Design and Implementation of a Low-Cost Characterization System for Photovoltaic Solar Panels

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Abstract- Testing photovoltaic (PV) modules are one of the important procedures to ensure the conformity with the standards and quality of this equipment. To implement some of the PV modules tests a data acquisition system is required. This paper presents the design and implementation of a data acquisition system for photovoltaic systems. The developed system is characterized by a low-cost board based on a microcontroller. The description of the hardware as well an application to test its performance is presented. The developed system can be used for reading, storing and analyzing information from several photovoltaic systems. Experimental results are presented to confirm the best characteristics of the developed data acquisition board.

Keywords- Solar, photovoltaic, diagnostic, acquisition, design, implementation, identification, characterization, variable loads.

1. Introduction

The development of renewable energy has become increasingly important in recent years due to the many positive benefits it offers for the environment. In conjunction with this, the use of PV generators has subsequently received greater attention. PV generators are used for the transformation of solar energy into electrical energy. A typical photovoltaic panel consists of several solar cells connected together. The current-voltage characteristic I(V) of a photovoltaic panel is nonlinear, and, importantly, it is also greatly impacted by variations in temperature and irradiance (changing weather conditions) [1-11]. The power which can be obtained from the photovoltaic panel is achieved through the use of a power converter, which makes use of a variety of tracking techniques in order to recover the maximum amount of power possible from the panel. This power can subsequently be consumed immediately, if required, or stored (e.g., using a battery) for future use [12-30].

At present, the use of photovoltaic generators has become a cost-effective solution to economic crises and fluctuations in oil prices. Their use has been developed widely in several forms: off-line, hybrid or interconnected to the network. Therefore, the diagnosis of these photovoltaic panels has become increasingly essential.

The price of diagnostic systems for photovoltaic panels varies according to the quality of the product and its performance. The most expensive ones use the maximum number of possible measurements to determine all the parameters. The cheapest ones use a reduced number of measurements and by interpolation try to obtain the most important parameters.

To obtain the parameters of a photovoltaic panel, some diagnostic systems use microprocessor-based devices [31-34]; others use data recording systems [35-42]. Although the latter can give useful results while taking into account the measurement conditions, they are not practical to operate in real time as they require much time for calculations.

In this paper, the prototype presented is able to obtain the parameters automatically in a short time that approaches real time conditions. These parameters are saved in order to create an identity for the photovoltaic panel. If any of the parameters change over time, this gives a good indication of a malfunction in the panel. These parameters can also be exploited, for example, by a reference model to control an Maximum Power Point Tracker (MPPT) regulator, or for numerical simulations in order to test strategies for controlling the MPPT regulator.

To draw the current-voltage I(V) and power-voltage P(V) characteristics, a variable resistor, at the base of the transistor, is used. The change of the base current of the transistor from the minimum to the maximum permits the change of the current which passes through its collector. In this case, the photovoltaic panel sees a variable load at its terminals [43-50].

2. Modelling

Various methods of modelling photovoltaic panels exist. In this case, a single exponential model has been selected, represented by the electrical circuit shown in Fig.1.

The characteristic equation of this model is:

$$I = I_{PH} - I_S \cdot \left(\exp\left(\frac{q \cdot (V + R_S I)}{\alpha k T} \right) - 1 \right) - \frac{V + R_S I}{R_P} \qquad (1)$$

With:

- I: Output current from the PV panel (A),
- I_{PH}: Photocurrent (A),
- I_S: Diode reversed saturation current (A),
- q: Electron charge constant (1.6021×10^{-19} C),
- α: Diode ideality factor (≈ 1.2),
- k: Boltzmann's constant (1.3854×10^{-23} JK^{-1}),
- T: Panel operating temperature (°K),
- V: Output voltage at the panel terminals (V),
- R_S: Equivalent series resistance of the panel (Ω),
- R_P: Equivalent parallel resistance of the panel (Ω).

It should be noted that if a non-null and non-infinite load is placed at the terminals of a photovoltaic panel, the situation is intermediate between that of a short circuit and that of an open circuit. This results in a working voltage lower than the open circuit voltage. Hence, the fundamental characteristic of photovoltaic panels is that for a given irradiance and temperature neither the current nor the operating voltage are imposed; only the I(V) curve is fixed and it is the value of the load at the terminals that determines the operating point.

