DEVELOPMENT OF A DATA ACQUISITION SYSTEM FOR PHOTOVOLTAIC SYSTEMS

Jonas Platini Reges[1] – jonasplatini1993@gmail.com
Francisco Ismael de Oliveira[2] - ismael.oliveira@ifce.edu.br
José Renato de Brito Sousa[2] - renato@ifce.edu.br
Paulo Cesar Marques Carvalho[1] - carvalho@dee.ufc.br
Auzuir Ripardo de Alexandria[2] - auzuir@gmail.com
[1]Universidade Federal do Ceará, Departamento de Engenharia Elétrica
[2]Instituto Federal do Ceará, Departamento da Indústria

Abstract. *The generation of energy through alternative renewable sources for the Brazilian energy matrix is very important for the safety of the electric energy network, due to the diversification of the fundamental elements for power generation. Therefore, photovoltaic systems are a good solution for this application for they have a relatively growing energy efficiency. The monitoring in the generation of electric energy is essential as a way to analyze statistically the yields of electric power generation and to validate the technical feasibility of the system. The objective of this work is the development of a data acquisition system which aims at an analysis on the performance of photovoltaic systems. This work is motivated by the implementation of a monitoring system with electrical insolation through optocouplers in the measurement, having the ability to readjust the modules and allowing the insertion of new sensors or shields. The monitoring system was developed in the Arduino platform, a platform of electronic prototyping of free hardware. The photovoltaic solar system was installed in the area of the Federal Institute of Education, Science and Technology of Ceará – Campus Jaguaribe. In total, 3 tests are performed with the monitoring system whose results are presented and evaluated. The results are analyzed with the purpose of evaluating the performance of the monitoring system as to measurement error and measurement accuracy. Then, a general analysis about the operation of the monitoring system is performed. The main contribution of this work is the development of the data acquisition system.*

Keywords: *Photovoltaic Systems, Data Acquisition, Measurement, Monitoring, Power Generation.*

1. INTRODUCTION

Since the beginning of technological advances, humanity has sought methods to evaluate the variables of various systems. Some examples are the production lines, human health, electricity distribution networks, vehicles, banking systems, gas pipelines, water supply systems, and other applications. In order to evaluate a system, it is necessary, firstly, the monitoring of the variables of its operation, such as: temperature, current, voltage, humidity, speed, density, irradiation, luminosity, frequency and time. Monitoring means observing, analyzing, monitoring and measuring, not obeying a pre-defined order. In other words, monitoring is analyzing the operating conditions of the system over a given period of time in order to see if it is within the standards. Monitoring differs from tracking, since tracking is the follow-up of the routes performed by an object or equipment (Han *et al*, 2017; Gow and Manning, 1999).

The variable chosen for monitoring will depend entirely on the type of system being monitored. Therefore, in the health area, specifically in cardiology, the main variable monitored is the heart rate (Akselrod *et al*, 1981). In the case of PV (The abbreviation PV will be used to refer to parts and components of a photovoltaic system, and may refer to the adjective photovoltaic) systems, the main variables monitored are: generated power (voltage and current) and solar irradiation (Armendariz-Lopez *et al*, 2016). Variable monitoring is indispensable when analyzing a functioning system, so with the monitoring system it is possible to make decisions either in the replacement of system components (analyzed), as well as in the use of other systems that maintain the same functioning (Rutes, 2006). In general, the monitoring of PV panels has the objective of measuring the performance of the equipment that is a characteristic of any energy conversion device, in which it is determined how much of the energy captured by the panels is effectively converted into electrical energy (Braga Junior, 2014).

However, it has to be taken into account that the efficiency of the PV module indicated in the equipment datasheet is measured under the following STC (Standard Test conditions) states: irradiance equal to 1000 W/m^2, cell temperature of 25 °C and air mass equal to 1.5 AM. These conditions are chosen to the executation of uniform comparisons of PV modules by different manufacturers (Birane *et al*, 2017).

Several authors have already studied the development of monitoring systems and the development of data acquisition systems. In the PV monitoring, several techniques are used, for example:

- Artificial Intelligence Technique: works through the mathematical analysis described through routines that use historical meteorological data (radiation, temperature, humidity, wind speed), are not applied in remote areas (Mellit and Kalogirou, 2008; Mellit and Kalogirou, 2014).

- Open Source Platforms: these plans allow the ease in the reproduction of techniques employed by several authors. Overall, they are low-cost platforms and the main development platforms are Arduino and Raspberry Pi (Oliveira Filho *et al*, 2017; Fornari *et al*, 2012).
- ZigBee-based data acquisition: This technique is applied to PV systems connected to the network, where monitoring is considered a crucial aspect to observe the stability and performance of the system (Shariff *et al*, 2015; Iskandar *et al*, 2016).
- Cyber-physical systems: cyber-physical method: use of machine learning techniques and computer vision as information, either through images or a series of physical parameters (temperature, current and voltage). In general, decisions are made (Rao *et al*, 2017; Macana *et al*, 2011).
- GSM technologies: this technique is applied in the monitoring of data in remote locations that have GSM coverage. Despite having a low data transmission, they are widely used due to their low cost and ease of implementation (Belghith and Sbita, 2014; Leccese, 2013).
- Real-time monitoring systems: In general, they are flexible, robust and reliable systems that are based on an architecture of wireless sensor networks. They are usually connected via wireless network and man-machine interface software (López *et al*, 2012; Allafi and Iqbal, 2017).

