Monitoring, modelling and simulation of PV systems using LabVIEW

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Abstract

This paper presents a detailed characterization of the performance and dynamic behaviour of photovoltaic systems by using LabVIEW real-time interface system. The developed software tool integrates several types of instruments into a single system which is able to offer online measurements all data sources and comparison simulation results with monitored data in real-time. Comprehensive monitoring and analyzing of PV systems play a very important role. The proposed method is a low-cost solution to provide fast, secure and reliable system by making the system database-ready for performance analysis of PV systems. The proposed method is also applied to a grid connected PV system in the Centre de Developpement des Energies Renouvelables (CDER) in Algeria. The results show that there is a good agreement between the measured and simulation results values. The integration methodology of robust simulation and monitored data in real-time can be extended to study the fault diagnosis of a PV system.

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1. Introduction

LabVIEW™ (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming language by National Instruments that uses icons instead of lines of text to create applications. Nowadays this programming environment has found its application in many scientific fields and technical engineering, so in this work we propose an integral LabVIEW platform of monitoring, modelling and simulation tools for photovoltaic (PV) systems.

Many applications of LabVIEW for monitoring PV systems have been reported before in the literature (Koutroulis and Kalaitzakis, 2003; Forero et al., 2006; Martínez Bohóquez et al., 2009; Vergura and Natangelo, 2009; Ulieru et al., 2010).

On the other hand different commercial software solutions are available for PV systems simulation (Silvestre, 2012) and standard simulation software, as Matlab (Yusof et al., 2004; Pater and Agarwal, 2008; Karatepe et al., 2008; Chouder and Silvestre, 2012) or Pspice (Castaner and Silvestre, 2002; Silvestre et al., 2009) have been also extensively used for this purpose. Furthermore Vergura and Natangelo (2010) have integrated Matlab and Simulink for monitoring energy performances of PV plants.

In this work we report the integration of monitoring, modelling and simulation of PV systems in the same environment able to give information of the system behaviour in real time. This solution allows the acquisition and control of all necessary data from the PV system, evaluate main model parameters of PV modules and array, calculate the performance ratio (PR) and Yields of the system, create HTML and XLS report files and visualize all these data and the dynamic system behaviour in real time. Moreover the integration of robust modelling and simulation gives
the opportunity to compare simulation results with monitored data in real time, allowing the development of new tools for fault detection as well as new prediction models with the objective of improving the performance and reliability of PV systems, optimizing the system output to achieve higher yields.

2. PV system description

The proposed method of monitoring, modelling and simulation of PV systems has been applied to a grid connected PV system located in the Centre de Développement des Energies Renouvelables (CDER), Algérie. The PV system is formed by 90 PV modules (Isofoton 106Wp-12 at STC) divided in three subgenerators of 3 kWp each one. The subgenerators are formed by two parallel strings of 15 PV modules in series. Each subgenerator is connected to a single phase inverter of 2.5 kW (IG30 Fronius) that injects the generated energy into a phase of the public low voltage distribution network of the National Company (Sonelgaz) 220 V–50 Hz (Hadj Arab et al., 2005). The block diagram of this PV system is shown in Fig. 1.

3. Monitoring PV systems using LabVIEW

Fig. 2 shows a schematic diagram of the sensors and acquisition data of the monitoring system implemented in the PV system. Different sensors are included to measure irradiance, temperature, as well as current and voltages at the DC and AC sides of the system.

The data acquisition is carried out using an Agilent 34970A and dedicated multiplexer module Agilent 34902A with sixteen channels. Data communication between PC and LabVIEW, where the incoming data is processed, is performed by GPIB bus.

Two pyranometers (Kipp & Zonen CM 11 type) and a reference solar cell are used to measure the irradiance. One of the pyranometers and the reference cell are installed at two different places of the PV plant to measure irradiance in the tilted plain. A second pyranometer measures the irradiance in the horizontal plane. Thermocouples have been used to measure the ambient temperature near the PV plant in order to predict the effective PV modules temperature.

