Modeling and simulation of a grid connected PV system based on the evaluation of main PV module parameters

Aissa Choudera, Santiago Silvestreb, Nawel Sadaouic, Lazhar Rahmani c

a Development Centre of Renewable Energies, BP 62, Route de l’Observatorie, Alger, Algeria
b MNT, Electronic Engineering Department, Universitat Politècnica de Catalunya, C/Jordi Girona 1-3, Mòdul C4, Barcelona 08034, Spain
c Laboratory of Automatic, University of Setif, Cite Maabouda, Setif 19000, Algeria

Article info
Article history:
Received 18 April 2011
Received in revised form 19 July 2011
Accepted 31 August 2011
Available online 1 October 2011

Keywords:
Photovoltaic systems
Parameter extraction
Modeling
Simulation

Abstract
In this work we present a new method for the modeling and simulation study of a photovoltaic grid connected system and its experimental validation. This method has been applied in the simulation of a grid connected PV system with a rated power of 3.2 kwp, composed by a photovoltaic generator and a single phase grid connected inverter. First, a PV module, forming part of the whole PV array is modeled by a single diode lumped circuit and main parameters of the PV module are evaluated. Results obtained for the PV module characteristics have been validated experimentally by carrying out outdoor $I-V$ characteristic measurements. To take into account the power conversion efficiency, the measured AC output power against DC input power is fitted to a second order efficiency model to derive its specific parameters.

The simulation results have been performed through Matlab/Simulink environment. Results has shown good agreement with experimental data, whether for the $I-V$ characteristics or for the whole operating system. The significant error indicators are reported in order to show the effectiveness of the simulation model to predict energy generation for such PV system.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction
Photovoltaic (PV) power systems have made a successful transition from small stand alone sites to large grid connected systems. The utility interconnection brings a new dimension to the renewable power economy by pooling the temporal excess or the shortfall in the renewable power with the connecting grid that generates base-load power using conventional fuel [1]. Several factors have lead to the evolution of intensive use of photovoltaic systems. The most significant factors are the worldwide increase in energy demand and the fact that the fossil energy sources are finite and that they are expensive. Another important issue is the impact of the energies technologies on the environment and the fact that photovoltaic has become a mature technology.

The increase in number of PV systems installed worldwide has introduced the need of supervision and control algorithms [2–4] as well as design and simulation tools for researchers and engineers involved in these kinds of applications. Between the different approaches for PV system design and simulation existing nowadays [5,6], most popular tools are specific commercial software helping in design of PV systems like PV*sol [7] and PVsyst [8]. These tools give a good approach of the PV system design and behavior in different conditions of work, but when a more detailed simulation is needed to a deep
understand of the different components involved in the whole system these tools are not powerful enough. More powerful approaches have been developed using different commercial software for technical and engineering applications as Pspice [9–11] or Matlab [12–16].

As it is well known, there are currently various photovoltaic technologies on the market. The characteristics parameters of PV modules, usually given by the manufacturer, never are the same in real condition of operation. The evaluation of these parameters in real conditions of work is essential for a good modeling and accurate simulation of PV systems. On the other hand, the produced DC energy is altered by the power conditioning units which consist of MPP tracker and DC/AC converter.

In this work we present a simulation study, and experimental validation, of a photovoltaic grid connected system with a rated power of 3.2 Kwp. The studied PV system is composed by a photovoltaic generator and a single phase grid connected inverter located in Argel. Algeria, despite it is known as a petrol producer, has for a long years ago experienced photovoltaic systems, particularly small stand alone systems sized for remote communities. The first photovoltaic grid connected systems was installed in 2004 at the renewable energy centre for experimentation and performance evaluation purpose. Until now the PV plant has been operating continuously. A monitoring system has been implemented; in which we monitor both solar cells and ambient temperature, horizontal and tilted irradiance and finally electrical variables in DC side as well as in AC side [17,18]. A PV module, forming part of the whole PV array is modeled by a single diode lumped circuit and the model has been validated experimentally by carrying out outdoor I–V characteristic measurements. To take into account the power conversion efficiency, the measured AC output power against DC input power is fitted to a second order efficiency model to derive the specific parameters.

2. Photovoltaic generator model

Photovoltaic cell models have long been a source for the description of photovoltaic cell behaviors. The most common model used to predict energy production in photovoltaic cell modeling is the single diode circuit model [19,20], shown in Fig. 1.

