15 06:30 | 611 | 51 | 28 | 2805,1914 | 235,7 | 11,88 | 268,30 | 5,39 | 268,30 | 5,42 | 268,30 | 10,81 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2017-12-15 06:35 | 626 | 51 | 28 | 2851,4866 | 234,9 | 12,12 | 267,20 | 5,50 | 267,20 | 5,53 | 267,20 | 11,03 |
| 2017-12-15 06:40 | 638 | 51 | 28 | 2894,1342 | 234,6 | 12,31 | 266,90 | 5,59 | 266,70 | 5,62 | 266,80 | 11,21 |
| 2017-12-15 06:45 | 654 | 53 | 29 | 2931,7624 | 234,9 | 12,48 | 266,50 | 5,68 | 266,60 | 5,71 | 266,55 | 11,39 |
| 2017-12-15 06:50 | 669 | 54 | 29 | 2977,4228 | 235,6 | 12,59 | 264,20 | 5,80 | 264,20 | 5,83 | 264,20 | 11,63 |
| 2017-12-15 06:55 | 685 | 54 | 29 | 3025,4362 | 235,0 | 12,85 | 264,10 | 5,90 | 264,30 | 5,93 | 264,20 | 11,83 |
| 2017-12-15 07:00 | 697 | 55 | 30 | 3064,2248 | 234,9 | 13,00 | 263,30 | 5,99 | 263,10 | 6,03 | 263,20 | 12,02 |
| 2017-12-15 07:05 | 709 | 55 | 30 | 3092,538 | 234,9 | 13,17 | 262,90 | 6,07 | 263,00 | 6,11 | 262,95 | 12,18 |

**PEARSON correlation coefficient and root of the mean quadratic error.**

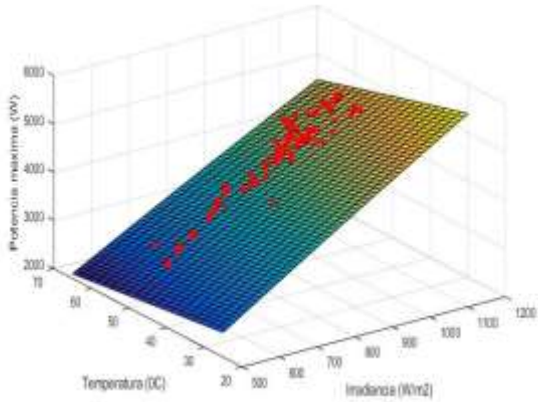
After obtaining the simulation of the GCPVS from the general model, the correlation coefficients were calculated, as well as the root of the mean quadratic error, the results can be shown in Table 4.

**Table 4. Statistical indexes result of the validation of the general model.**

| Mathematical model | PEARSON correlation coefficient | Root of the mean quadratic error |
|---|---|---|
| Model General SPVCN | **0.982** | **5.3 W** |

The results obtained from the evaluation of the general model of the GCPVS, proposed in this work, corroborate its accuracy, achieving a correlation index for the power of 0.982, as well as a root of the mean quadratic error of 5.3 W.

From the simulation of the GCPVS was able to build the power plane depending on the irradiation and temperature, Figure 6, observing the accuracy of the model against the measurements obtained.



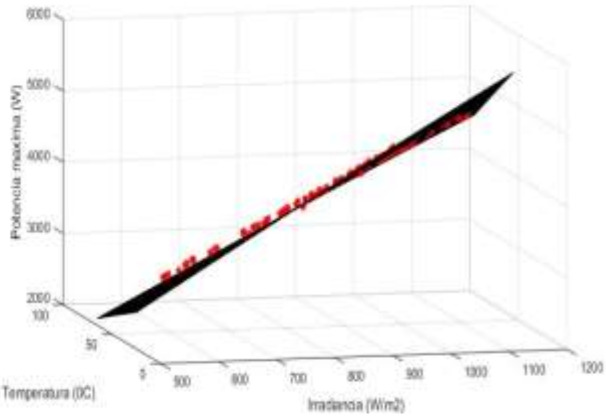




**Figure 6. Theoretical behavior of the general model compared to the measurements carried out.**

## Conclusions

In a real system, the answer differs from the models, on the one hand, that the characteristic of the actual PV components does not coincide exactly with those established by manufacturer (the actual power of the GPV is usually lower than the nominal one, and the same applies to the Efficiency of the IPV) and, on the other hand, that the behavior of the GCPVS is affected by some phenomena of second order, not contemplated in the equations that define the general model (spectral sensitivity, effects of the angle of incidence, own consumptions of the GCPVS).

The results obtained from the evaluation of the general model of the GCPVS corroborate the accuracy of the same, achieving a correlation index greater than 0.97. The fundamental disadvantage of the general model lies in the solution of the mathematical equations that define the system, but, with the available computing resources and processing capacity, the simulations are efficient and fast.

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