This article proposes the development of a data acquisition system for FV monitoring, built through an open source platform and with electrical isolation through photocouplers. The main objective of this work is the experimental validation of the data acquisition system. The present work is divided into five sections: section 1 reports on the development of PV monitoring systems and their technological advances; in section 2, a bibliographic review and theoretical basis on the issues addressed for the development of a data acquisition, section 3 presents the methodology used for the construction and validation of the system, section 4 presents and discusses the results obtained and lastly, in section 5 the conclusions are extracted.

2. THEORETICAL FOUNDATION AND STATE-OF-THE-ART

The topology of the PV plant is decisive in the choice of the type of monitoring equipment that will be used in the project. Therefore, when the PV system is large, the use of wireless communication networks to carry out data transmission is extremely important. However, small systems, with few panels, do not require wireless networks; they only demand a datalogger to record the power generation data (Birane *et al*, 2017; Badave *et* al, 2018; Blaesser and Rossi, 1988).

The monitoring system is a set of interconnected components that perform a measurement activity of a particular specific quantity or of various quantities. In systems of such nature, a component does not function separately, but in conjunction with other components forming a measurement system. The sensors used in monitoring systems generally work with continuous outputs with the information displayed varying continuously over time. Measurements of analogic systems can be electrical signals or signals of physical quantities converted into electrical signals (Klempous *et al*, 1999; Canto, 2007).

Some caution must be taken in monitoring systems, such as electrical insolation, signal transmission noises and correct sensor calibration. Unwanted signals such as noise can be weakened by using appropriate filters and grounding. Sensors are sensitive elements that capture how physical quantities, one or more, are being measured. Generally, in a data acquisition system the term transducer is used for devices that convert a measured signal into another, generally an electrical one (Vilela, 2010). According to Vilela (2010), the monitoring system consists of transducers, a digital display with keyboard (IHM), USB communication interface and a microcontroller. These elements are connected to one another and work together.

A decisive factor for the installation of a PV plan is what type of PV module technology should be acquired. Therefore, the ideal is to carry out the monitoring of the parameters of several panels in order to obtain the electrical conversion efficiency (El-Baz *et al*, 2018). Researches such as the work of (Braga Junior, 2014) help in deciding the type of PV panel that should be chosen because the author performed a work of performance monitoring in an experimental way with 13 PV modules of 5 different technologies. The study was conducted at the Federal University of Pará, from October 21, 2012 to August 30, 2013.

Real-time monitoring systems enable better detection of failures, as well as the possibility of checking the parameters that are being worked (monitored) in relatively small time intervals. Ribeiro (2015) present a system of monitoring and control of a water distribution process, using Arduino and GSM protocol which has a facility in the implementation for having been made with the help of a free hardware and software platform, in addition to the use of low cost components such as temperature and current sensors and a SIM900 GSM modem.

In order to perform the analysis of the PV performance of the different panels, Braga Junior (2014) used a monitoring system. The system consists of two PV cell-type irradiance sensors, a PT100 temperature sensor for each panel installed, a meteorological station responsible for measuring wind speed, air humidity and ambient temperature, a commercial datalogger with a memory card of the Compact Flash type, a data acquisition system (voltage and current) and an external power supply. According to the author, dataloggers are connected to a datacenter for real-time monitoring.

However, PV monitoring systems can be a good option to reduce the initial costs in PV installations, according to Coelho (2013) who developed a low-cost data acquisition system for monitoring PV generation systems. The system consists of a microcontroller PIC16F877A, a liquid crystal display and a RTC; in the monitoring of variables, the system is equipped with an ACS756 current sensor, a voltage divider (voltage sensor) and three LM35 temperature sensors. This type of system monitors power generation only.

Dias (2015) developed a monitoring system for load control in a PV micro-installation. The system used for data management and control is developed in Arduino and the model used is the Atmega 2560. The sensors used were the ACS712 (Current sensor), Voltage sensor, LM35 (Temperature sensor) and the monitoring of the irradiance was through a PV module calibrated with the aid of a weather station.

Monitoring systems that use multiple sensors to measure various variables has a higher level of complexity. However, parting from the increase of the number of sensors, the performance of analysis on a certain monitored system becomes more reliable. In their respective works, (Fornari *et al*, 2012), Canto (2007) used several sensors such as: temperature sensors, photoresistance, photodiode, relative humidity sensor, barometric pressure sensor, precipitation sensor, wind speed sensor (using reed switch) and anemometers. Fornari *et al* (2012) and Leccese (2013) in addition to using the various sensors, installed them in three different towers, putting data acquisition systems together with different transmission systems.

In their work Vera and Krenzinger (2007), made the comparison between the simulated values and the real values for an autonomous PV system. To obtain the real values, the researcher developed a monitoring system consisting of a computer, an HP-34970A data acquisition unit, sensors and a computer program to manage the process. The variables monitored in this work were: current, voltage and temperature of the panel, current and voltage of the battery bank, current consumed by the load, incident solar radiation, ambient temperature, direction and wind speed.

Rutes (2006) set up a monitoring and control system for a reversible fuel cell-powered vehicle composed of two transceivers, two microcontrollers and one didactic vehicle. The vehicle has an PV panel that performs the electrolysis of water in the fuel cell itself, generating hydrogen and oxygen. A microcontroller in the vehicle manages the acquisition of data such as distance traveled by the vehicle, temperature and currents (fuel cell and PV panel). Through the transceivers and microcontrollers, the data is sent to a microcomputer. Finally, it is possible to check the efficiency of the fuel cell.