This model includes a current source $I_{ph}$, which depends on solar radiation and cell temperature, a diode which the inverse saturation current $I_0$ depends mainly on the operating temperature, a series resistance $R_s$ and a shunt resistance $R_{sh}$, taking into account the resistive losses. The current–voltage relationship of a photovoltaic cell is given by:

$$I = I_{ph} - I_0 \left( \exp \left( \frac{V + R_s I}{A} \right) - 1 \right) - \frac{V + R_s I}{R_{sh}}$$  \hspace{1cm} (1)

where $I_{ph}$ is the photocurrent in (A), $I_0$ the diode saturation current (A), $A = n k T / q$ modified ideality factor, $n$ the diode ideality factor, $k$ the Boltzmann constant ($1.38 \times 10^{-23}$ J K$^{-1}$), $q$ the electronic charge ($1.602 \times 10^{-19}$ C), $T$ the cell temperature (K), $V_t$ the thermal voltage ($V_t = kT / q$, V), $R_s$ the series resistance (Ω) and $R_{sh}$ is the shunt resistance (Ω).

The nonlinear and implicit equation given by Eq. (1) can be solved using the Newton Raphson iterative method [21]. The five parameters in Eq. (1) depend on the incident solar irradiance, the cell temperature, and on their reference values. These reference values are generally provided by manufacturers of PV modules for specified operating condition such as STC (Standard Test Conditions) for which the irradiance is 1000 W/m$^2$ and the cell temperature is 25 °C. Real operating conditions are always different from the standard conditions, and mismatch effects can also affect the real values of these mean parameters. So the evaluation of the five parameters in real conditions of work is of prime interest in this work to provide an accurate PV module mathematical model. Furthermore, the reference parameters given by the manufacturer at STC are not accurate for outdoor conditions [22]. Thus, in the present work, a procedure based on outdoor measurement and mathematical formulation to determine the reference values of these parameters is proposed. The evaluation of the five model parameters at real condition of irradiance and temperature of the target PV module are then determined according to their reference values. The detailed steps for this procedure are given hereafter.

![Fig. 1. Equivalent Electrical circuit of the single diode model.](image-url)
3. Reference parameters calculation

At reference conditions, Eq. (1) can be written as:

\[ I = I_{\text{ph ref}} - I_{\text{ref}} \left( \exp \left( \frac{V + R_{\text{ref}} I}{A_{\text{ref}}} \right) - 1 \right) - \frac{V + R_{\text{ref}} I}{R_{\text{sh ref}}} \]  

(2)

where \( I_{\text{ph ref}}, I_{\text{ref}}, A_{\text{ref}}, R_{\text{ref}}, \) and \( R_{\text{sh ref}} \) are evaluated in particular points in the \( I-V \) curve, such as:

**Short circuit condition:** \( I = I_{\text{SC}}, V = 0 \)

\[ I_{\text{scref}} = I_{\text{ph ref}} - I_{\text{ref}} \left( \exp \left( \frac{R_{\text{ref}} I_{\text{scref}}}{A_{\text{ref}}} \right) - 1 \right) - \frac{R_{\text{ref}} I_{\text{scref}}}{R_{\text{sh ref}}} \]  

(3)

**Open circuit conditions:** \( I = 0 \) and \( V = V_{\text{OC}} \)

\[ I_{\text{ph ref}} - I_{\text{ref}} \left( \exp \left( \frac{V_{\text{oc ref}}}{A_{\text{ref}}} \right) - 1 \right) - \frac{V_{\text{oc ref}}}{R_{\text{sh ref}}} = 0 \]  

(4)

At the maximum power point: \( V = V_{\text{m}}, I = I_{\text{m}} \)

\[ I_{\text{mref}} = I_{\text{ph ref}} - I_{\text{ref}} \left( \exp \left( \frac{V_{\text{m ref}} + I_{\text{m ref}} R_{\text{ref}}}{A_{\text{ref}}} \right) - 1 \right) - \frac{V_{\text{m ref}} + I_{\text{m ref}} R_{\text{ref}}}{R_{\text{sh ref}}} \]  

(5)

The derivative of Eq. (1) at \( V = V_{\text{oc ref}} \) gives:

\[ \frac{dV}{dI} \bigg|_{V=V_{\text{oc ref}}} = -R_{\text{oc}} \]  

(6)

And at \( I = I_{\text{scref}} \):

\[ \frac{dV}{dI} \bigg|_{I=I_{\text{scref}}} = -R_{\text{sh0}} \]  

(7)

where \( R_{\text{oc}} \) and \( R_{\text{sh0}} \) are respectively the slopes of the \( I-V \) curve in open circuit and short circuit points. In this work, \( R_{\text{oc}} \) and \( R_{\text{sh0}} \) are initially evaluated using manufacturer’s data.