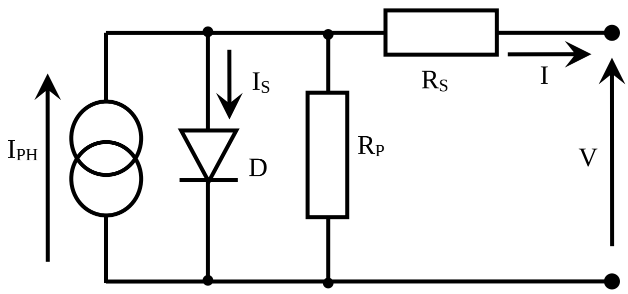

Fig. 1. Single exponential model of a photovoltaic panel.

3. Concept

For specific weather conditions, the photovoltaic panel can be verified with the factory settings for use as a reference panel. The parameters of this reference panel can orient the MPPT controller to maximize the power of the whole field of solar energy capture.

In order to estimate the parameters of a photovoltaic panel, they are based on the usual characteristics: current-voltage I(V) and power-voltage P(V).

The general principle of this system is simple: if the resistance across the photovoltaic panel is manually varied from zero to infinity, it is possible to produce these characteristics. Such a manual variation will not guarantee the measurements for the same irradiance and the same temperature. For this purpose, a rapid variation of the load is necessary. In addition, an acquisition system must be activated automatically during this variation, to measure voltage, current, irradiance and temperature.

Such a goal could not be achieved without a microcontroller. A Microchip-PIC18F4550 microcontroller contains several interesting interfaces, including analog/digital conversion, PWM output and communication in USB 2.0 mode.

At the base of the transistors, a variable load controlled by a microcontroller was designed. The very rapid change in the duty cycle from 0 to 100% of the PWM output allows the variation of the resistance seen by the photovoltaic panel from 0 to infinity. In this way, the characteristics of a photovoltaic panel can be captured for the same weather conditions.

During the acquisition phase, the microcontroller continuously transmits the measurements to a graphical interface using USB 2.0 communication with the PC. This graphical interface has been designed using LabView software to visualize the different measurements received and to save them as the microcontroller does not have a large backup memory.

With the various measurements performed, the microcontroller constitutes the current-voltage characteristic and launches an algorithm for estimating the parameters. These parameters will be displayed thereafter on an LCD screen and transmitted to the graphical interface.

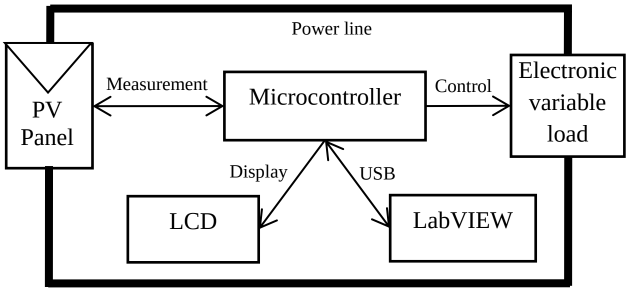

Fig. 2. System operation diagram.

These parameters, necessary for the simulation of the model in Fig.1, will be obtained from the knowledge of three operating points: short circuit, open circuit, and maximum power.

From these three operating points, a system equation can be written for all the parameters of the model. In a second step, this system equation is solved as a function of the series resistance; and an iterative calculation is applied according to the Newton-Raphson method in order to find the value of the series resistance as well as the other parameters of the model. Once the parameters of the model are identified, other equations can be considered to take into account the effect of irradiance and temperature.

This approach to determining the parameters governing the behavior of a single exponential model of the photovoltaic panel can be schematized by the following flowchart. The parameters of this model will be determined by the knowledge of three operating points: short circuit, open circuit and maximum power. Details of this approach are presented in the reference [51].