Monitoring systems that have the largest type of properties provide the user with a better analysis of their data. Certain monitoring systems are built with various types of sensors and in large quantities. The diversity of sensors depends directly on the variables that the user needs for monitoring. In addition to the sensors, the datalogger is important, as it is a component for storing and recording the levels of monitored variables. A summary of the properties of the monitoring systems of each author is shown in Tab. 1.

Table 1 - Properties of monitoring systems.

Researcher	**Sensor**					**Datalogger**
	Irradiation	**Temperature**	**Currente**	**Voltage**	**Wind Speed**	
Braga junior (2014)	Yes	Yes	Yes	Yes	Yes	Yes
Ribeiro *et al* (2015)	No	No	Yes	Yes	No	No
Coelho *et al* (2013)	No	Yes	Yes	Yes	No	Yes
Canto (2007)	Yes	Yes	Yes	Yes	Yes	No
Fornari *et al* (2012)	Yes	Yes	No	No	Yes	Yes
Vera and Krenzinger (2007)	Yes	Yes	Yes	Yes	Yes	Yes

By observing Tab. 1 it is possible to verify that the Braga junior (2014) monitoring system has 5 types of sensors and is equipped with a datalogger, while the monitoring system of Ribeiro *et al* (2015) has only 2 types of sensors and does not have a datalogger. Comparing these works, one is able to verify that there are better systems indicated for a more comprehensive analysis, that have a greater number of sensors when compared to others. A larger range of sensors enables a more complex analysis, due to the diversity of analyzed variables.

3. MATERIALS AND METHODS

The work is developed in three stages: in the first one, the development of the PV monitoring system is carried out, as well as the realization of the calibration of the sensors separately in bench; in the second one, the calibration of the complete system is carried out and in the third one, the installation of the monitoring system in the field is carried out, together with the solar PV system.

3.1 PV monitoring system

The monitoring is installed in three points, measuring current and voltage:

- Point 1: Between the panel and the charge controller (power of the PV panel).
- Point 2: Between the battery and the charge controller (Battery power).
- Point 3: Between the charge controller and the charge (Power delivered to the load).

The monitoring process is performed by sensors that pick up the voltage and current values of the battery, the panel and the charge. These levels are sent to a microcontroller that, in the scope of this work, is the Arduino. The data sent to the Arduino is organized and registered through the SD card module in a micro SD 8 Gigabyte memory card. The monitoring is performed in real time by means of a display that shows voltage, current and power levels in addition to the schedule. A diagram illustrating the steps that make up the monitoring system is shown in Fig. 1.

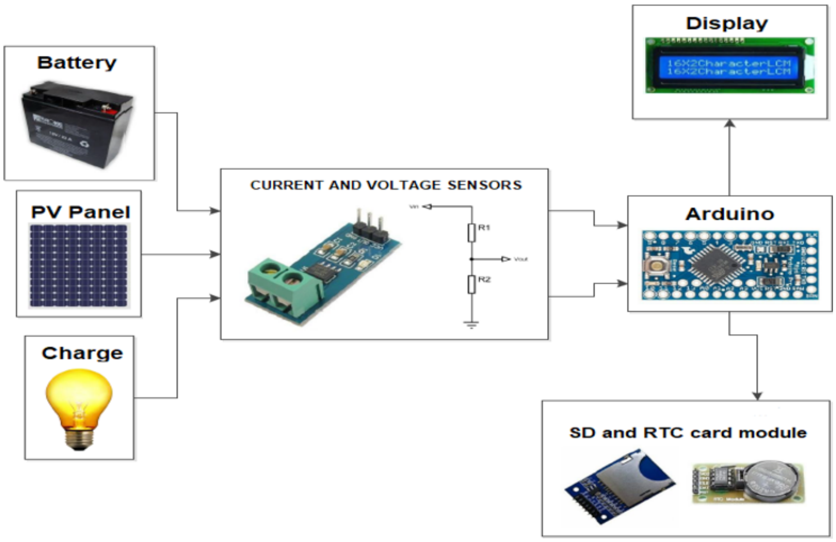


Figure 1 - Diagram of a) the components of the complete system.

Each component of the system requires a different connection type with Arduino. Some of these components must be connected to specific microcontroller ports. The sensors used in this work are connected to the analog ports of the Arduino Pro Mini, because they work with quantities that vary continuously over time within a range of values. The wiring schemes of the components were designed in the program Fritzing electronics made easy Version 0.9.3 (Fritzing, 2012).

The system consists of 3 current sensors ACS712 that measure the electric current through the hall effect, having an electrical insolation; 3 voltage sensors that basically are 3 voltage dividers, which have an electrical insolation through the optocoupler HCPL-7520, used for application of isolation of analogic signals; 1 datalogger which is composed of an SDcard module and a RTC module DS1302; 1 16x2 LCD display with I2C serial module and 1 Arduino Pro Mini Atmega328 microcontroller.

The PV system used in this work is an autonomous system, equipped with a load controller, bank of batteries and a load of continuous voltage. The charge controller used is the Solar Charge Controller - Black 12 V / 24 V 30 A. The battery used is the Unipower UP1272 Acid Lead Regulated Valve (VRLA), has a nominal voltage of 12 V and a rated capacity of 7.2 Ah. The solar panel used in the experiment is a monocrystalline with a power of 10 W of the company Sun Home Solar Energy model: ST-M10. Finally, as load of the experiment was used a automotive lamp of 12 V 5 W.