Here \( I_{\text{scref}}, V_{\text{oc ref}}, I_{\text{mref}}, \) and \( V_{\text{mref}} \) have been determined by combining outdoor measurements of several \( I-V \) curves on an Isofoton (106/12) PV module and mathematical translation equations given hereafter [10].

\[ I_{\text{scref}} = I_{\text{sc mes}} \left( \frac{G_{\text{ref}}}{G_{\text{mes}}} \right) + \alpha_{\text{ic}} (T_{\text{C}} - T_{\text{ref}}) \]  

(8)

\[ V_{\text{oc ref}} = V_{\text{oc mes}} - \beta (T_{\text{C}} - T_{\text{ref}}) + V_{\text{t}} \ln \left( \frac{G_{\text{ref}}}{G_{\text{mes}}} \right) \]  

(9)

\[ I_{\text{mref}} = I_{\text{m mes}} \left( \frac{G_{\text{ref}}}{G_{\text{mes}}} \right) + \alpha (T_{\text{C}} - T_{\text{ref}}) \]  

(10)

\[ V_{\text{mref}} = V_{\text{m mes}} - \beta (T_{\text{C}} - T_{\text{ref}}) - R_{\text{ses}} (I_{\text{m mes}} - I_{\text{m ref}}) + V_{\text{t}} \ln \left( \frac{G_{\text{ref}}}{G_{\text{mes}}} \right) \]  

(11)

where \( I_{\text{sc mes}} \) and \( V_{\text{oc mes}} \) are the measured short circuit current and open circuit voltage respectively, \( I_{\text{m mes}} \) and \( V_{\text{m mes}} \) are the measured current and voltage at the maximum power point respectively, \( G_{\text{ref}} \) and \( G_{\text{mes}} \) are the reference and measured irradiances, \( \alpha_{\text{ic}} \) is the temperature coefficient of the short circuit current, \( T_{\text{ref}} \) and \( T_{\text{C}} \) are the reference and measured temperatures, \( \beta \) is the temperature coefficient of the module voltage, \( R_{\text{ses}} \) is the measured series resistance and \( V_{\text{t}} \) the thermal voltage.

Introducing these parameters in Eq. (2) and solving for \( I_{\text{ref}}, I_{\text{ph ref}}, A_{\text{ref}}, R_{\text{ref}}, \) and \( R_{\text{sh ref}} \) we find the following five expressions for the reference parameters of the PV module:

\[ A_{\text{ref}} = \frac{V_{\text{m ref}} + I_{\text{m ref}} R_{\text{so}} - V_{\text{oc ref}}}{\ln \left( I_{\text{scref}} - \frac{V_{\text{oc ref}}}{A_{\text{ref}}} - I_{\text{ref}} \right) - \ln \left( I_{\text{scref}} - \frac{V_{\text{oc ref}}}{A_{\text{ref}}} \right) + \left( \frac{I_{\text{m ref}} - V_{\text{oc ref}}}{R_{\text{sh ref}}} \right)} \]  

(12)

\[ I_{\text{ref}} = \left( I_{\text{scref}} - \frac{V_{\text{oc ref}}}{R_{\text{sh ref}}} \right) \exp \left( -\frac{V_{\text{oc ref}}}{A_{\text{ref}}} \right) \]  

(13)

\[ R_{\text{sh ref}} = R_{\text{sh0}} \]  

(14)
\[ R_{\text{ref}} = R_0 \]  

\[ I_{\text{ph,ref}} = I_{\text{sc,ref}} \left( 1 + \frac{R_{\text{ref}}}{R_{\text{sh,ref}}} \right) + I_{\text{ref}} \left\{ \exp \left( \frac{I_{\text{sc,ref}} R_{\text{ref}}}{A_{\text{ref}}} \right) - 1 \right\} \]  

4. PV module parameters at real conditions of work

Now after having determined the five main parameters at reference conditions, their values at any condition of temperature and irradiance are given by the following expressions [10]:

- **Modified ideal factor**
  \[ A = A_{\text{ref}} \left( \frac{T}{T_{\text{ref}}} \right) \]

- **Saturation current of the diode**
  \[ I_0 = I_{\text{ref}} \left( \frac{T}{T_{\text{ref}}} \right)^3 \exp \left[ \frac{E_g N_s}{A_{\text{ref}}} \left( 1 - \frac{T_{\text{ref}}}{T} \right) \right] \]
  where \( E_g \) is the band gap energy of the semiconductor and \( N_s \) the number of solar cells serially connected forming the PV module.