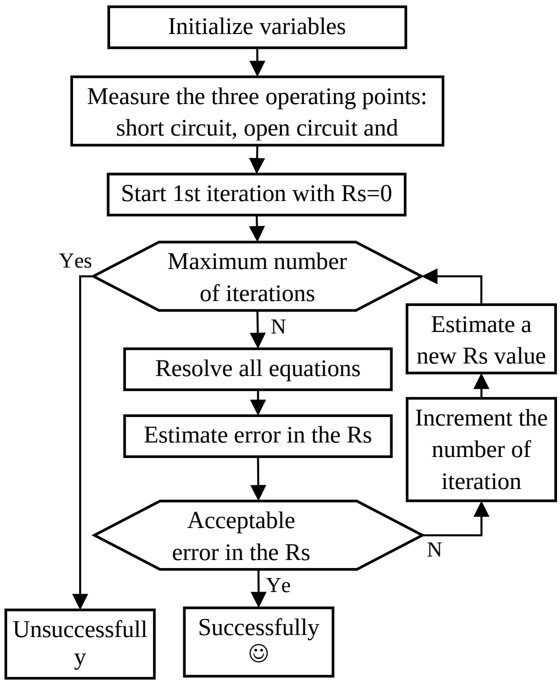

Fig. 3. Flowchart for determining the parameters of a photovoltaic panel.

4. Simulation

Before the realization of the system, some simulations were made to eliminate all design errors. In this phase, the parameter estimations with the data of the photovoltaic panel "LUXOR - Solo line 80W"; namely, the operating points: short-circuit, open circuit and maximum power, were simulated.

With several values of irradiance and temperature, the characteristics obtained by simulations were close to those given by the manufacturer. However, these obtained parameters were judged useful for experimenting with the single exponential model as shown in Fig. 4.

5. Implementation

The implementation has been divided into three parts: electronic realization, programming of the microcontroller, and development of a software interface on a PC.

The topology of the electronic realization was based on the automatic load variation at the terminals of the photovoltaic panel. The base of the transistor was chosen for simplicity and in order to obtain a lighter device, although other topologies may be used instead.

A transistor in a circuit operates in one of three modes:

- Cut-off mode (no collector current) useful for 'switching off' operations.
- In the active region (a collector current proportional to the base current), useful for amplification applications.
- In saturation mode (a large collector current), useful for 'switching on' operations.

From these three operating modes, a power transistor Q1 (BD142), which supports a current of 15 A and a voltage of 45 V, was connected in parallel with the photovoltaic panel.

The synoptic diagram of this electronic realization is illustrated in the Fig. 5.

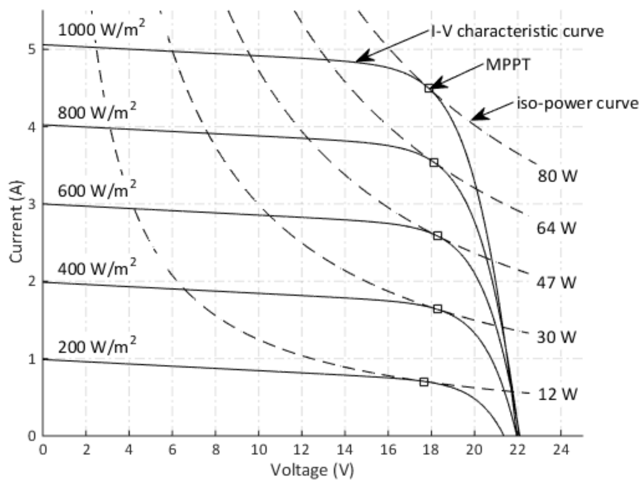

Fig. 4. The effect of irradiance in I-V characteristic curve.

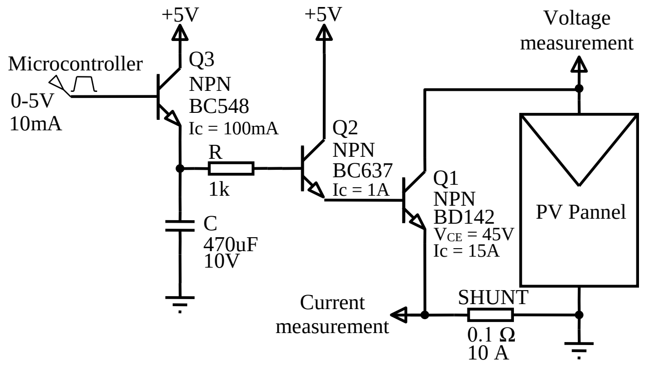

Fig. 5. Synoptic diagram of the electronic realization.