Eq. (1) is used to calculate this effective solar cell temperature, $T_c$:

$$
T_c = T_a + \left(\frac{NOCT - 20 \degree C}{800}\right) G
$$

where $T_a$ is the ambient temperature, $G$ the irradiance and NOCT the Normal Operating Cell Temperature given by the PV modules manufacturer.

For the measurements of currents, DC ($I_{dc}$) and AC ($I_{ac}$), we have used two CLSM-50 closed loop Hall effect current sensors and a dual operational amplifier LM 1458N.

The DC output voltage of the PV system is measured by means of a voltage divider, while the AC output voltage is measured at the secondary of the transformer used for the voltage supply of the hall sensors. All data coming from the acquisition system are processed in LabVIEW using the VI shown by Fig. 3, where the appearing coefficients are used to calibrate the different monitored parameter. The VI allows the following tasks: Communication with the data acquisition Agilent 34970A in order to setup the different channels via GPIB bus (DC/AC and temperature measurements), processing the output string coming from the data acquisition, splitting the output string to the corresponding measured variable and the calibration of each channel with
Fig. 2. Sensors and acquisition data system to monitor the PV system.

Fig. 3. VI developed to obtain the monitored data.

<table>
<thead>
<tr>
<th>Measured variables</th>
<th>Channel number</th>
<th>Sensors</th>
<th>Calibration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{I,P}$</td>
<td>101</td>
<td>Reference cell: $R_{th} = 0.037 , \Omega$</td>
<td>7901.4</td>
</tr>
<tr>
<td>$G_{H,P}$</td>
<td>102, 103</td>
<td>CM 11: sensitivity $= 5 , \mu V/(W , m^{-2})$</td>
<td>19,920.32</td>
</tr>
<tr>
<td>$T_{amb}$</td>
<td>104</td>
<td>Κ type Thermocouple</td>
<td>Direct measure in Agilent 34,970</td>
</tr>
<tr>
<td>$V_{DC,meas}$</td>
<td>105</td>
<td>Resistive divider</td>
<td>29</td>
</tr>
<tr>
<td>$V_{AC,meas}$</td>
<td>106</td>
<td>AC adapter</td>
<td>220/18</td>
</tr>
<tr>
<td>$I_{DC,meas}$</td>
<td>107, 108</td>
<td>Hall effect</td>
<td>1.6</td>
</tr>
</tbody>
</table>
the corresponding scaling factor. Table 1 shows the calibration factors and channels associated to each measured variable as well as the sensitivity of the irradiance sensors used.

4. Description of PV system modelling and simulation

4.1. Modelling the PV module

The model of the PV module is based on the one diode model of the solar cell shown in Fig. 4, where \( G \) and \( T \) are irradiance and temperature respectively, \( I_{ph} \) is the photo generated current depending on irradiance and temperature conditions, \( D \) is the diode modelling the P/N junction of the solar cell and \( R_{sh} \) and \( R_s \) are the shunt and series resistances respectively, modelling the power losses in the device (Overstraeten and Mertens, 1986; Castan˜er and Silvestre, 2002). The output current of the solar cell, \( I \), can be written as:

\[
I = I_{ph} - I_d - I_{sh}
\]

where \( I_{ph} \) is the photo generated current, \( I_d \) is the diode current and \( I_{sh} \) is the current across \( R_{sh} \).

These currents are given as:

\[
I_{ph} = \frac{G}{G_{ref}}(I_{ph,ref} + \mu_{Icc}(T - T_{ref}))
\]

where \( G \) and \( T \) are respectively the irradiance and temperature conditions of work, \( G_{ref} \) and \( T_{ref} \) are irradiance and temperature at standard test conditions (STCs): 1000 W/m\(^2\) and 25 °C. \( I_{ph,ref} \) is the photo generated current at STC and \( \mu_{Icc} \) the temperature coefficient of current.

\[
I_d = I_{sat} \left( \exp \left( \frac{V + R_s I}{n V_t} \right) - 1 \right)
\]

where \( I_{sat} \) is the is the reverse saturation current of diode, \( n \) is the diode ideality factor and \( V_t \) the thermal voltage.