- **Photocurrent**
  \[ I_{\text{ph}} = \frac{G}{G_{\text{ref}}} \left( I_{\text{ph,ref}} + \alpha (T - T_{\text{ref}}) \right) \]

- **Series resistance** \( R_s \)
  \[ R_s = R_{s,\text{ref}} - \left[ \frac{A}{I_0} \exp \left( - \frac{V_{oc}}{A} \right) \right] \]

- **Shunt resistance** \( R_{sh} \)
  \[ R_{sh} = R_{sh,\text{ref}} \left( \frac{G_{\text{ref}}}{G} \right) \]

Short circuit current \( I_{sc} \) and the open circuit voltage \( V_{oc} \) at any operating condition are given by:

\[ I_{sc} = I_{\text{sc,ref}} \left( \frac{G}{G_{\text{ref}}} \right) + \alpha_{\text{sc}} (T - T_{\text{ref}}) \]

\[ V_{oc} = V_{oc,\text{ref}} - \beta(T_{\text{ref}} - T) + A \ln \left( \frac{G}{G_{\text{ref}}} \right) \]

The current and the voltage corresponding to the maximum power point \((I_m, V_m)\) are given by:

\[ I_m = I_{\text{m,ref}} \left( \frac{G}{G_{\text{ref}}} \right) \]

\[ V_m = V_{\text{m,ref}} - \beta(T_{\text{ref}} - T) \]

By introducing the calculated parameters in Eq. (1) and solving for \( I \), the predicted output current can be determined in real working conditions.

5. Model validation

In order to validate the modeling and simulation method presented above for PV modules, the model output and experimental measurement are compared for a commercial mono-crystalline PV module from Isofoton (106/12), composed of two parallel strings of 36 solar cells.

The simulation of the developed model has been conducted in Matlab/Simulink environment [12] for \( G = 762 \text{ W/m}^2 \) and \( T_c = 26.2^\circ \text{C} \).

Table 1 shows the five PV module parameters evaluated at both reference and real conditions.

Figs. 2 and 3 give the predicted and measured \( I-V \) characteristic and the error evolution respectively. As can be seen, a good agreement has been obtained between simulation results and real measured data.

Fig. 4 shows the plot of the power versus voltage \((P-V)\), obtained in simulation results and from the monitoring system.
Table 1
Parameters values at reference and real conditions.

<table>
<thead>
<tr>
<th>Parameters at reference conditions</th>
<th>Parameters at real conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{ph}$ (A)</td>
<td>6.7043</td>
</tr>
<tr>
<td>$I_0$ (A)</td>
<td>5.1102</td>
</tr>
<tr>
<td>$A$ (V)</td>
<td>1.2358$^{-7}$</td>
</tr>
<tr>
<td>$R_s$ (Ω)</td>
<td>0.1531</td>
</tr>
<tr>
<td>$R_{sh}$ (Ω)</td>
<td>144.3570</td>
</tr>
<tr>
<td>$I_{sc}$ (A)</td>
<td>6.6950</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>19.8327</td>
</tr>
<tr>
<td>$I_{m}$ (A)</td>
<td>5.9600</td>
</tr>
<tr>
<td>$V_{m}$ (V)</td>
<td>16.4570</td>
</tr>
</tbody>
</table>

Fig. 2. Simulated and experimental $I$–$V$ characteristic. $G = 762$ W/m$^2$, and $T = 26.2$ °C.

Fig. 3. Error evolution between simulated and experimental characteristic. $G = 762$ W/m$^2$, and $T = 26.2$ °C.
Fig. 5 shows a comparison between the measured $I-V$ characteristic of the PV module and the characteristic obtained from simulation using the standard PV model and reference parameters. Fig. 6 shows the error evolution, as can be seen the error is bigger in the case of using the standard PV model than in the simulation using extracted parameters shown in Fig. 3.