If the base current is zero, transistor Q1 operates in the first mode (switch off mode). The collector current remains null and the voltage V_{CE} will be the open circuit voltage V_{OC} (≈ 21 V). When the base current of transistor Q1 is slightly increased, the collector current in turn increases and the voltage V_{CE} decreases. This is the second operation mode (active region mode). If the base current is increased much more, transistor Q1 saturates and switches to the third operating mode. In this situation, the collector current approaches the short-circuit current I_{SC} of the photovoltaic panel (≈ 6 A) and the voltage V_{CE} of transistor Q1 becomes almost zero.

This variation in the behavior of transistor Q1 as a function of the variation of the current at its base enables the photovoltaic panel to be operated over its entire current-voltage characteristic. Hence, transistor Q1 plays the role of a variable resistor at the terminals of the photovoltaic panel.

To switch transistor Q1 from cut-off mode to saturation mode, the base current in this case must be increased to about 600 mA. For this purpose, another low-power transistor Q2 (BC637) (collector current of 1 A) was used. The supply voltage of its collector must be independent of that of transistor Q1 in order to guarantee a sufficient basic current to transistor Q1 during the short circuit operation (collector current $I_C \approx I_{SC}$ and voltage $V_{CE} \approx 0$ V).

The principle of variation of the base current of transistor Q1 is simple. An output pin of the microcontroller is activated for one instant (less than one second). During this time, the output current of this pin does not exceed 1 mA. This current makes the three transistors Q3, Q2 and then Q1 switch on. The conduction of transistor Q1 causes a variation of the operating point of the photovoltaic panel from the open-circuit point to the short-circuit point while passing through the other intermediate points, including the maximum power operating point. If the microcontroller is clocked at a fast frequency, it can acquire the voltage and the current of the photovoltaic panel during this stage.

Since the change in the operating point during the preceding step is very fast, it is preferred to lengthen the variation time of the behavior of the photovoltaic panel in order to minimize acquisition errors. Hence, a capacitor C which is charged during activation of the output pin of the microcontroller is added. When this output is deactivated, the capacitor begins to discharge slowly through the resistor R and the internal resistance of the base-emitter junction of transistors Q2 and Q1. During this phase, the microcontroller can now acquire the measurements required more easily, over a longer time period compared to previously.

The addition of transistor Q3 allows for the minimization of the current output of the microcontroller and at the same time avoids the discharge of the capacitor C inside the microcontroller when the output is deactivated.

The acquisition system is based on a Microchip PIC18F4550 microcontroller. The acquisition signals are sent directly to the analog inputs of the microcontroller by means of simple electronic circuits. Voltage and current are measured by a simple voltage divider and a 0.1 Ω / 10 A shunt resistor, respectively.

The system also includes other analog inputs for measuring irradiance and temperature. To measure the irradiance, a pyrometer can be used. While to make the temperature measurement, either a thermistor or a specialized integrated circuit such as the LM35 can be used.

When the capacitor C begins to discharge slowly, voltage and current are measured and stored in the internal memory EEPROM. The use of this memory or other SD card of sufficient size is required to have more storage space for a series of measurements. This saved data will be transmitted by USB to the software interface in order to make a graphical representation.

All system components were assembled on a double-sided printed circuit board (PCB), as shown in the Fig. 6.

The structure of the program embedded in the microcontroller is described in Fig.7. This program must deal with the control data sent by the software interface through the USB link.