\[
I_{sh} = \frac{V + R_s I}{R_{sh}}
\]

Eq. (2) can be rewritten, considering Eqs. (3)–(5), as

\[
I = I_{ph} - I_{sat} \left( \exp \left( \frac{V + R_s I}{n V_t} \right) - 1 \right) - \left( \frac{V + R_s I}{R_{sh}} \right)
\]

Eq. (6) is an implicit and not linear equation than gives the \( I(V) \) characteristic of the solar cell. Commercial photovoltaic modules are composed by association of solar cells in series forming a branch. Some higher power PV modules include various branches in parallel. If we consider \( N_s \) solar cells in series in each branch and a total number of \( N_p \) branches for a PV module, the total number of solar cells forming the PV module is \( N_s \times N_p \). So, Eq. (6) can be conveniently scaled to obtain a similar equation for the \( I(V) \) characteristic of a PV module, taking into account the following equations (Castan˜er and Silvestre, 2002; Chenni et al., 2007; Karatepe et al., 2007):

\[
I_m = N_p I
\]

\[
V_m = N_s I
\]

\[
R_{sm} = \frac{N_s}{N_p} R_s
\]

\[
R_{shm} = \frac{N_s}{N_p} R_{sh}
\]

where parameters with subscript \( m \) stands for the PV module.

The model that allows to obtain the \( I(V) \) characteristic of a PV module, considering Eqs. (6)–(10), has been implemented in LabVIEW environment. The \( I(V) \) and \( P(V) \) characteristics as well as the coordinates of the maximum power point (MPP) of both, solar cell and PV module are available results of the developed model. The input parameters for the calculations are: Open circuit voltage of the solar cell \( (V_{oc}) \), short circuit current of the solar cell \( (I_{sc}) \), \( R_s \), \( R_{sh} \), \( N_s \), \( N_p \), \( G \), \( T \), \( \mu_{Icc} \) and the solar cell ideality factor \( (n) \). The flowchart for the obtention of the \( I(V) \) and \( P(V) \) characteristics is shown in Fig. 5.

4.2. Inverter model

The inverter model developed in LabVIEW environment is based in the performance model inverter presented by King et al. (2007). The AC output power of the inverter, \( P_{AC,sim} \), is defined by the following equation:

\[
P_{AC,sim} = \left[ \left( \frac{P_{aco}}{A - B} \right) - C(A - B) \right] (P_{dc} - B) + C(P_{dc} - B)^2
\]

where \( P_{aco} \) is the maximum AC output power for inverter at reference or nominal rating conditions, \( P_{dc} \) is the DC power at the inverter input and parameters \( A \), \( B \) and \( C \) are given by the following equations:

\[
A = P_{dco}[1 + C_1(V_{DCsim} - V_{dco})]
\]

\[
B = P_{dco}[1 + C_2(V_{DCsim} - V_{dco})]
\]

\[
C = C_0[1 + C_3(V_{DCsim} - V_{dco})]
\]

where \( V_{DCsim} \) is the DC voltage at the inverter input, \( V_{dco} \) and \( P_{aco} \) are respectively the DC voltage and power inputs at which the AC-power rating is achieved at the reference rating condition, \( P_{aco} \) is the DC power required at the inverter input to start working properly and \( C_1 \), \( C_2 \) and \( C_3 \) are empirical coefficients to adjust the \( P_{AC}(P_{DC}) \) characteristic of the inverter.