5.1. Accuracy of the model

In order to quantify the goodness of the modeling procedure for the $I-V$ characteristics of a commercial PV module, the following indexes of error are calculated:

- Root Mean Square Error (RMSE): It is given by:

$$\text{RMSE}(A) = \sqrt{\frac{\sum_{i=1}^{N} (I_{\text{real}} - I_{\text{exp}})^2}{N}}$$

(26)
where $I_{ical}$ is the predicted current and $I_{iexp}$ is the experimental current, and $N$ the number of measured points.

The RMSE in percent is also given by:

$$\text{RMSE} (%) = 100 \sqrt{\frac{\sum_{i=1}^{N} (I_{ical} - I_{iexp})^2}{N}}$$

(27)

- The mean relative error of calculated parameters: $I_{iscref}$, $V_{ocref}$, $I_{mref}$, and $V_{mref}$:

$$E_X = 100 \frac{X_{cal} - X_{exp}}{X_{exp}} (%)$$

(28)

where $X = [I_{isc}, V_{oc}, I_{m}, V_{m}]$.

Table 2 shows the values for the relative error, RMSE (A) and RMSE (%).

In the simulations done using the model parameters, the deviation is almost negligible at short circuit current and at the maximum power point current. Furthermore errors below 3.3% and 2.3% are obtained at open circuit voltage and at the maximum power point voltage, respectively. In the simulation carried out using the reference parameters, the obtained value of RMSE is 23%.

6. Dynamic behavior of the photovoltaic generator

For constant irradiance and temperature the $I$–$V$ characteristic describes the static behavior of the PV module, but for variable irradiance and temperature during a day the current, $I$, will be evaluated depending time.

We introduce in the model of the PV generator a profile of temperature and irradiance during four days of March stored in the central acquisition of our monitoring system (sampling period = 1 min).

The DC and AC output variables, current and voltage, from the PV system as well as the in-plane irradiance and module temperature are recorded by a data acquisition system for every 1 min. The monitoring system is formed by a reference solar cell to measure the irradiance, a Pt100 sensor to measure the temperature profile, sensors of voltage and current at both, DC and AC sides of the PV system.

All sensors of the monitoring system are connected to a data acquisition system Agilent 34970A that transfer all data using a GPIB bus to the main computer. Table 3 shows the accuracies of the sensors used in the monitoring system.

<table>
<thead>
<tr>
<th>Error</th>
<th>Values respect to the model parameters</th>
<th>Values respect to the reference parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{isc}$ (%)</td>
<td>0.0705</td>
<td>-1.7435</td>
</tr>
<tr>
<td>$E_{voc}$ (%)</td>
<td>-3.2550</td>
<td>-6.0945</td>
</tr>
<tr>
<td>$E_{im}$ (%)</td>
<td>0.0342</td>
<td>2.3833</td>
</tr>
<tr>
<td>$E_{vm}$ (%)</td>
<td>2.2176</td>
<td>2.5814</td>
</tr>
<tr>
<td>RMSE (A)</td>
<td>0.5012</td>
<td>1.1968</td>
</tr>
<tr>
<td>RMSE (%)</td>
<td>9.8276</td>
<td>23.4658</td>
</tr>
</tbody>
</table>
Table 3  
Sensors accuracies used in the monitoring system.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature sensor (Pt1000)</td>
<td>±0.8 °C (20–100 °C)</td>
</tr>
<tr>
<td>Reference solar cell</td>
<td>$I_{sc} = 3.42$ A, 1000 W/m²</td>
</tr>
<tr>
<td>DC current</td>
<td>±560 mA (nominal value = 1 A)</td>
</tr>
<tr>
<td>DC voltage</td>
<td>±12 mV (nominal value = 300 V)</td>
</tr>
<tr>
<td>AC current</td>
<td>±1.4 mA (nominal value = 1 A)</td>
</tr>
<tr>
<td>AC voltage</td>
<td>±600 mV (nominal value 300 V)</td>
</tr>
</tbody>
</table>

![Fig. 7. Monitored Irradiance profile.](image)

![Fig. 8. Monitored Temperature profile.](image)
The irradiance and temperature profiles, obtained from the monitoring system, that have been used as input data for these simulations are shown in Figs. 7 and 8 respectively.