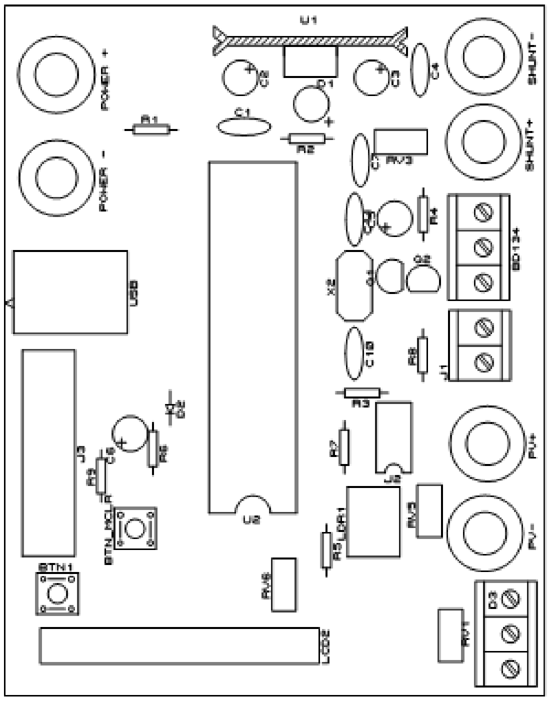

Fig. 6. PCB layout (component side).

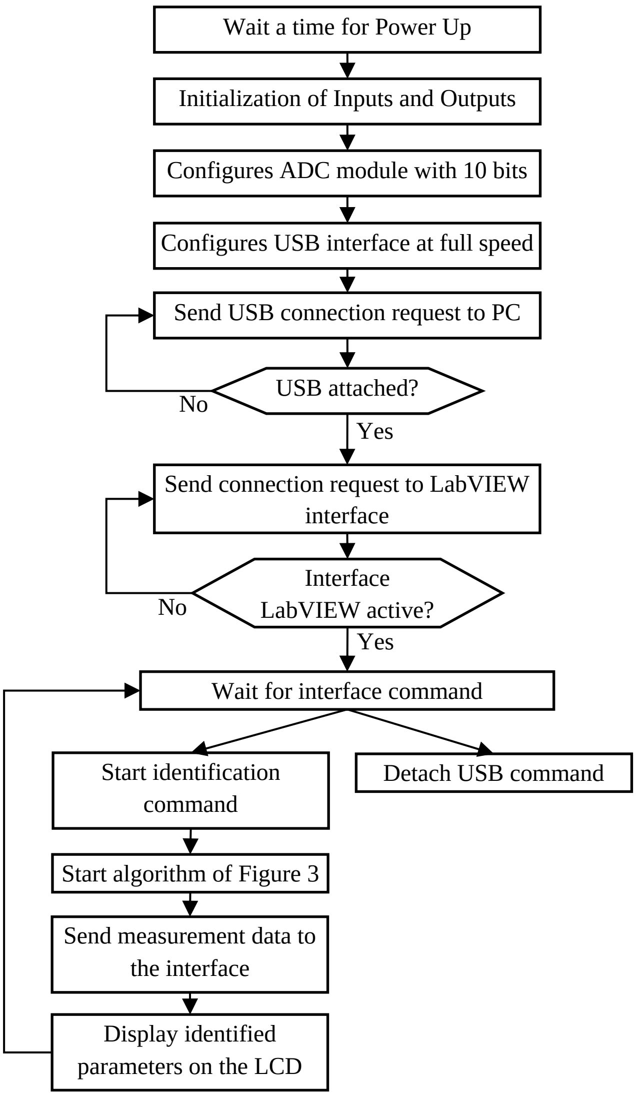

Fig. 7. Microcontroller program structure.

After power-up, the microcontroller initializes its input/output ports, and adjusts the ADC converter with 10-bits resolution and configures the USB interface. A “crystal clock speed” of 20 MHz was used to feed the microcontroller. In order to operate the USB interface at full speed (12 MIPS), the microcontroller multiplies the “crystal clock speed” internally, in the PLL stage, to obtain the “CPU clock speed” of 48 MHz.

After the initialization step, the microcontroller sends a request to connect the USB link with the PC. If this operation is successful, it tests the communication with the software interface. When the microcontroller finds this interface active, it waits for the command to start the parameter identification and send the measurements in real time.

To respond to this command, the microcontroller switches the output pin which controls the base of transistor Q3 ON then OFF during one second.