3.2 Calibration methodology

Firstly, the current and voltage sensors were separately calibrated in pairs, the PV panel, charge and battery. In the calibration, two multimeters of Politerm model POL-41A were applied. A multimeter was used in parallel with a lamp to perform the voltage measurement and another multimeter in series with the charge to carry out the current measurement. An adjustable voltage source was used in the calibration of the monitoring system. The system was applied by inserting a voltage of 21 V and a current of 33 mA. Two 12 V and 5 W lamps in series were used as charge to divide the voltage used in the calibration. The values shown on the two multimeters were noted and taken with the standard for the calibration. The connection scheme of the multimeters for calibration of the monitoring system is shown in Fig. 2.

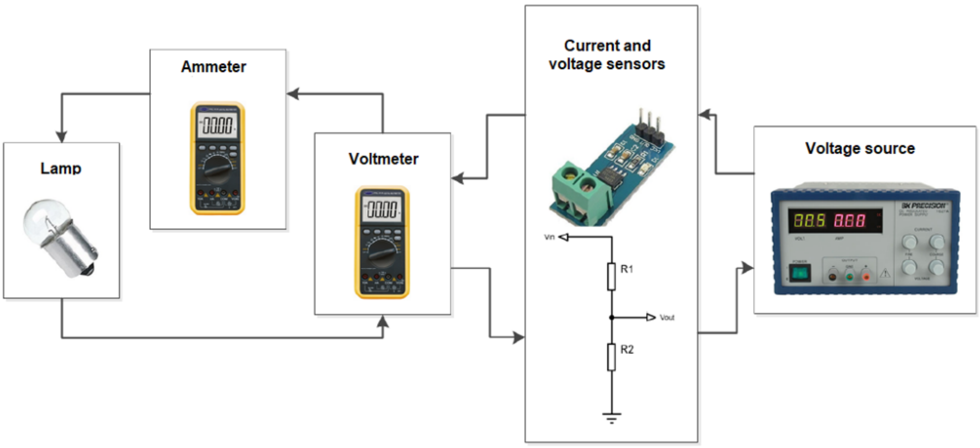


Figure 2 - Diagram of the connection of the multimeters.

Measurement by the voltage sensor is performed by the simple average of 500 samples per second, providing a good stabilization in the real value of the measurement. Larger sampling could not be used due to Arduino's own memory capacity. The voltage and current measurements by sensor were collected in a time period of 10 minutes, in which information was collected at 1 second totaling 600 measurements. Calibration occurred within the IFCE - Campus Jaguaribe, at the Electricity Laboratory (geographical coordinates: 5° 52' 45.2" S 38° 36' 32.4" W), with an ambient temperature of 25 °C.

After calibration of the sensors of the monitoring system separately in pairs, the calibration of the complete system was performed. In this step, the charge controller that works in parallel with the monitoring system was connected, along with the PV panel, a battery and the same charge used in the previous calibration. The monitoring system remained within the Electricity Laboratory and a PV panel was installed in the field without tilting and on a wooden support.

The calibration of the complete system occurred over a period of 60 minutes with measurements taken every 1 second, with a total of 3600 measurements. This calibration was important to improve small errors that went undetected in the previous calibration and to verify the operation of the complete monitoring system. Next, the PV panel was installed in the surroundings of the Federal Institute of Education, Science and Technology of Ceará - Campus Jaguaribe in a lot near the parking lot and the administrative block. The angle of inclination to the horizon (azimuth angle) is 10°. After the installation, the PV panel temperature measurement was performed with a Leetools infrared digital thermometer. The panel showed a temperature of 45 °C.

The methodology used in this stage of the work intends to measure the voltage and current magnitudes (generated, stored and consumed) through the monitoring system. After the measurements are stored and stored, the evaluation metrics will be performed.

3.3 Evaluation metrics

The metrics used to analyze the performance of solar PV generation in this work will be: Average, Standard deviation, Average hit rate (efficiency) and Average quadratic error. The performance of electric power generation will be evaluated based on the evaluation metrics. The value of the average points to where the data of a distribution is most concentrated, being calculated by combining the values of a set given by the formula:

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n}x_1 \tag{1}$$

where $\bar{x}$ is the average, n is the quantity of values and x i is the real value.

Standard deviation is the most common measure of statistical dispersion, indicating what the "error" is, if one wishes, to replace one of the values collected by the average or expected value given by:

$$SD=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_1-\bar{x})^2} \tag{2}$$

where *SD* is the standard deviation.

The average accuracy rate is used for comparison and quality of measured values. This rate measures the percentage of predictions in which the desired patterns and patterns whose measurements return coincide. The average accuracy rate of all the embodiments are given by:

$$ARR(\%)=\frac{1}{n}\sum_{i=1}^{n}\frac{x_1}{x}\times 100 \tag{3}$$

where *AAR* is the average accuracy rate, *n* is the quantity of values, *x* is the default value and x_1 is the real value.

The average square error is an estimator of a scalar parameter, widely used to compare estimators. The sum of the differences between the estimated value and the real value of the data, weighted by the number of terms, given by:

$$ASE=\sum_{i}\frac{(x_1-\hat{x}_1)^2}{n} \tag{4}$$

where x_1 is the real value and $\hat{x}_1$ is the estimated value.

4. RESULTS AND DISCUSSIONS

According to the proposed methodology, the results of the PV solar energy generation were obtained. In this section, the data acquisition system is validated experimentally, as well as an analysis on the calibration of the monitoring system is performed. Finally, the operation of the field-installed solar PV system is analyzed and discussed.