The values of main parameters involved in Eq. (11) used in this work for modelling the inverters are shown in Table 2.
4.3. Grid connected PV system simulation

The main objective of the simulation of grid connected PV system is to obtain expected evolution of voltages and currents at the DC side of the system as well as at the AC side, at the inverter output. So, simulation results will give the expected behaviour, in a dynamic way, of the whole system taking into account real conditions of climate parameters. From simulation results the values of power \( P \) and energy, instantaneous \( (E_{\text{inst}}) \) and cumulative \( (E_{\text{cum}}) \) energies, can be evaluated as follows:

\[
E_{\text{inst}} = P \Delta t \tag{15}
\]

\[
E_{\text{cum}} = \sum_0^t E_{\text{inst}} \tag{16}
\]

The simulation of the whole grid connected PV system is based on the models presented above for PV modules and for the inverter and is carried out also in LabVIEW environment. The flowchart of the simulation process is depicted in Fig. 6.

The calculation of the power and cumulative and instantaneous energies, AC and DC, generated by the photovoltaic system in dynamic regime is evaluated using another VI.
Finally, the expected values of the system yields: Reference yield \( (Y_r) \), array yield \( (Y_a) \) and final yield \( (Y_f) \), as well as the performance ratio \( (PR) \), can be evaluated from the simulation results using the following expressions (Häberlin and Beutler, 1995; Commission of the European Communities, 1997):

\[
Y_r = \frac{G}{G_{ref}}
\]

\[
Y_a = \frac{E_{dc}}{P_o}
\]

\[
Y_f = \frac{E_{ac}}{P_o}
\]

\[
PR = \frac{Y_r}{Y_f}
\]

where \( G_{ref} \) is the irradiance at STC, \( G \) is the measured irradiance and \( P_o \) is the nominal PV system power.

Fig. 7 shows the evolution of \( Y_r \) along a day and its value for this day obtained from LabVIEW simulations.

5. Results and discussion

5.1. PV module model validation

In order to validate the PV module model used to predict the whole PV system performance, a procedure based on outdoor measurement and analytic derivation of the expected five main parameters \( (I_{ph}, I_{sat}, n, R_s, R_{sh}) \) (Chouder and Silvestre, 2012) has been integrated in LabVIEW environment as a separated module. The developed procedure finds out the five parameters at STC \( (1000 \text{ W/m}^2 \text{ and } 25 \degree \text{C}) \) and then calculates them for any other real operating condition. The effect of variation of the parameter values of a single PV module affects the entire PV system performance (D’Alessandro et al., 2011). Our method includes parameter extraction techniques for the whole system that allow a good estimation of the system output. If some parameter of a PV module changes and important differences between simulation results and monitored data are observed, is necessary to run again the parameter extraction algorithm and check again if simulation results show a good agreement with monitored data.

Main results obtained, applying the parameters extraction procedure, are summarized in Table 3. The visualization panel performing this task is shown in Fig. 8. The validation of the procedure is carried out by comparing real measurement of I–V characteristics measured at outdoor conditions and the simulated one generated by introducing the expected five model parameters. The result of this comparison is consolidated by plotting the error curve between simulated and measured I–V characteristics and quantifying the main error indicator as seen in Fig. 9 and reported in Table 4. These values are below previous reported values for errors obtained in simulations of PV modules (Mahmoud et al., 2012; Villalva et al., 2009).

The resolution of Eq. (6) shows an increasing error between simulation and measurement near the open circuit voltage, as can be seen in Fig. 9. It is essentially due to numerical stability, because the number of points generated by the simulation is less than the number of points given by the IV tracer PVPM2516, so the calculation of the error is also affected at high voltage.

5.2. Analysis of PV system simulation Results

The variable climates used in the simulations carried out to analyze and validate the simulation procedure of the PV system, presented before in Section 4.2, are temperatures and irradiances obtained from the monitoring system shown in Fig. 10. The samples have been measured with a time step of 1 min.

The simulation of the PV system behaviour, following the flow chart shown in Fig. 6, was done in real time. Main results obtained for DC voltage and current at the output of the PV array are shown in Fig. 11. As can be seen, a good agreement is obtained between simulation results and monitored data. Main differences observed between 15.00 h and 18.00 h for the current are due to inverter disconnection forced by grid disturbances at the end of the day.

The results obtained for the generated power at the DC and AC sides of the system are shown in Fig. 12, where the effect of the inverter disconnection is present again.