After this, the voltage and the current of the photovoltaic panel are measured for each 1 ms of time. These data are stored inside the internal EEPROM memory and then sent through the USB link to the software interface to present them in graphical form.

6. Experimentation

Our experimental device was designed for only one photovoltaic panel. Figure 8 shows a picture of this realization. In addition to the USB interface, there are several LED that make it easier to use the final system.

This device was tested with the same photovoltaic panel “LUXOR - Solo line 80” used in the simulation. The tests were carried out with different irradiance and temperature values, in order to check the robustness and stability against external disturbances. It is possible to obtain both the power output and current curves in less than 10 seconds.

The software interface is shown in Fig.9, where several measurements are displayed.

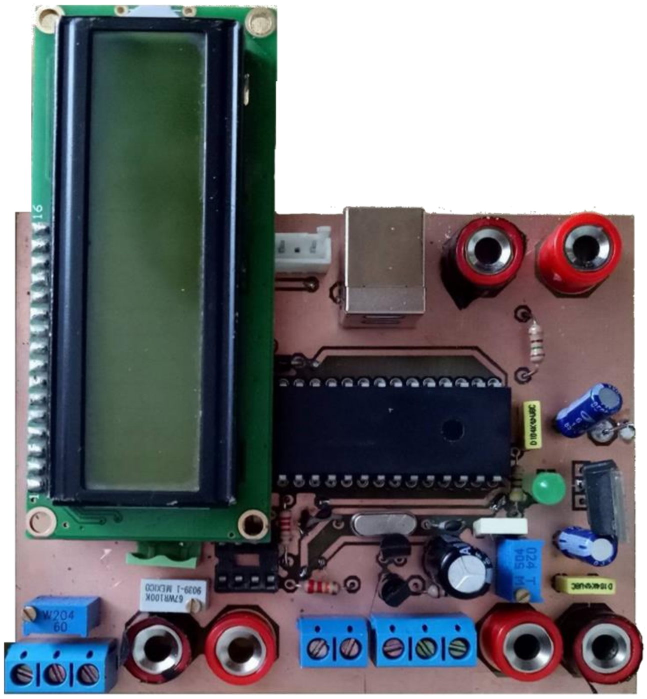

Fig. 8. PCB of the completed system.