4.1 Result for sensor calibration

The calibration occurred during the period of 10 minutes per sensor. The results obtained were analyzed according to the evaluation metrics and are presented in Tab. 2.

Table 2 - Evaluation of the calibration by sensors.

Element	Sensor	Standard	Average	SD	AAR	ASE
PV Panel	Voltage	20.56 V	20.66 V	0.15	99.51%	0.033
	Current	0.336 A	0.338 A	0.00	99.39%	
Battery	Voltage	20.71 V	20.69 V	0.15	99.47%	0.023
	Current	0.337 A	0.330 A	0.00	97.94%	
Charge	Voltage	20.95 V	20.95 V	0.15	99.37%	0.035
	Current	0.339 A	0.340 A	0.00	99.71%	

One can note that for all sensors (voltage and current) the average of the values obtained has a small variation from the standard measurement performed through the multimeters, explained by the absence of the voltage and current variation supplied by the controlled voltage source. By analyzing the average rate of accuracy, all measurements promote good accuracy, taking the sensor to an average accuracy rate close to 100%. As for the standard deviation, it is observed that the current and voltage sensors have standard deviations close to 0. This fact occurs due to the use of a controlled voltage source that practically does not have significant variations in the instantaneous values of tension and current. Finally, when analyzing the average square error, it turns out that the difference between the real value and the measurement value is zero.

4.2 Verification Results of the Monitoring system

The verification occurred for the period of 60 minutes, when the voltage, current and power values of the panel, battery and load were obtained. For the analysis, values for an average measure with time intervals of 5 minutes, for example, were obtained. Calibration was performed for a period of 60 minutes. In Tab. 3 shows the monitoring system verification evaluation.

Table 3 - Evaluation of the verification of the monitoring system

Module	Sensor	Average	SD	ASE
Current (A)	Panel	0.15	0.16	0.024
	Battery	0.21	0.01	0.000
	Charger	0.10	0.04	0.002
Voltage (V)	Panel	11.85	0.90	0.743
	Battery	11.60	0.89	0.728
	Charger	12.54	0.28	0.073
Power (W)	Panel	1.98	2.11	4.068
	Battery	2.64	0.13	0.015
	Charger	1.14	0.42	0.165

It was observed that the charge voltage remained practically constant throughout the verification period. As for the panel and the battery, the voltages vary. In the PV panel, the variation occurs due to the variation of temperature and incident direct solar radiation. In the battery, the variation occurs due to the reduction in power supply of the PV panel and the energy consumption by the charge. Current results remain virtually constant during the verification period. The panel showed, during the verification, abrupt variations of current, with a maximum of 0.37 A and a minimum of 0.02 A. One possible explanation for this is the presence of clouds in the sky during the verification. The presence of clouds in the sky interferes in the direct incidence of solar radiation. As for the charge, the observation shows that in the first 30 minutes, the current undergoes a small variation. However, the remaining 30 minutes of the verification show an increase in the current requested by the electric charge.

Analyzing the power results, it is observed that the power supplied by the panel is reduced during the verification. The charge has an average consumption of 1 W and the battery a power of 2.7 W. At the start of the verification (initial 30 minutes), the panel supplies power to the battery (charging) and the charge (consuming). In the final 30 minutes of the verification, the panel does not provide power, in contrast, the battery (discharging) feeds the charge (consuming).

One can note that the standard deviation of all sensors has a small value, what indicates that the measurement error over the 60-minute period was low, except for the panel power which has a standard deviation of 2.107. As for the average square error, it is noted that the power of the panel has the highest value, which shows that the measurement error is relatively high. However, the average squared error is minimal in the battery and charge sensors. This result is explained by the low variation in current, voltage and battery and charge power values. By analyzing the results of the verification, one may conclude that the monitoring system presents errors, mainly in the voltage sensor of the panel. This error can be explained by the presence of noise during the measurement. One measure of noise reduction is the insertion of a capacitive filter at the input of the optocoupler.

4.3 Result of installation of the field monitoring system

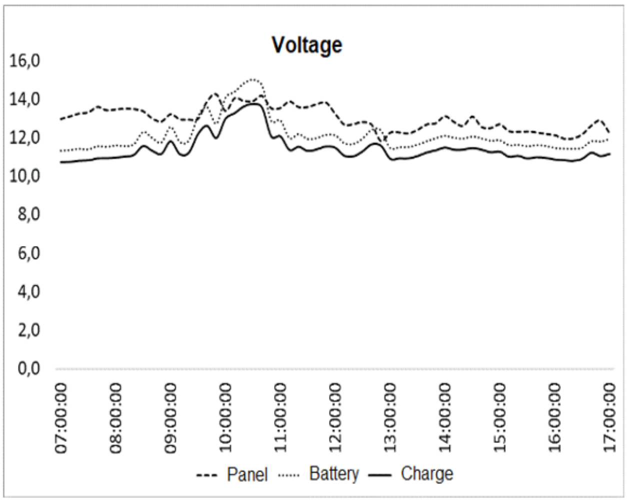
In this section the results of the measurements performed by the field-based monitoring system are presented and discussed. The measurements are voltage, current and power of the PV panel, battery and load, during the period from 07:00:00 to 17:00:00 between April 1, 2017 and April 11, 2017. The results are presented by the average of the eleven measurements performed. Finally, an analysis is performed on the evaluation metrics used on the field-based monitoring system.