Table 5 summarizes the errors observed between monitored values and simulation results for power and energy...
generated by the PV system, giving a good approach to the accuracy of the simulation procedure.

Root mean square errors (RMSEs) below 4% are obtained for power and energy delivered by the PV array, these values are below previous RMSE values reported in the literature in simulations of PV systems (Chouder and Silvestre, 2009) and in the same order of magnitude than MSE errors obtained using neural networks algorithms (Yu and Chang, 2011).

The whole system has been monitored along the months of June, August and September 2012 using the presented procedure. Simulations of the dynamic system behaviour...
have been carried out in the same period of time. Fig. 13 shows the values obtained for the reference yield, $Y_r$, for the second and third weeks of June and Fig. 14 shows the same information for different days corresponding to these 3 months.

The comparison between monitoring (meas) and simulation results (sim) for the array and final yields are given in Figs. 15 and 16 for the same weeks of June. This information is enlarged in Figs. 17 and 18 for several days for these 3 months.

Table 4
Main error values between measured and simulated parameters.

<table>
<thead>
<tr>
<th>Relative error</th>
<th>$E_{Isc}$ (%)</th>
<th>$E_{V_{oc}}$ (%)</th>
<th>$E_{P_{m}}$ (%)</th>
<th>$E_{R_{m}}$ (%)</th>
<th>RMSE(A)</th>
<th>RMSE(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.97</td>
<td>-1.07</td>
<td>1.63</td>
<td>0</td>
<td>0.13</td>
<td>2.66</td>
</tr>
</tbody>
</table>
On June 19 we removed intentionally one string from the whole PV array to show the effectiveness of the model to detect malfunctions. So in this day the simulation results gave the result of a healthy system, while the monitored data gives lower output power. As can be seen in Figs. 15 and 16, the comparison of monitored data and simulation results gives the opportunity to detect a malfunction in the system.

Finally the values obtained for the performance ratio are given in Figs. 19 and 20. As can be seen a good agreement is found between simulation results and monitored data.

### Table 5
Indicators of the accuracy of the simulation procedure.

<table>
<thead>
<tr>
<th></th>
<th>$P_{DC}$</th>
<th>$P_{AC}$</th>
<th>$E_{DC}$</th>
<th>$E_{AC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean error</td>
<td>61.13 W</td>
<td>80.97 W</td>
<td>0.17 Wh</td>
<td>0.22 Wh</td>
</tr>
<tr>
<td>RMSE</td>
<td>6826 W</td>
<td>95.17 W</td>
<td>0.19 Wh</td>
<td>0.26 Wh</td>
</tr>
<tr>
<td>RMSE%</td>
<td>2.73</td>
<td>3.81</td>
<td>2.73</td>
<td>3.81</td>
</tr>
</tbody>
</table>

### 6. Conclusion

This work presents an integral LabVIEW platform of monitoring, modelling and simulation of grid connected PV systems. In the same platform, we propose the modelling of the PV module identified with outdoor measurements of $I-V$ curves in order to extract the main PV module parameters. The PV module modelling and extraction parameters procedure has been successfully validated experimentally.

For the dynamic behaviour modelling of the PV system, an accurate model of the Inverter is included. The inverter model allows to predict AC output power as a function of DC input voltage and DC input power. The simulation methodology of the PV system in real dynamic conditions of work has also been been validated successfully in a grid connected PV system located in Argelia.

The developed platform allows the acquisition and control of all necessary data from the PV system, the simulation in real time of the whole PV system working in...
dynamic behaviour, calculates the performance ratio, PR and Yields of the system, create HTML and XLS report files and visualize all these data and the dynamic system behaviour in real time. This toolbox results in robust modelling, advanced simulation incorporating predictions of system output with respect to solar resource, local weather
Fig. 16. Final yield June 2012.

Fig. 17. Array yield along summer 2012.

Fig. 18. Final yield along summer 2012.
and system behaviour. The output results obtained from this toolbox could allow the inclusion in the same platform an algorithm for automatic supervision and fault detection of the PV system.

References