![Fig. 9. Comparison between simulated and experimental current at maximum power point.](image1)

![Fig. 10. Comparison between simulated and experimental maximum power.](image2)

<table>
<thead>
<tr>
<th>Table 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE for current and power.</td>
</tr>
<tr>
<td>Error</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>RMSE</td>
</tr>
<tr>
<td>RMSE (%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters model values.</td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Values</td>
</tr>
</tbody>
</table>

The irradiance and temperature profiles, obtained from the monitoring system, that have been used as input data for these simulations are shown in Figs. 7 and 8 respectively.
This study has been carried out for a photovoltaic generator composed of 30 modules. Fig. 9 shows the comparison between the experimental current and the simulation results for the maximum power point dynamic evolution.

The maximum power generated by the PV generator is given by the following relation:

$$P_{\text{max}} = I_m V_m$$  \hspace{1cm} \text{(29)}

Fig. 10 shows the comparison between the experimental maximum power output and the predicted one obtained by simulation results.

Table 4 shows the error between simulated and measured current at the maximum power point and also between predicted and measured maximum power output.

As seen in Table 4 the error is reasonable for current, and the maximum power output gives an acceptable registered error relatively with the global provided power.

In the simulation results shown in Figs. 9 and 10, there are two spikes in the current and power output of the PV system at times of 600 and 1050 min. These spikes are not present in the monitored data. These spikes are also present in the irradiance profile, monitored from the irradiance sensor, used as input data for the simulations. The explanation to the difference of these spikes in simulation results and monitored data is that the solar cell used as irradiance sensor could be shadowed at these times, as reflected in the irradiance profile, while the PV modules of the system are not working under the same shadow, so, current and output power measured do not reflect the effect of the shadow covering the sensor.
7. Inverter model

The inverter is the device which transforms the DC input to AC output. For modeling the inverter we use a power conversion model described by power and efficiency curves which will be validated by experimental measurements during four days of operation [23]. The output power supplied by the inverter to the utility grid is given by the following expression:

\[ P_{\text{out}} = c_0 + c_1 P_{\text{in}} + c_2 P_{\text{in}}^2 \] (30)

where \( P_{\text{in}} \) is the DC power supplied by the photovoltaic generator, and \( P_{\text{out}} \) is the AC power supplied by the inverter.

The values of the model parameters: \( c_0, c_1, \) and \( c_2 \) are extracted using a Curve Fitting Toolbox in MATLAB [24,25]. Table 5 gives the calculated values of these parameters.

The output power, \( P_{\text{out}} = f(P_{\text{in}}) \), is obtained and compared with the measured one, in real conditions of work as shown in Fig. 11.

Fig. 12 shows the comparison between the predicted power \( P_{\text{out}} \) and measured power for 4 days and the deviation between them in function of the inverter input power. The evolution of absolute error between these two parameters is depicted by Fig. 13.

![Fig. 13. Error between simulated and experimental power for 4 days.](image1)

![Fig. 14. Inverter efficiency given by the manufacturer.](image2)
The inverter efficiency is given by the following relation:

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \]  

Fig. 15. Comparison between simulated and experimental inverter efficiency.

Fig. 16. Error between simulated and experimental efficiency for 4 days.

<table>
<thead>
<tr>
<th>Error</th>
<th>Power (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (W)</td>
<td>8.7948</td>
<td>0.0625</td>
</tr>
<tr>
<td>RMSE (%)</td>
<td>0.3752</td>
<td>7.4030</td>
</tr>
</tbody>
</table>

Table 6
RMSE for inverter power and efficiency.
Fig. 14 shows the inverter efficiency given in the manufacturer data sheet.

Figs. 15 and 16 show the comparison between simulated and measured inverter efficiency and differences between both parameters. As can be seen, the efficiency of the inverter, in real conditions of work, is below the values given by the manufacturer.

Finally, Table 6 shows the RMSE values obtained for the inverter power output and efficiency. From the comparison between measured and predicted powers and efficiencies, we can see that the noted error is acceptable, which describe that the used model gives good results.

8. Conclusion

In this work we have presented a new procedure for the modeling and simulation study of the main components of a grid connected photovoltaic system.

The simulations results obtained using this method, based in the evaluation of the main PV module parameters, have shown that the presented model of the PV module characterizes the I–V characteristic with a good degree of accuracy. The dynamic behavior of the photovoltaic generator can be also be evaluated in real conditions of work using this method.

Finally the simulation of the whole system: PV generator and single phase inverter, including the inverter modeling, offers a good choice to predict the energy production of the whole plant connected to the utility grid.

References