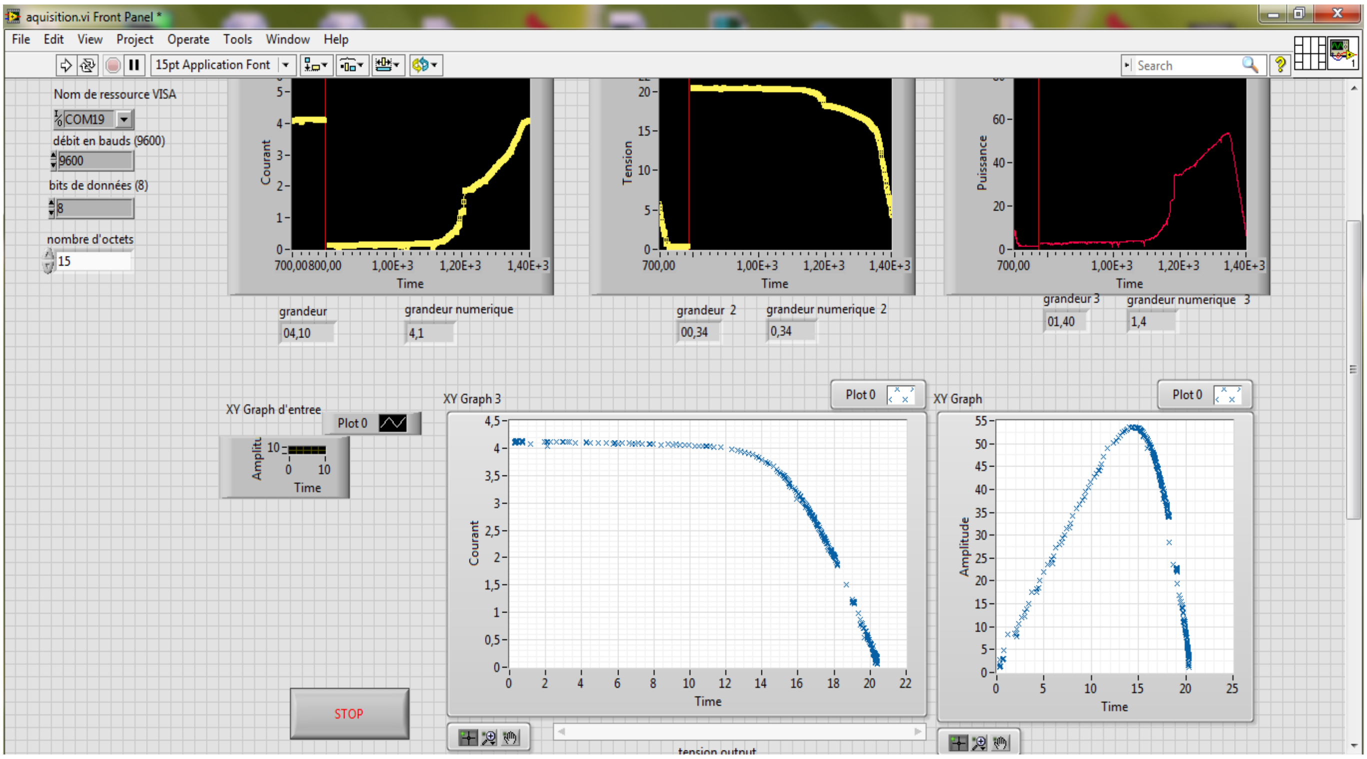

Fig. 9. Sample of the HMI interface.

With the current-voltage and power-voltage curves, the software interface display the value of all estimated parameters, the open-circuit voltage, the short-circuit current, the maximum power, and the date and time when the analysis was performed.

The comparison between the results of simulation and those of the experiment shows the good approximation of this model.

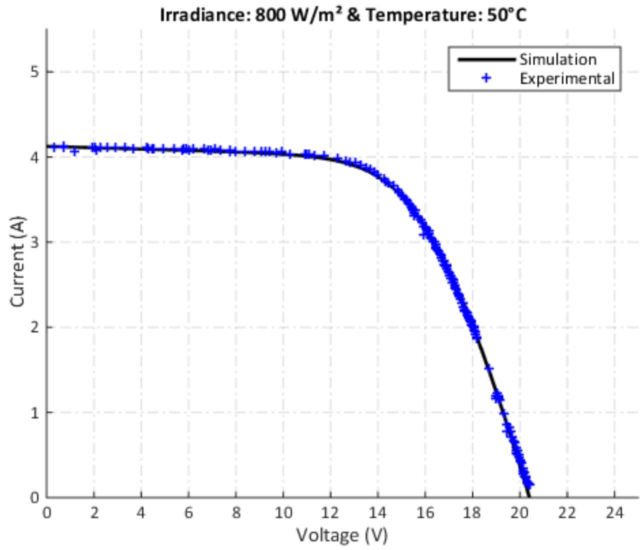

Fig. 10. Comparison between simulation and experiment results.

7. Conclusion

The rapid increase in demand for renewable energy has resulted in photovoltaic systems (solar cells) being installed at an ever-increasing rate, and on a greater scale than previously. This has also resulted in an increased demand for diagnostic ability in relation to such photovoltaic systems.

Against this background, this work suggests a low-cost solution to the analysis and diagnosis of such photovoltaic panels able to identify the parameters of each panel for modelling which allows for digital simulations to be performed and stored in order to create a panel profile, which allows the tracking of its operational status and efficiency, and identification of problems.

In the model suggested, a programmed microcontroller (microchip-PIC18F4550) was employed to automate the identification of the required photovoltaic panel parameters; this permits the control of a variable resistance in order to track the current-voltage characteristic and capture the required data to generate identifiable parameters for each one-diode model.

Using LabView, a software interface was generated in order to control the diagnostic device, and through analysis of the test results obtained it was possible to verify that the photovoltaic panel under test was in a good operational state with the desired level of efficiency.

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