In Fig. 3a shows the voltage chart of the PV panel, battery and charge. It is observed that the PV panel generated 14.2 V of maximum voltage in the period between 10:00 and 12:00 and 11.8 V of minimum voltage in the periods of 12:30 and 16:00. However, throughout the measurement period, the PV solar energy generation remained practically constant, with small variations. However, by observing the voltage and current graphs on the battery and the charge, it is noted that both follow an equal inclination, differentiating them only by their voltage level. In the period between 10:00 a.m. and 11:00 a.m., the battery voltage level was higher than the PV generation level. This fact is explained due to the charge controller that, minutes before, was in the charge function of the battery.

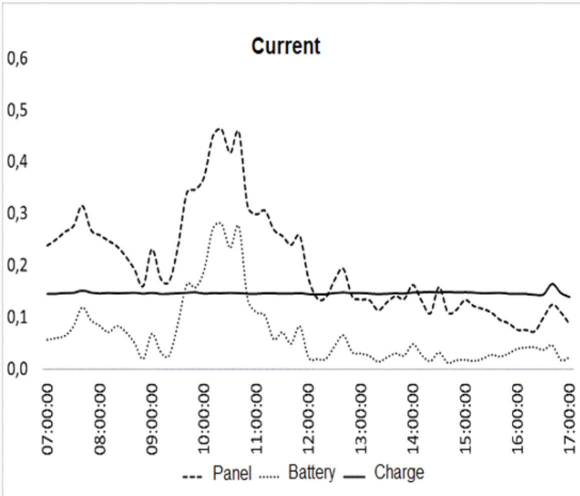
In Fig. 3b, the current graphs of the PV panel, battery and charge are presented. By observing the panel and the battery current graphs, one can note that the battery current is directly connected to the current supplied by the PV power generation. However, at the end of the day, the current of the charge depends on the sum of the PV generation and battery currents. In the period between 07:00 and 12:00 hours, the battery remained in charge. By observing the graph, one can note that, because the current demanded by the load is constant at 0.2 A and the current generated by the

PV system is higher than the requested current, the rest of the current was directed to the charging of the battery. In the period between 10:00 a.m. and 11:00 a.m., the current generated by the PV system obtained a maximum value of 0.5 A and the current delivered to the battery (charging) was higher than the current requested by the charge.

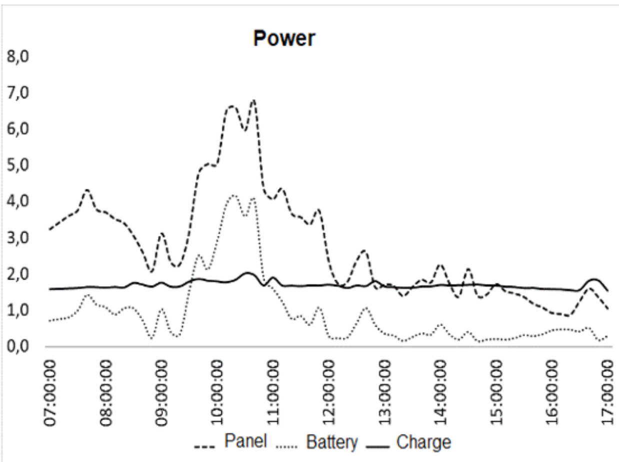
In Fig. 3c shows the power outputs through the PV panel, energy storage through the battery and energy consumption through the charger. The PV panel has a high power generation at the beginning of the day between 09:30 and 12:00 hours. By observing the power of the battery all day, its behavior is similar to the power generated by the PV panel. However, after noon, because the power consumption remains stable, the power drops as the PV generation decreases. As for the power consumed by the charger, it is observed that it remains practically constant over time. However, there are small variations in power throughout the day and in the low generation of PV energy. When the PV power generation is reduced, the load controller has power management failures. This fact is observed in Fig. 3, at the end of the day, showing battery charging with reduced generation and increasing consumed power when power generation increases again.



(a) Voltage.



(b) Current.



(c) Power.

Figure 3 - Average energy generation graph.

The metric results are presented in Tab. 4. One can note that the standard deviation value of all sensors are relatively small, indicating that the measurement error over time was low, except for panel power (1.507) and battery power (0.990). The standard deviation of the sensors that make up the power generation (PV panel) is higher due to the various current and voltage variations provided by the external environment. Since the panel is subject to variation of the Sun's inclination relative to Earth (reducing or increasing power generation) and the passage of clouds that block the direct incidence of solar radiation, the standard deviation in the sensors related to power generation is high, when compared to others (battery and charge). Observing the ASE, we could verify that the power of the panel was the one that presented the biggest error, while the others were relatively low and even null.

Table 4 - Metric evaluation on the monitoring system

Module	Sensor	Average	SD	ASE
Current (A)	Panel	0.204	0.101	0.010
	Battery	0.069	0.066	0.004
	Charger	0.148	0.003	0.000
Voltage (V)	Panel	12.997	0.621	0.379
	Battery	12.135	0.874	0.752
	Charger	11.449	0.716	0.504
Power (W)	Panel	2.768	1.507	2.233
	Battery	0.936	0.990	0.964
	Charger	1.699	0.098	0.009

The productivity and the daily power with the respective standard deviations are shown in Fig. 4. The average power of the PV panel remained practically constant over the 11 days with an average standard deviation of 2. During some days, the power had a maximum of 4 W, with a daily productivity of 32.29% and a minimum of 2.5 W, with a daily productivity of 20.19%. However, the average productivity over the measurement period was 23.07%.

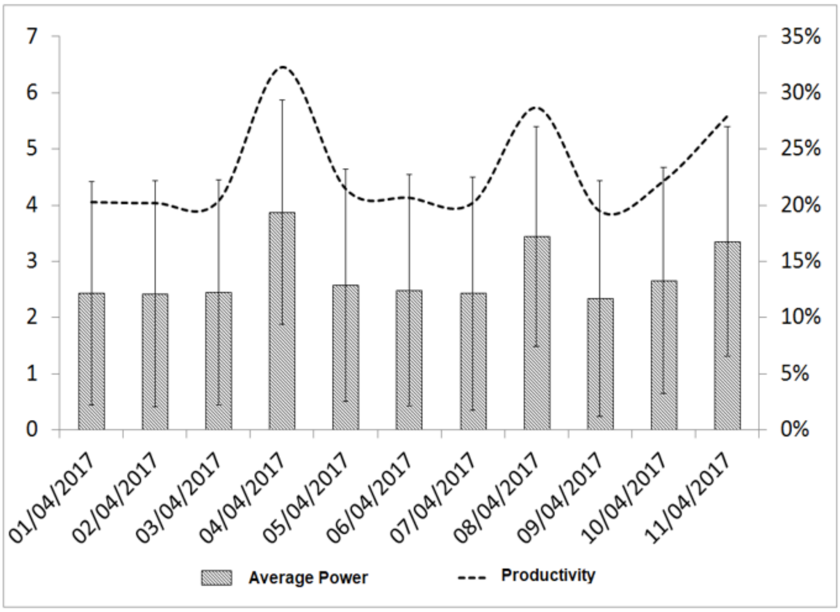


Figure 4 - PV panel installed in the field for calibration of the monitoring system.

However, we noted that the field monitoring system obtained good results, although it did not present a good precision in the sensors related to the panel and load. This fact is explained due to the variations provided by the external environment that directly influence the monitoring.

5. CONCLUSION

The monitoring system was developed based on the Arduino platform, which facilitated adaptations and modifications in the structure, since it is a free and very versatile platform. In the first stage, the calibration of the sensors occurred in a positive way presenting low values in the standard deviation and in the average square error, indicating that the error is practically nonexistent. It presented na average square error with values very close to zero, indicating that the monitored value is very close to the estimated value (measurement made through the multimeters).

In the second stage, the verification of the monitoring system occurred positively. The system, in some sensors, did not present any error, as in the current sensor of the battery with the average square error of value 0, indicating that it practically does not have any error. However, in contrast, the power of the panel had na average square error of 4.068 and a standard deviation of 2.11. These values show that the indicator has the relatively considerable error and a high variation of the measured value.

In the third stage, the monitoring system was installed in the field together with the PV system where the generation, storage and consumption of energy were analyzed during the period from April 1, 2017 to April 11, 2017 from 07:00 a.m. to 5:00 p.m. At the beginning of the day, power generation was higher with a maximum power of 6.5 W (11:00 a.m.), and a reduction throughout the afternoon reaching almost 1 W. The charge remained practically constant with an average power of 1.7 W. The energy storage behaved just like the panel at the beginning of the day and at the end of the day remained practically constant.

Analyzing the metric evaluation of the field-installed monitoring system, it is apparent that the standard deviations were relatively low with the exception of panel power with 1.507. The system obtained high values in the average square error indicating that part of the system has a low accuracy in the panel current and charge sensors. However, the PV system presented a reasonable productivity during the experiment with an average power of 2.7 W, since the PV panel used has a low energy efficiency. The average income from energy generation is 23.07%, although the INMETRO (National Institute of Metrology, Quality and Technology) seal shows a lowest energy efficiency value. It is noteworthy that some days were sunny and others cloudy due to the rainy season in the city of Jaguaribe - CE. In general, we can assert that the data acquisition system got a good functioning, being able to monitor and register the requested data. It has presented some measurement errors and low precision in certain sensors, however, when analyzing the system completely, a good operation has been verified.

Acknowledgment

To the Federal Institute of Education, Science and Technology of Ceará - Campus Jaguaribe and Federal Institute of Education, Science and Technology of Ceará - Campus Fortaleza for the availability of equipment and space for conducting the research. The authors would like to thank the financial support of CNPq for the present project.

REFERENCES

Akselrod , S. Gordon, D. Ubel, F. A. Shannon, D. C. Berger, A. Cohen, R. J. 1981. Power spectrum analysis of heart rate fluctuation: a quantitative probe of beat-to-beat cardiovascular control, Science, vol. 213, n. 4504, pp. 220-222.

Armendariz-Lopez, J. Luna-Leon, A. Gonzalez-Trevizo, M. Arena-Granados, A. Bojorquez-Morales, G. 2016. Life cycle cost of photovoltaic technologies in commercial buildings in baja California, Mexico, Renewable Energy, vol. 87, pp. 564-571.

Allafi, I. Iqbal, T. 2017. Design and implementation of a low cost web server using esp32 for real-time photovoltaic system monitoring, Electrical Power and Energy Conference (EPEC), pp. 1-5.

Badave, P. M. Karthikeyan, B. Badave, S. Mahajan, S. Sanjeevikumar, P. Gill, G. S. 2018. Health monitoring system of solar photovoltaic panel: An internet of things application, Advances in Smart Grid and Renewable Energy, pp. 347-355.

Belghith, O. B. Sbita, L. 2014. Remote gsm module monitoring and photovoltaic system control, Green Energy, pp. 188-192.

Birane , M. Larbes, C. Cheknane, A. 2017. Comparative study and performance evaluation of central and distributed topologies of photovoltaic system, International Journal of Hydrogen Energy, vol. 42, n. 13, pp. 8703-8711.

Blaesser, G. Rossi, E. 1988. Extrapolation of outdoor measurements of pv array i–v characteristics to standard test conditions, Solar Cells, vol. 25, n. 2, pp. 91-96.

Braga Junior, W. 2014. Monitoramento do desempenho de diferentes tecnologias de módulos fotovoltaicos, Dissertação de Mestrado, UFPA, Para.

Canto, M. A. R. 2007. Projeto e desenvolvimento de um sistema automatizado para monitoramento de fontes alternativas de energia, Dissertação de mestrado, Universidade Estadual Paulista (UNESP), São Paulo.

Coelho, F. Silva, V. Borges neto, M. R. Lopes, L. Silva, R. G. Cunha, L. D. B. 2013. Desenvolvimento de um sistema de aquisição de dados de baixo custo para monitoramento de sistemas de geração fotovoltaica, Congresso Norte Nordeste de Pesquisa e Inovação, p. 1.

Dias, R. M. 2015. Instalação de uma microrrede fotovoltaica conectada/isolada com estocagem e monitoramento com controle da carga alimentada, Dissertação de Mestrado, Universidade do Vale do Rio dos Sinos, Porto Alegre.

El-Baz, W. Honold , J. Hardi, L. Tzscheutschler, P. 2018. High-resolution dataset for building energy management systems applications, Data in brief, vol. 17, pp. 157-161.

Fornari, C. I. Beloto, A. F. Vilela, W. A. Berni, L. A. 2012. Unidade de monitoramento ambiental visando o estudo da irradiância solar em função da temperatura e umidade, IV Congresso Brasileiro de Energia Solar e V Conferência Latino-Americana da ISES, pp. 1-8.

Fritzing. 2012. Fritzing electronics made easy. [Online]. Available: http://fritzing.org/support-us/

Gow, J. Manning, C. 1999. Development of a photovoltaic array model for use in power-electronics simulation studies, IEE Proceedings-Electric Power Applications, vol. 146, n. 2, pp. 193-200.

Han, J. Jeong, J. D. Lee, I. Kim, S. H. 2017. Low-cost monitoring of photovoltaic systems at panel level in residential homes based on power line communication, IEEE Transactions on Consumer Electronics, vol. 63, n. 4, pp. 435-441.

Iskandar, H. R. Purwadi, A. Rizqiawan, A. Heryana, N. 2016. Prototype development of a low cost data logger and monitoring system for pv application, Power Engineering and Renewable Energy, pp. 171-177.

Klempous, R. Lysakowska, B. Nikodem, J. 1999. A data acquisition and processing system, Africon, vol. 1, pp. 549-552.

Leccese, F. 2013. Remote-control system of high efficiency and intelligent street lighting using a zigbee network of devices and sensors, IEEE transactions on power delivery, vol. 28, n. 1, pp. 21-28.

López, M. E. A. Mantiñan, F. J. G. Molina, M. G. 2012. Implementation of wireless remote monitoring and control of solar photovoltaic (pv) system, Transmission and distribution: Latin America conference and exposition (T&D-LA), pp. 1-6.

Macana, C. A. Quijano, N. Mojica-Nava, E. 2011. A survey on cyberphysical energy systems and their applications on smart grids, Innovative Smart Grid Technologies (ISGT Latin America), pp. 1-7.

Mellit, A. Kalogirou, S. A. 2008. Artificial intelligence techniques for photovoltaic applications: A review, Progress in energy and combustion science, vol. 34, n. 5, pp. 574-632.

Mellit, A. Kalogirou, S. A. 2014. Mppt-based artificial intelligence techniques for photovoltaic systems and its implementation into field programmable gate array chips: Review of current status and future perspectives, Energy, vol. 70, pp. 1-21.

Oliveira Filho, J. I. Coelho, W. M. Zurita, M. E. D. P. V. Melo, M. 2017. Acquisition system for photovoltaic panels with data storage in remote server platforms using open source platforms raspberry pi and arduino, Journal of Electrical Engineering, vol. 5, pp. 157-162.

Rao, S. Katoch, S. Turaga, P. Spanias, A. Tepedelenlioglu, C. Ayyanar, R. Braun, H. Lee, J. Shanthamallu, U. Banavar, M. 2017. A cyberphysical system approach for photovoltaic array monitoring and control, Information, Intelligence, Systems & Applications (IISA), pp. 1-6.

Ribeiro, J. M. Santos, E. C. B. F. Oliveira, G. R. Miranda, R. A. Resende, I. T. F. 2015. Sistema de monitoramento e controle de um processo de distribuição de água, usando arduino e protocolo gsm. Blucher Chemical Engineering Proceedings, vol. 1, n. 2, pp. 11143-11150.

Rutes , M. A. 2006. Sistema de monitoramento e controle de um veículo movido a célula a combustível reversível, Monografia, Centro Universitário Positivo, UnicenP, Curitiba.

Shariff, F. Rahim, N. A. Hew, W. P. 2015. Zigbee-based data acquisition system for online monitoring of grid-connected photovoltaic system, Expert Systems with Applications, vol. 42, n. 3, pp. 1730-1742.

Vera, L. H. Krenzinger, A. 2007. Comparação entre valores simulados e medidos para um sistema fotovoltaico autônomo, I Congresso Brasileiro de Energia Solar, pp. 1-10.

Vilela, W. A. 2010. Estudo, desenvolvimento e caracterização de radiômetros para medidas da radiação solar, São José dos Campos: INPE.